

NASA SPACE TECHNOLOGY MISSION DIRECTORATE EARLY CAREER INITIATIVE

# PTERODACTYL: AN UNCOUPLED RANGE CONTROL APPROACH TO FULLY NUMERICAL PREDICTOR-CORRECTOR ENTRY GUIDANCE

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# What is Pterodactyl?

A design, build, and test capability for finding optimal, scalable Guidance & Control (G&C) solutions for Deployable Entry Vehicles (DEVs) to enable precision targeting

# MOTIVATION

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



# BASELINE MODELS AND PARAMETERS

Baseline vehicle (Aeroshell is fixed)

Lifting Nano-ADEPT (LNA)

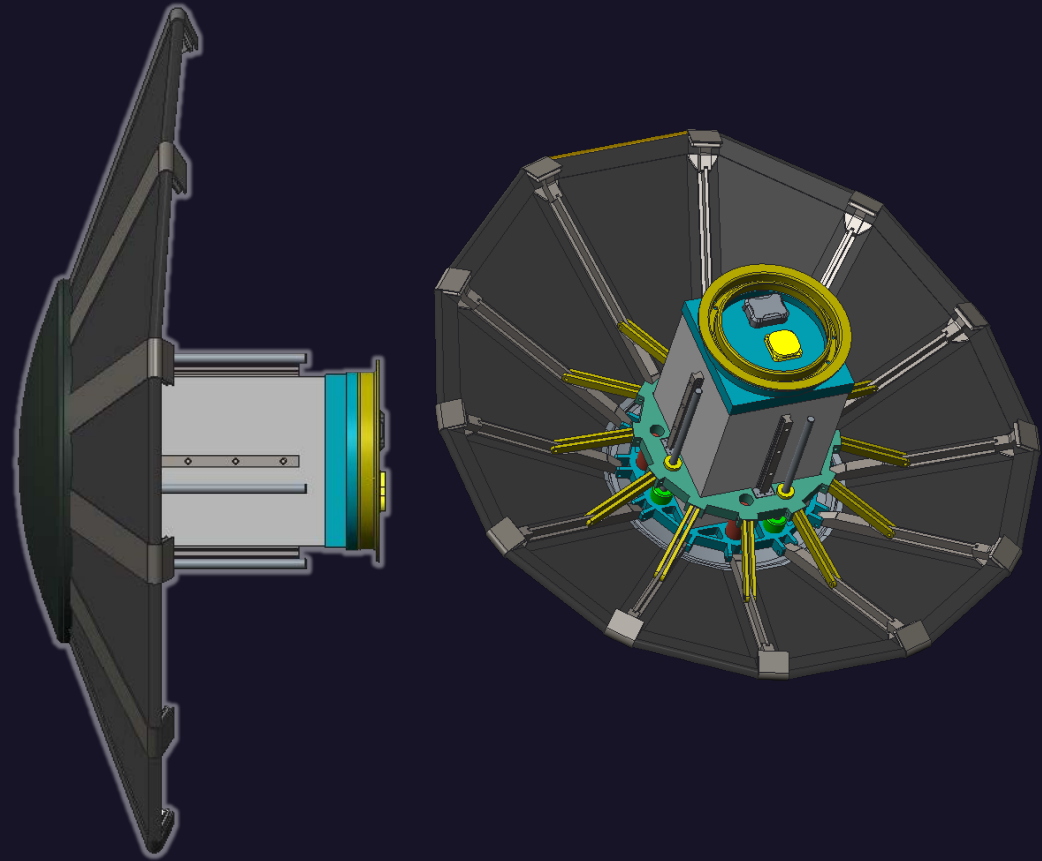
1 m diameter

Mass = 54 kg

Loading Constraints

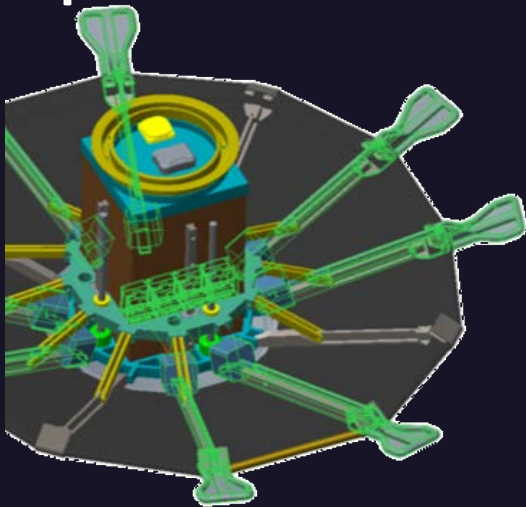
Heating Rate  $\leq 250 \text{ W/cm}^2$

G-load  $\leq 15g$ 's

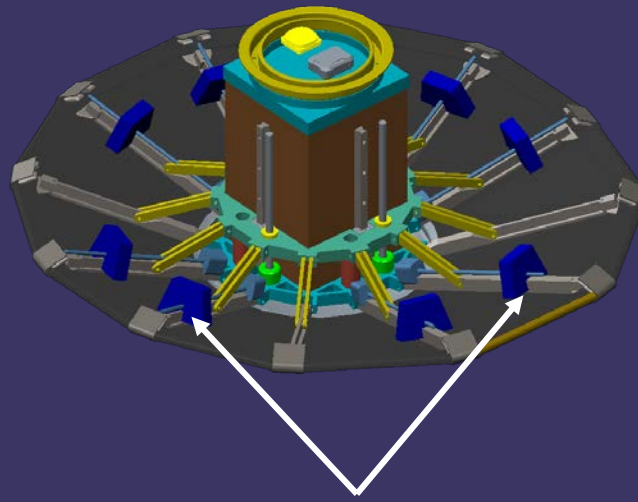


# CONTROL SYSTEM TRADE STUDY

Flaps

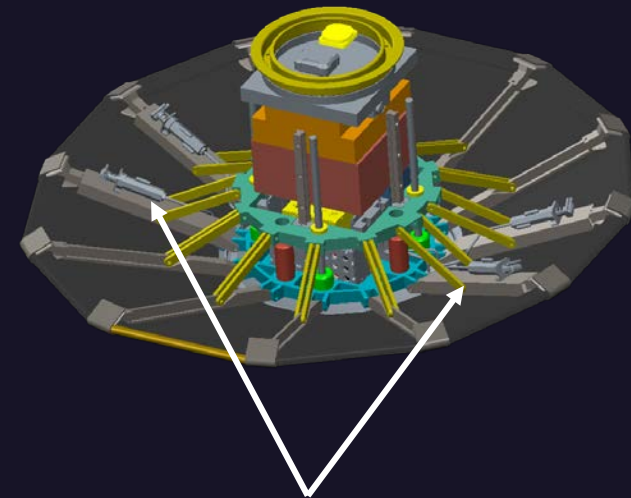


Mass Movement



Independent  
Moveable Masses

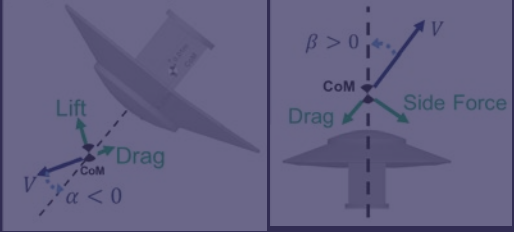
Reaction Control  
System (RCS)



4 RCS Jets



# MODELS AND SIMULATIONS

Model	New Development	Purpose
Aerodynamics & Aeroheating	Multi-flap modeling to generate database of forces and moments @ specific flow conditions and attitudes	
Guidance Algorithm	Develop methodology for identifying $\alpha/\beta$ control	Precision targeting by reducing down range and cross range errors
Control Algorithm	Identify flap deflections to track guidance commands	<ul style="list-style-type: none"> <li>- 6DOF simulation development</li> <li>- Define control requirements for mechanical design</li> </ul>
Mechanical Design	Identify mechanical components to achieve flap angles, rates, and acceleration	Ensure hardware integration feasibility and stowing capability
TPS/Structures Mass Estimate	Flaps mass estimation model TPS of thickness and mass	TPS estimation key to estimation flap control system mass

# NEW TARGETING APPROACH

**Uncoupled Range Control (URC) - Integrated  $\alpha/\beta$  control for targeting in the Fully Numerical Predictor-corrector Entry Guidance (FNPEG<sup>1</sup>)**

WHY? It is robust and adaptable to different configurations

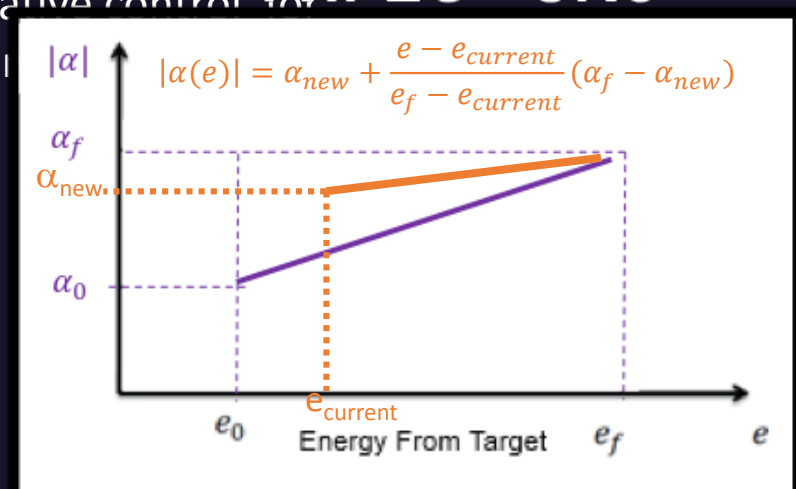
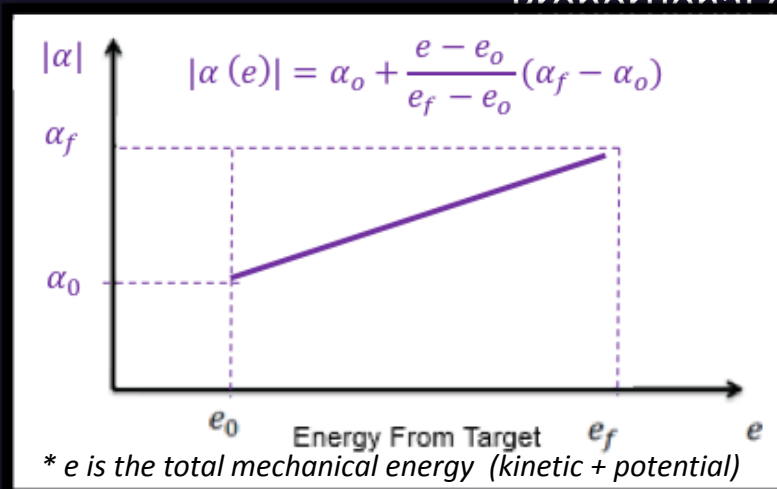
## $\alpha$ -command method

INITIAL GUESS – Linear function of mechanical energy

TARGETING – corrects down range error by finding a modified linear profile

## $\beta$ -command method

Proportional derivative control for



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

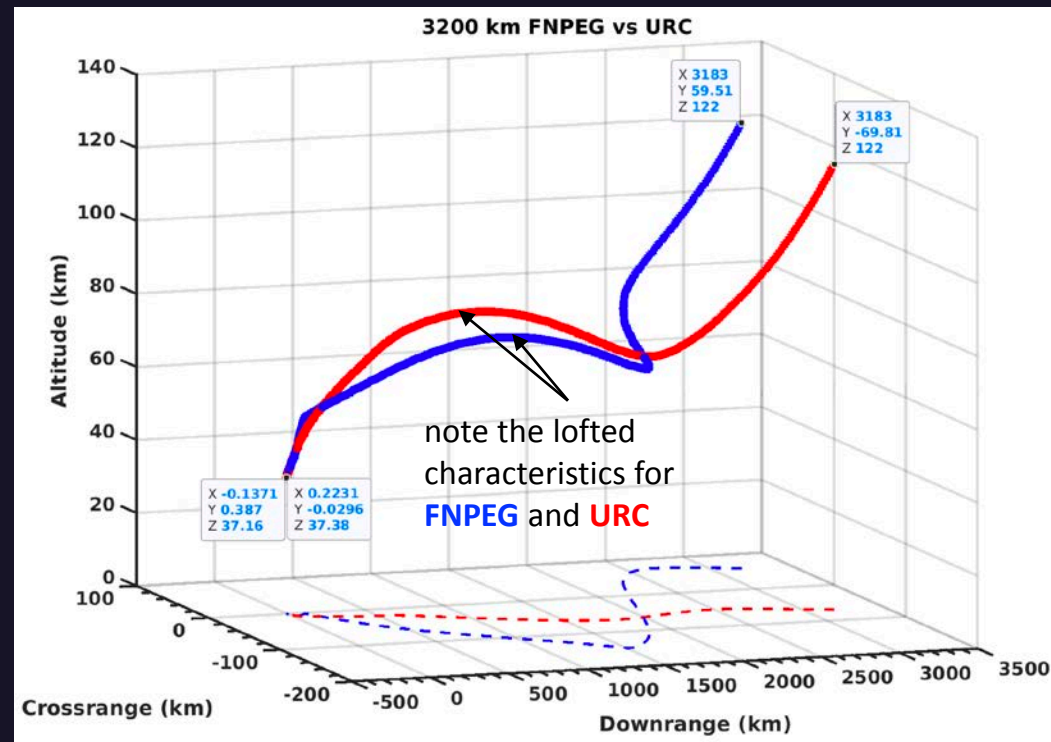


# FNPEG URC PROFILE

This is an example trajectory path for an FNPEG-URC flaps controlled LNA, 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,  $\leq 5$ km miss distance is desired

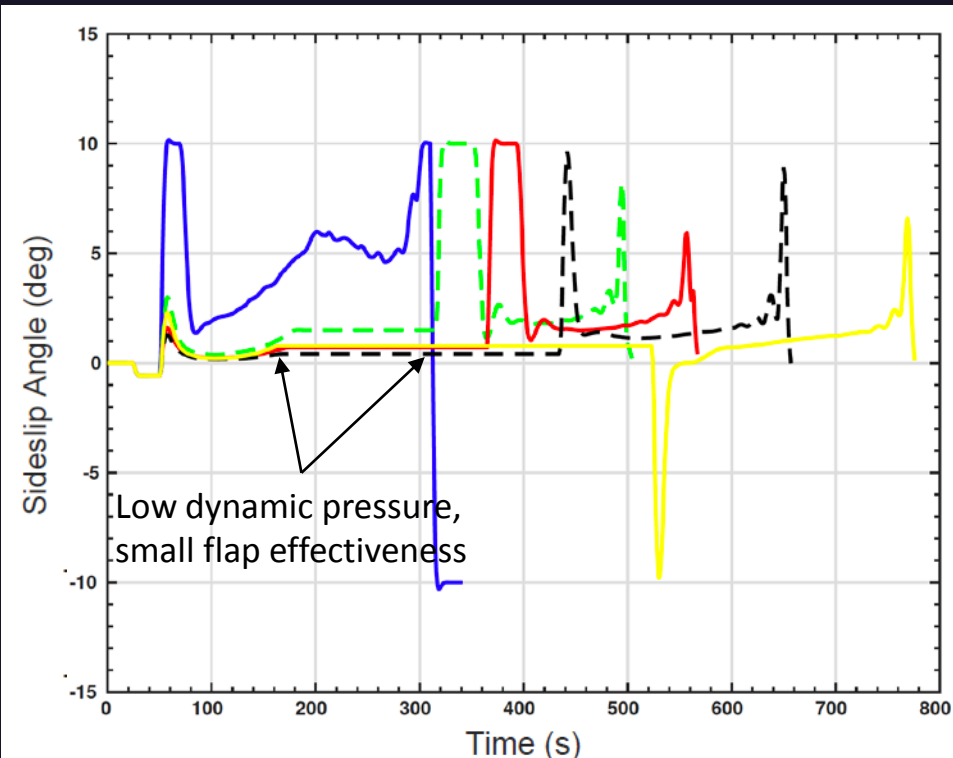
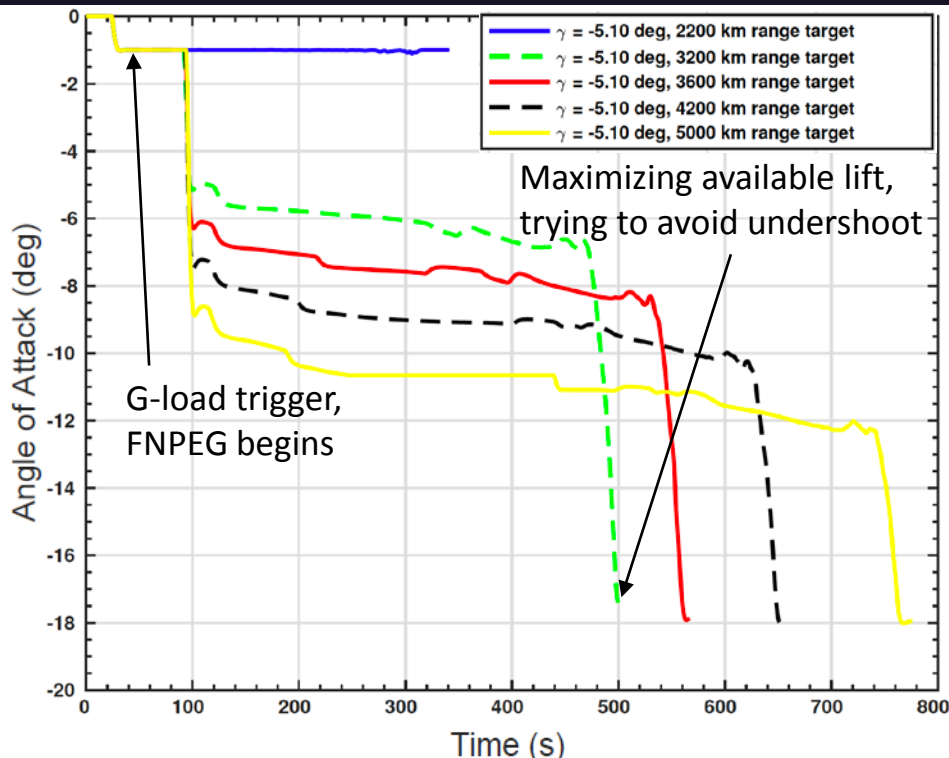




# URC TARGETING PERFORMANCE

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 0.5km 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 ( $<250 \text{ W/cm}^2$ ), g-load ( $<15 \text{ g's}$ ), and miss distance ( $<5 \text{ km}$ ) desired limits

Monte Carlo Variables	Standard Deviation $\sigma$
Initial Velocity	$\pm 3.33 \text{ m/s}$
Initial FPA	$\pm 0.03^\circ$
Initial Azimuth	$\pm 0.1^\circ$
Initial Lat	$\pm 0.1^\circ$
Initial Lon	$\pm 0.1^\circ$
Initial Altitude	$\pm 100 \text{ m}$
Initial Mass	$\pm 1\% \text{ kg}$

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



# EXAMPLE PERFORMANCE FOR CANDIDATE CONTROL SYSTEMS

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):**

- $\alpha_{trim} = -16.6^\circ$
- $L/D_{trim} = 0.27$
- $\beta_{ball\ coef} = 54\text{ kg/m}^2$

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

$\gamma_{EI} = -5.2^\circ$ , Range to target = 3400 km

- **Mass Movement Performance Statistics (URC):**

- $[\alpha_{range}, \beta_{range}] = [-9^\circ, -17^\circ], [\pm 10^\circ]$
- $L/D_{range} = [0.15, 0.29]$
- $[\beta_{ball\ coef}] = 64\text{ kg/m}^2$

1000-case MC	Mean	Max
Miss Distance	0.154 km	0.426 km
Peak Heat Rate	232 W/cm <sup>2</sup>	245 W/cm <sup>2</sup>
Peak G-load	7.7 g	8.1 g

$\gamma_{EI} = -5.8^\circ$ , Range to target = 4200 km

- **Flaps Performance Statistics (URC):**

- $[\alpha_{range}, \beta_{range}] = [-1^\circ, -18^\circ], [\pm 10^\circ]$
- $L/D_{range} = [0.04, 0.30]$
- $[\beta_{ball\ coef}] = 58\text{ kg/m}^2$

1000-case MC	Mean	Max
Miss Distance	0.42 km	0.87 km
Peak Heat Rate	W/cm <sup>2</sup>	217 W/cm <sup>2</sup>
Peak G-load	g	7.49 g

$\gamma_{EI} = -5.2^\circ$ , Range to target = 3400 km



# GUIDANCE PERFORMANCE FOR CANDIDATE CONTROL SYSTEMS

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

- **Example Performance Statistics (FNPEG):**

- $\alpha_{trim} = -16.9^\circ$
- $L/D_{trim} = 0.27$
- $\beta_{ball\ coef} = 58\text{ kg/m}^2$

1000-case MC	Mean	Max
Miss Distance	0.43 km	2.4 km
Peak Heat Rate	203 W/cm <sup>2</sup>	218 W/cm <sup>2</sup>
Peak G-load	5.7 g	6.5 g

$\gamma_{EI} = -5.2^\circ$ , Range to target = 3400 km

- **Altered Performance Statistics (FNPEG):**

- $\alpha_{trim} = -14^\circ$
- $L/D_{trim} = 0.23$
- $\beta_{ball\ coef} = 58\text{ kg/m}^2$

1000-case MC	Mean	Max
Miss Distance	0.44 km	1.2 km
Peak Heat Rate	198 W/cm <sup>2</sup>	212 W/cm <sup>2</sup>
Peak G-load	5.8 g	6.4 g

$\gamma_{EI} = -5.2^\circ$ , Range to target = 3400 km

- **Example Performance Statistics (URC):**

- $[\alpha_{range}, \beta_{range}] = [-9^\circ, -17^\circ], [\pm 10^\circ]$
- $L/D_{range} = [0.15, 0.29]$
- $[\beta_{ball\ coef}] = 64\text{ kg/m}^2$

1000-case MC	Mean	Max
Miss Distance	0.154 km	0.426 km
Peak Heat Rate	232 W/cm <sup>2</sup>	245 W/cm <sup>2</sup>
Peak G-load	7.7 g	8.1 g

$\gamma_{EI} = -5.8^\circ$ , Range to target = 4200 km

- **Altered Performance Statistics (URC):**

- $[\alpha_{range}, \beta_{range}] = [-9^\circ, -17^\circ], [\pm 4.5^\circ]$
- $L/D_{range} = [0.15, 0.29]$
- $[\beta_{ball\ coef}] = 64\text{ kg/m}^2$

1000-case MC	Mean	Max
Miss Distance	0.76 km	3.58 km
Peak Heat Rate	243 W/cm <sup>2</sup>	260 W/cm <sup>2</sup>
Peak G-load	8.12 g	8.81 g

$\gamma_{EI} = -5.8^\circ$ , Range to target = 4200 km

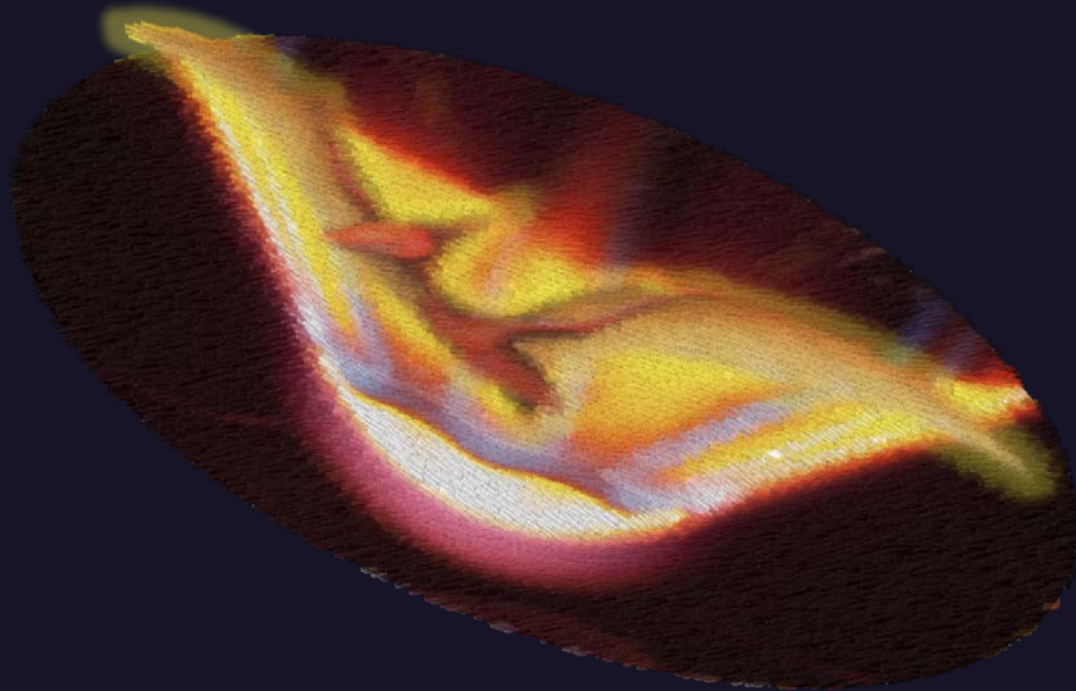


# WHAT HAVE WE LEARNED?

- 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 (<5 km)
- Success of FNPEG-URC driven designs (Mass Movement, Flaps) is strongly driven by operational angle of attack & sideslip range



# QUESTIONS?



# BACK UP SLIDES



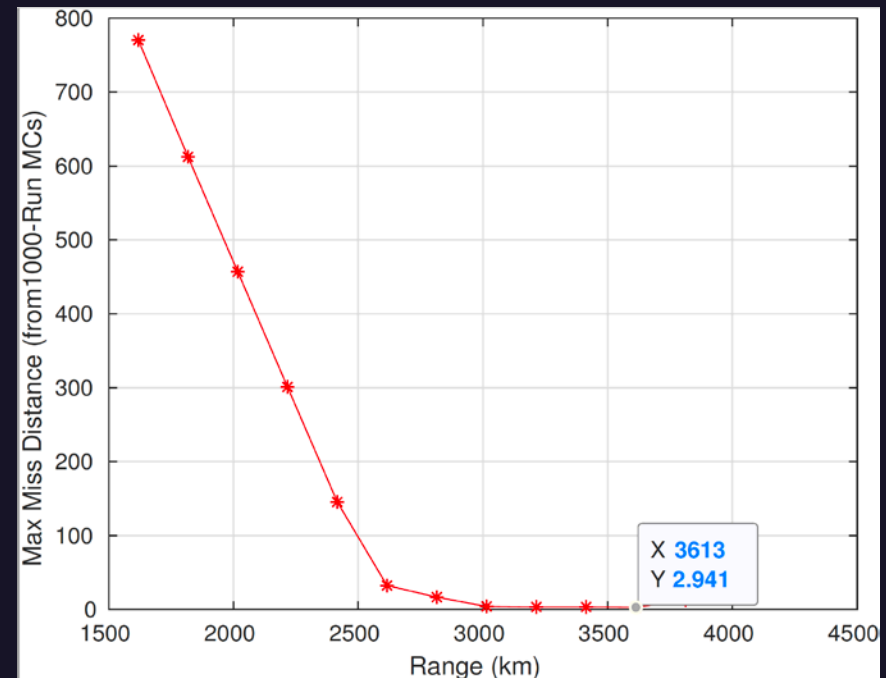
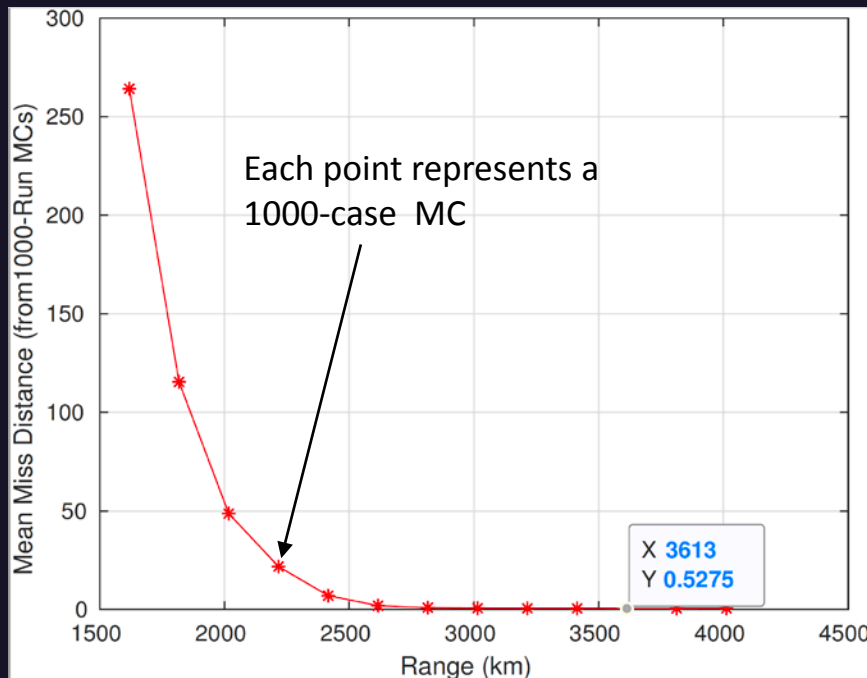


# URC TARGETING PERFORMANCE

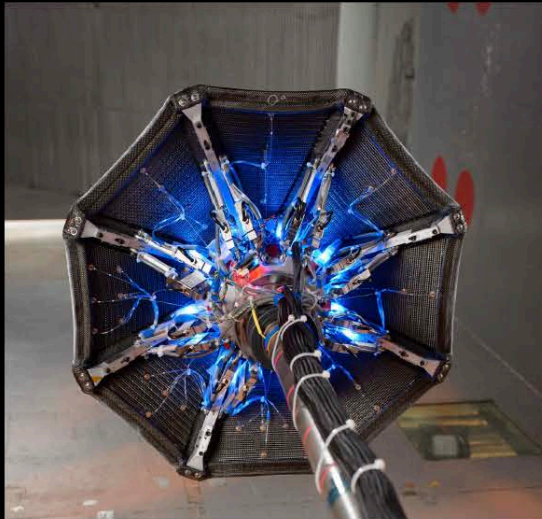
- Monte Carlos (MCs) were run with typical dispersions for a lunar entry mission
- All runs for example FNPEG-URC case satisfy heating (<math> < 250 \text{ W/cm}^2 </math>), g-load (<math> < 15 \text{ g's}</math>), and miss distance (<math> < 5 \text{ km}</math>) desired limits

Monte Carlo Variables	Standard Deviation $\sigma$
Initial Velocity	$\pm 3.33 \text{ m/s}$
Initial FPA	$\pm 0.03^\circ$
Initial Azimuth	$\pm 0.1^\circ$
Initial Lat	$\pm 0.1^\circ$
Initial Lon	$\pm 0.1^\circ$
Initial Altitude	$\pm 100 \text{ m}$
Initial Mass	$\pm 1\% \text{ kg}$

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



# Large to Small Mass Missions are driving the development of DEVs!

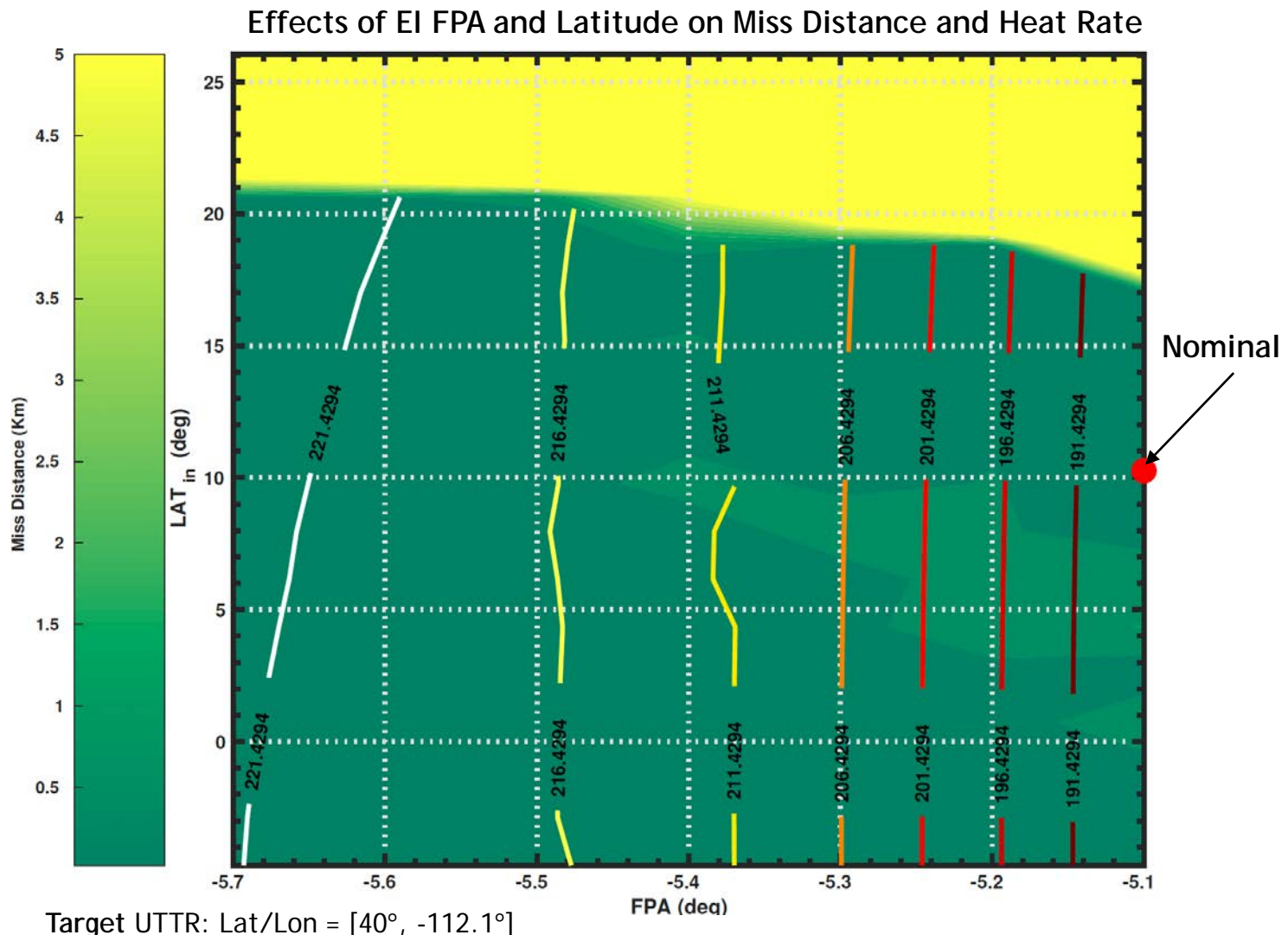


Adaptable, Deployable Entry Placement Technology (ADEPT)

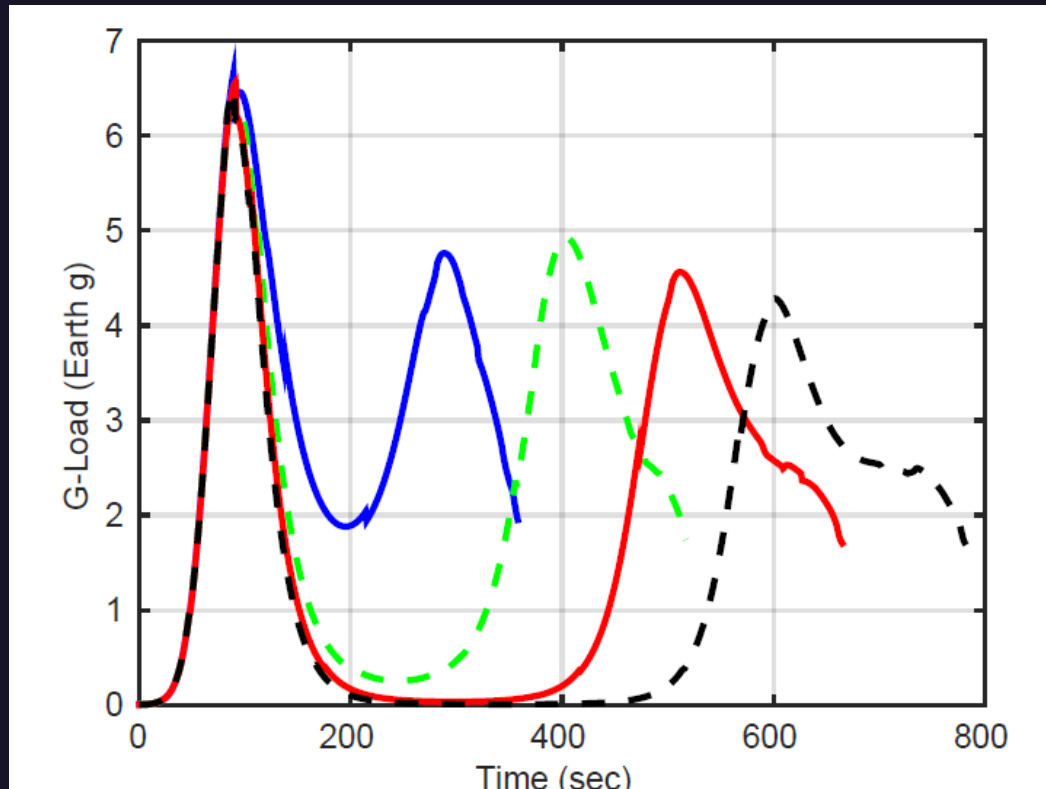


Hypersonic Inflatable Aerodynamic Decelerator (HIAD)

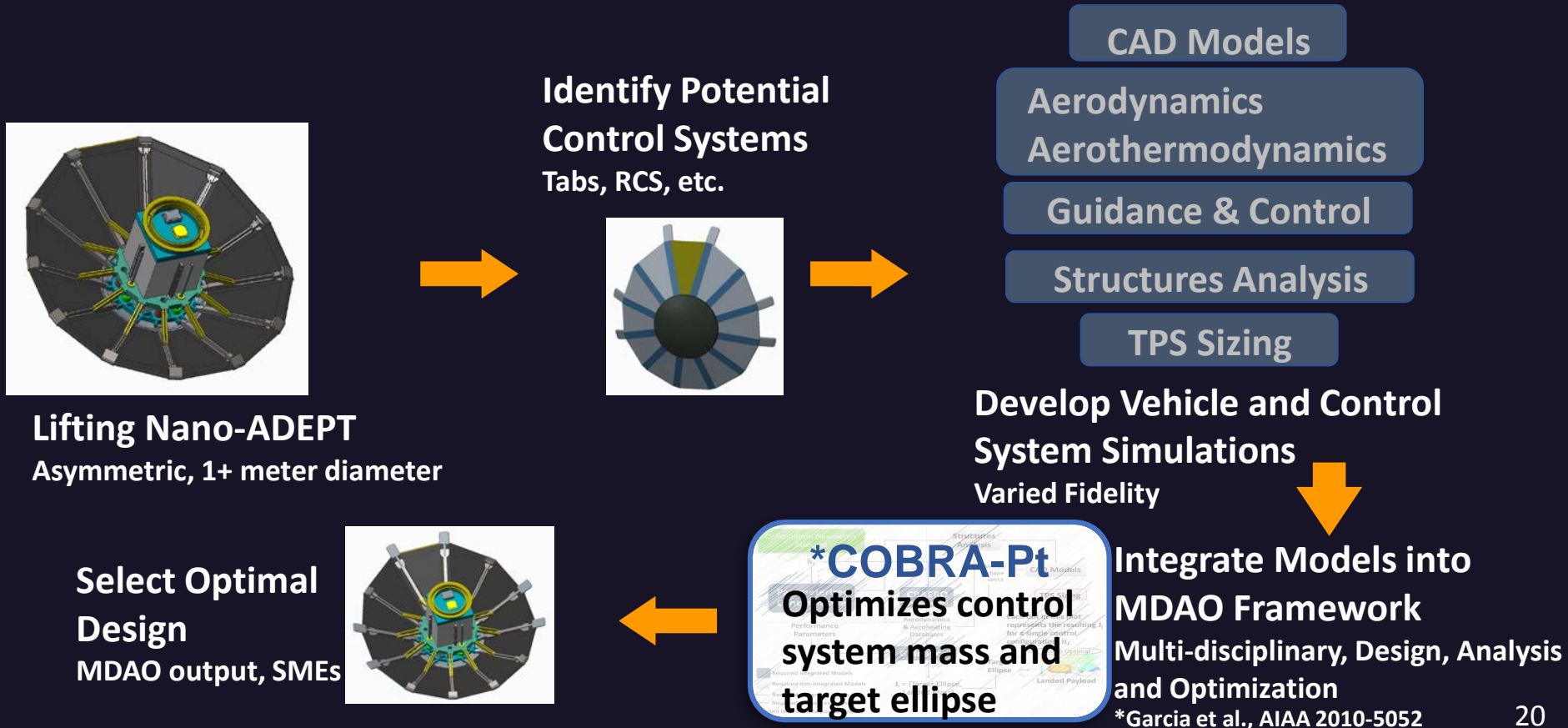
# EI STUDY : IN SEARCH OF CONVERGENCE



# FNPEG URC G-LOAD CURVES

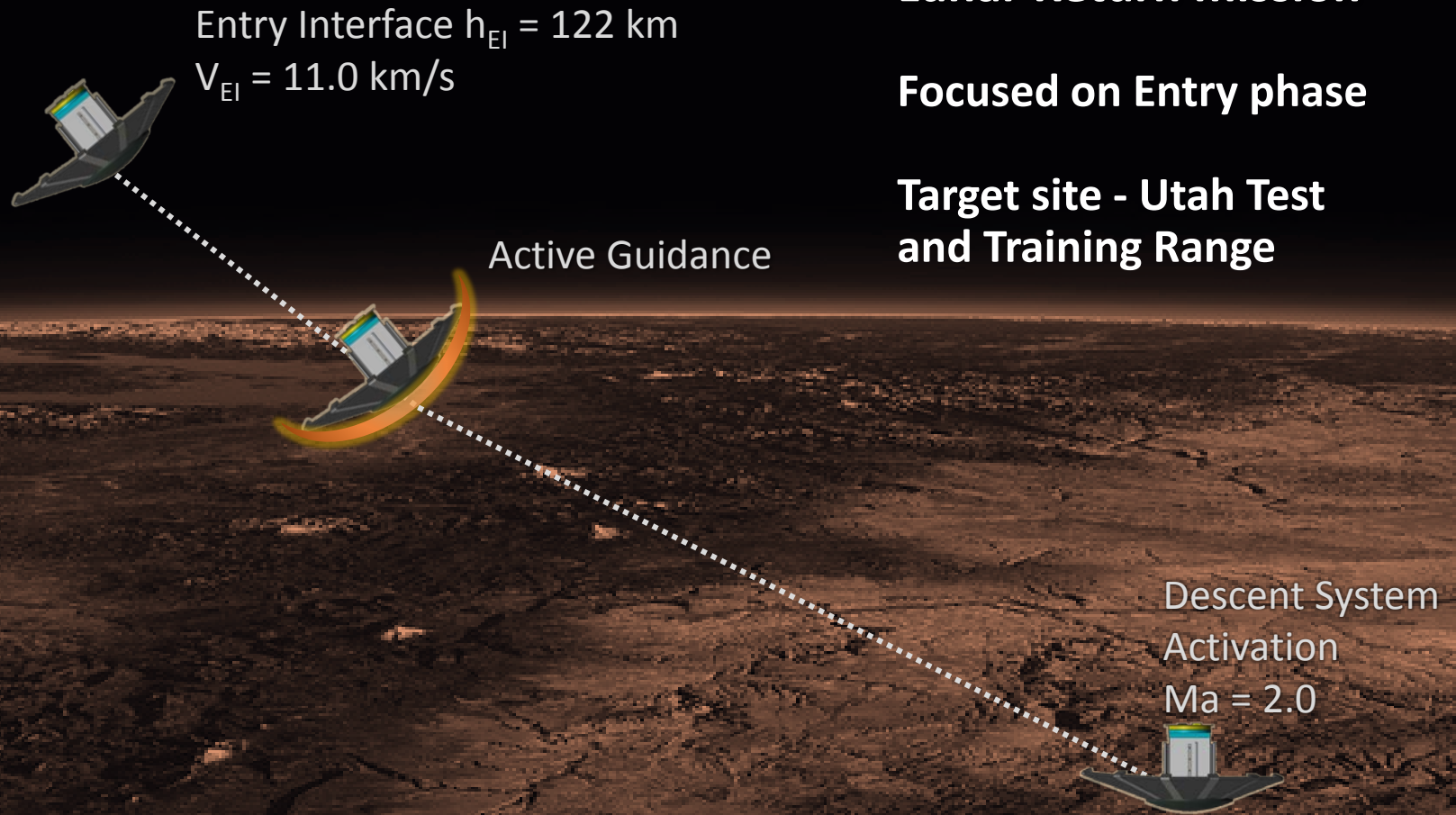


# Pterodactyl Design Process Overview

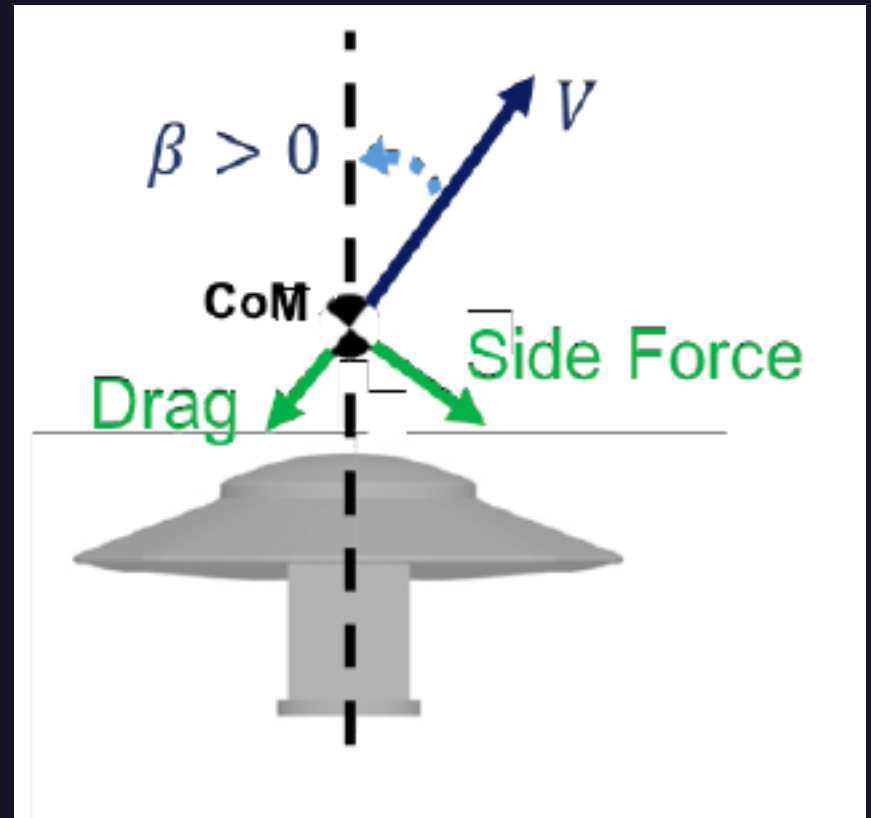
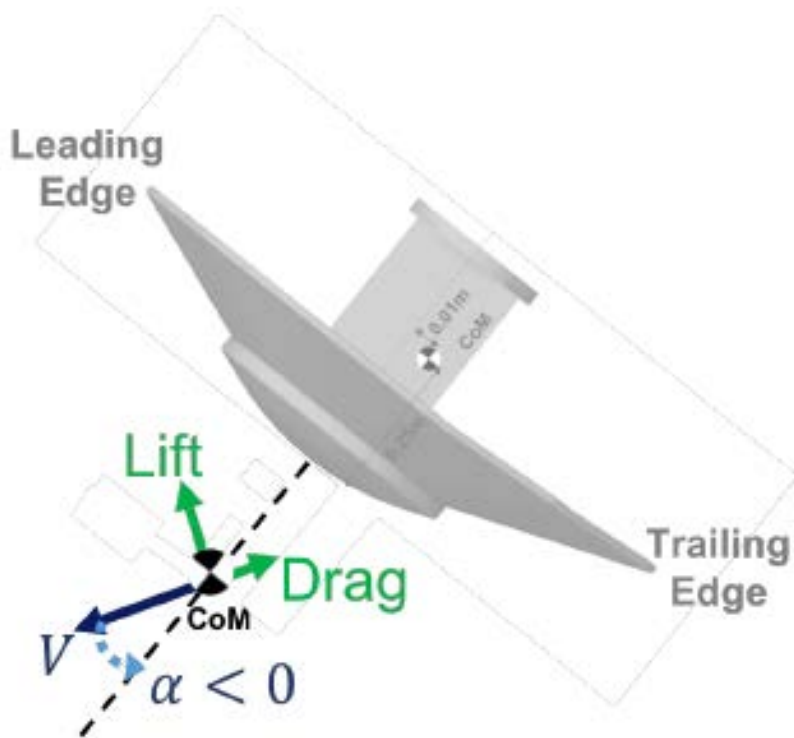


# BASELINE MODELS AND PARAMETERS

(CONT'D)



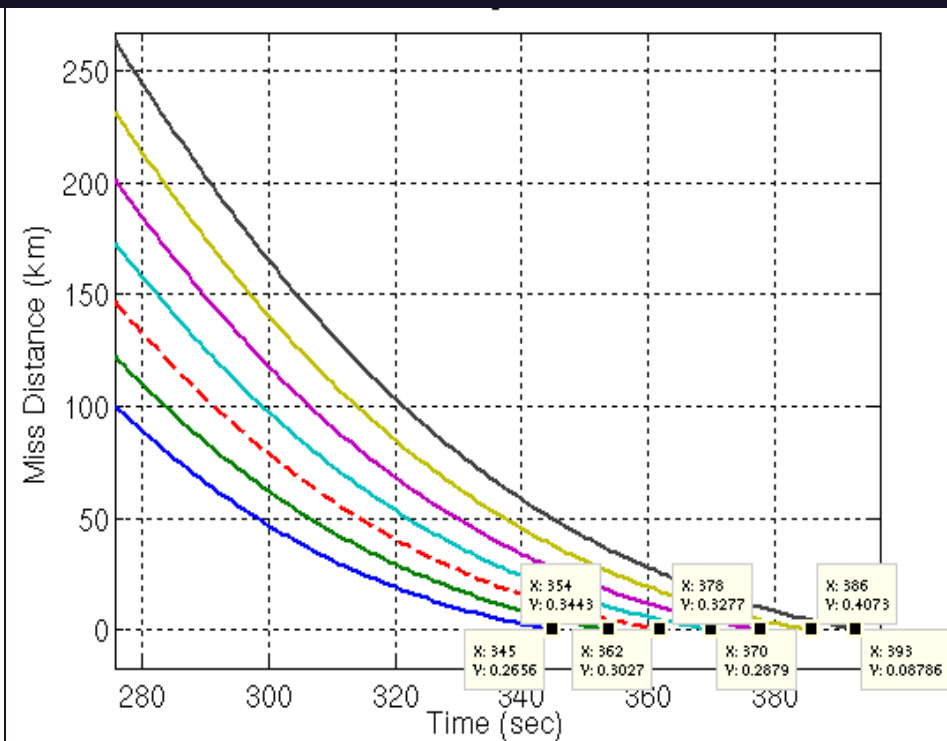
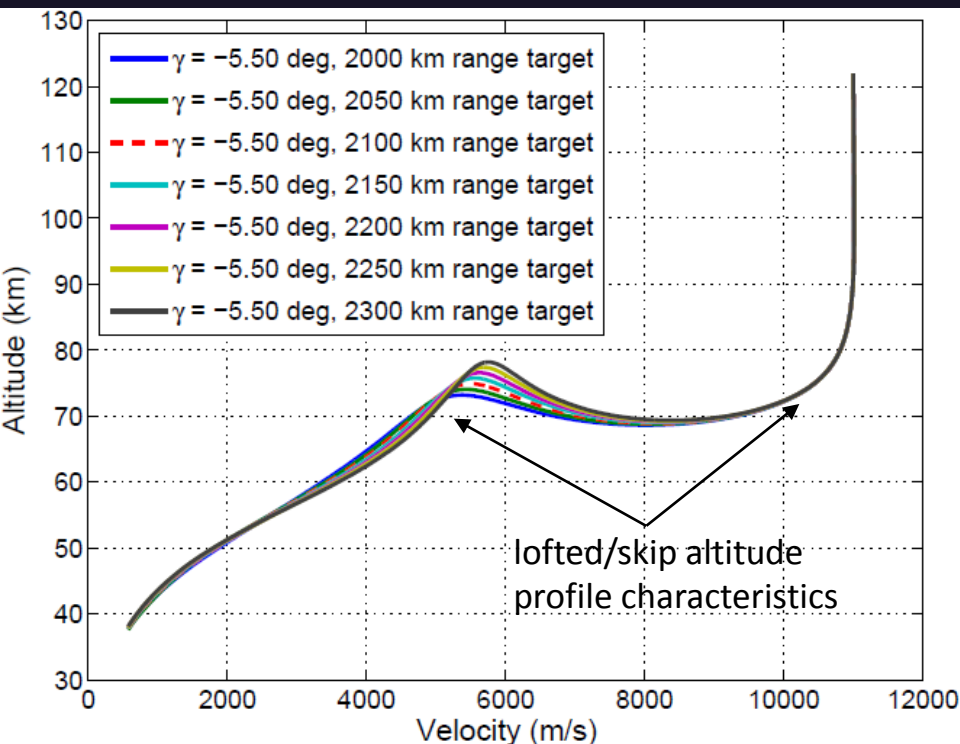
# FLAP CONFIGURATION OVERVIEW





# $\alpha$ - $\beta$ GUIDANCE

- Achieved precision targeting for downranges of 2000 to 2300 km, all satisfying the desired footprint (in the sky) of 5 km radius

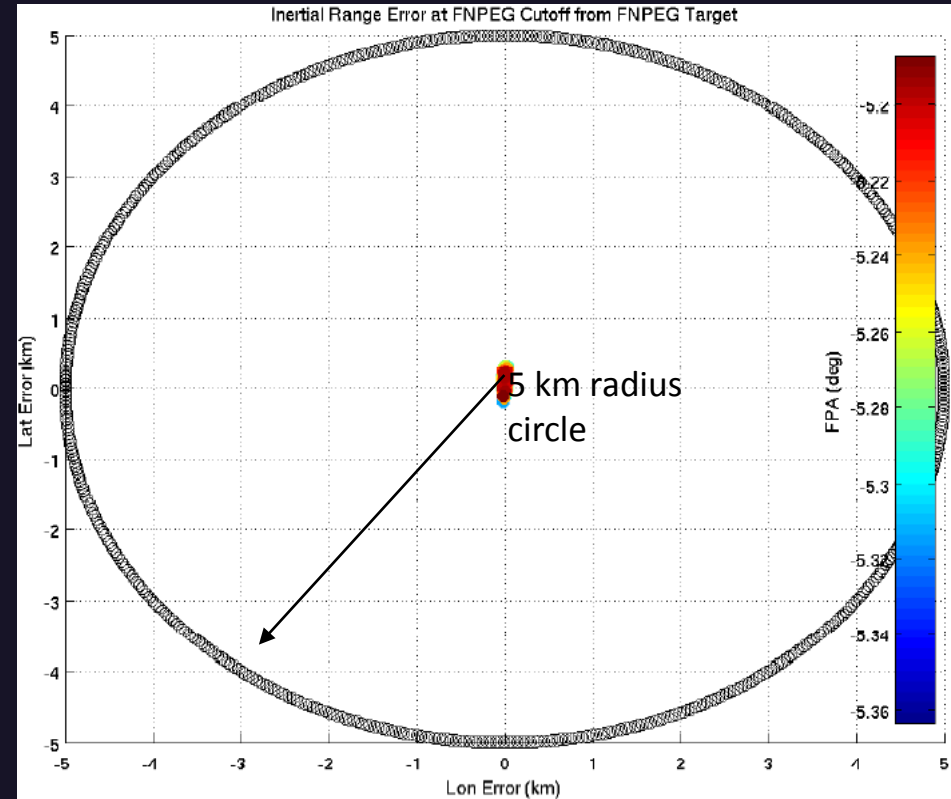
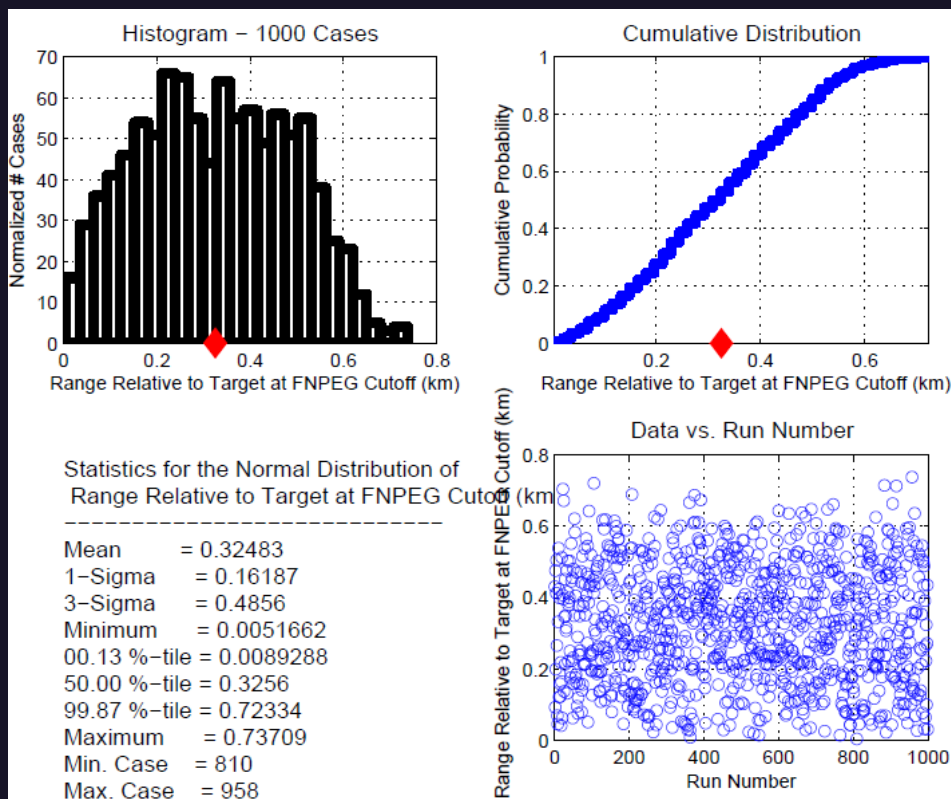


# $\alpha$ - $\beta$ GUIDANCE

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

Monte Carlo Variables	Standard Deviation $\sigma$
Initial Velocity	$\pm 3.33$ m/s
Initial FPA	$\pm 0.03^\circ$
Initial Azimuth	$\pm 0.1^\circ$
Initial Lat	$\pm 0.1^\circ$
Initial Lon	$\pm 0.1^\circ$
Initial Altitude	$\pm 100$ m
Initial Mass	$\pm 0.4$ kg

- Monte Carlos (MCs) were run for the FNPEG and FNPEG URC trajectories, with dispersions consistent with a typical lunar entry mission
- All runs for baseline satisfy heating, g-load, and miss distance constraints
- Multiple MCs were run for different ranges to converge on best input entry interface (EI)



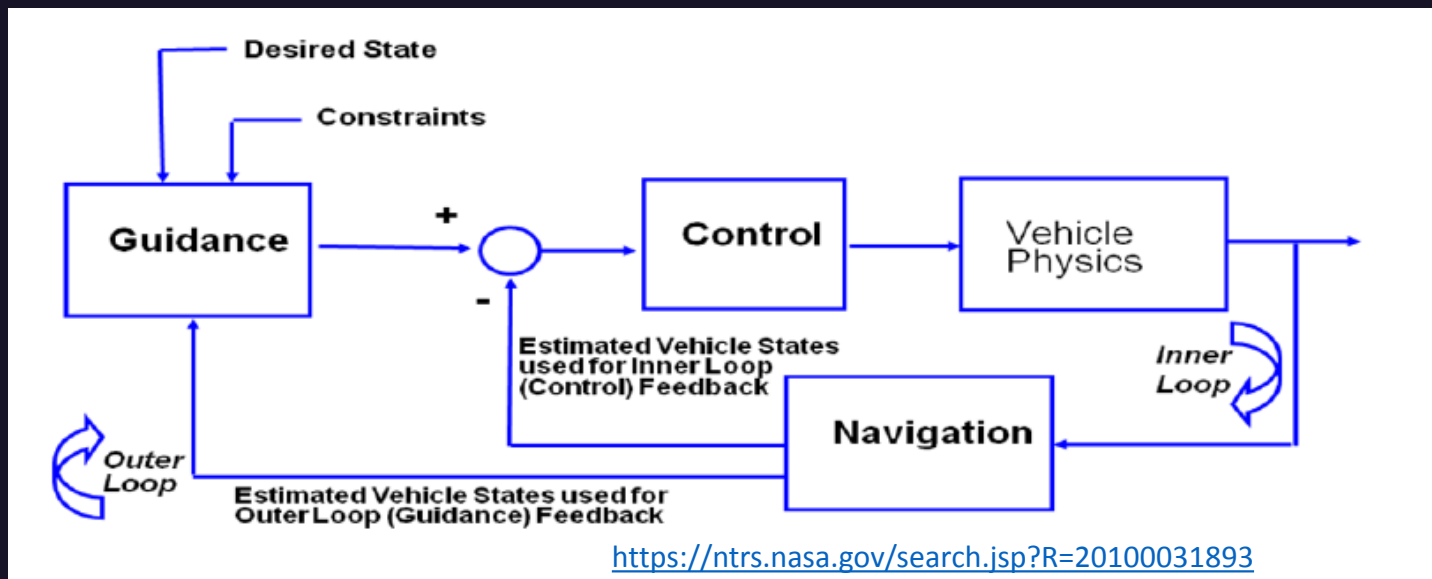
# GUIDANCE WORK COMPLETED

- Investigated entry corridor characteristics for non-guided constant bank angle trajectories to extract notional FPA, g-load, heating, range envelope (for Con Ops & Guidance inputs)
- Delivered FNPEG trajectory with bank-only modulated profile
  - Cases included: Mars, LEO return, Lunar return
- Converted FNPEG to FNPEG URC and re-derived Equations of Motion for FNPEG to determine bank angle only vs. angle-of-attack (alpha) & sideslip angle (beta) assumptions
- Delivered 3DoF Monte Carlo results from FNPEG and FNPEG URC (single and range of MCs)
- Completed an angle rate/acceleration limit study to inform 6DoF work
- Created scripts to help auto generate inputs for the MDAO process
- Transferred FAST over to Ames' Pleiades supercomputer and worked to get compilation
- Found that alpha is a strong parameter to vary range, but may be more susceptible to aero errors than bank guidance



# GUIDANCE

- **Guidance:** determines a moving vehicle's current position/velocity/attitude state to a desired position/velocity/attitude state, while satisfying specified constraints such as fuel expenditure, safety, dynamic/thermal loading, and time criticality
- **Navigation:** determines the current dynamic state (position, velocity, attitude etc.) of a vehicle provided noisy sensor measurement data in a specified frame of reference
- **Control:** determines and applies the force and torque commands needed to utilize the chosen vehicle actuators to both stabilize the vehicle and achieve the provided guidance state, usually in a closed-loop manner

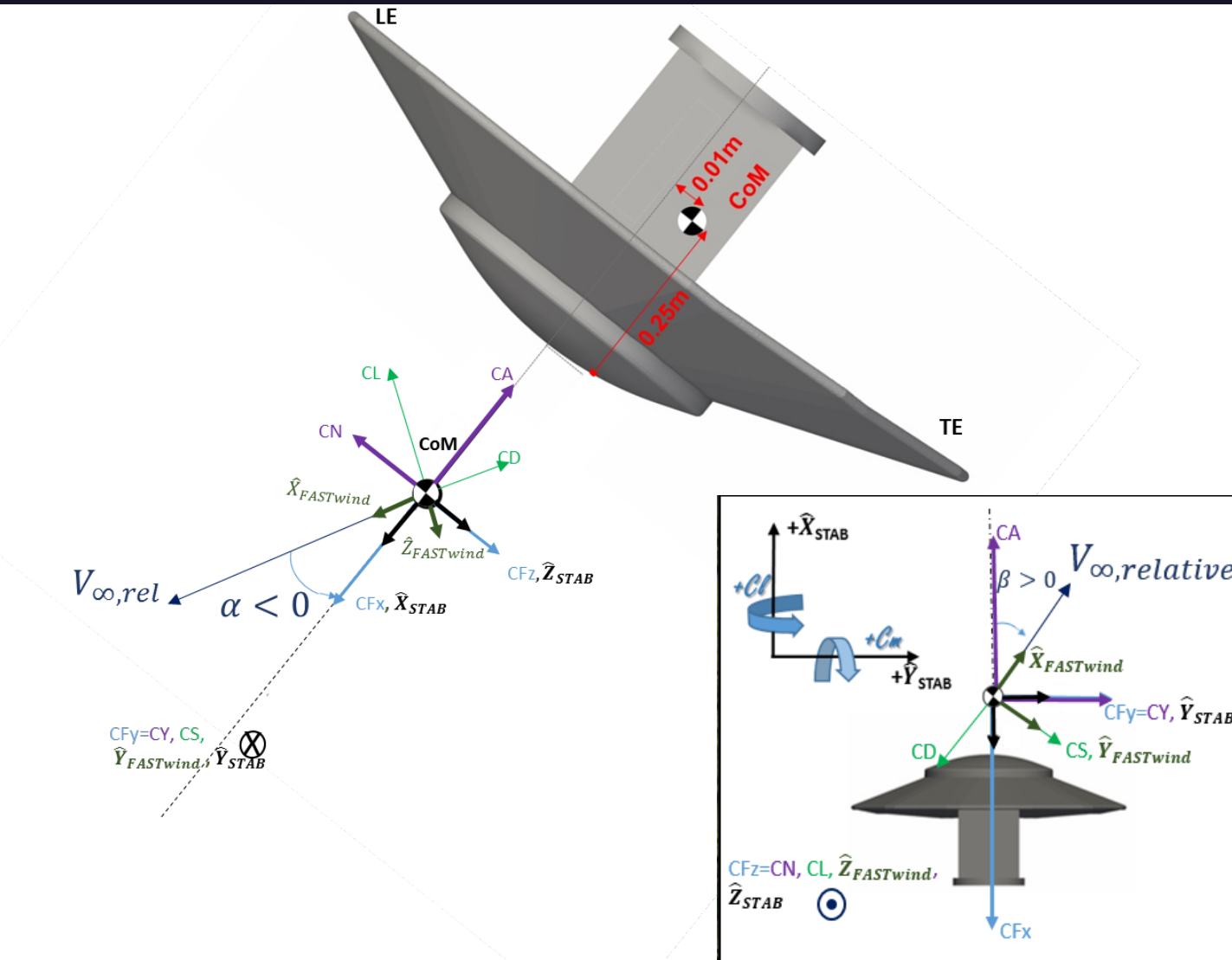


# DYNAMICS

- **Lift** defines the aerodynamic force perpendicular to the velocity vector
- **Drag** defines the aerodynamic force in the anti-velocity direction
- **Trim** defines the stability points where all aerodynamic moments about the CG are in equilibrium

## Example Variables Important for Guidance

Altitude	$r$
Velocity	$V$
Latitude	$\theta_{Lat}$
Longitude	$\theta_{Lon}$
Flight Path Angle	$\gamma$
Heading Angle	$\sigma$
Bank Angle	$\phi$
Sideslip Angle	$\beta$
Angle of Attack	$\alpha$
Lift	$L$
Drag	$D$
Density	$\rho$
Mass	$m$
Time	$t$



# 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 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

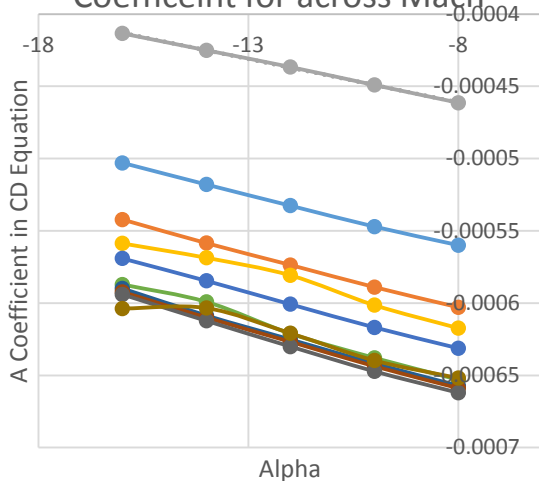




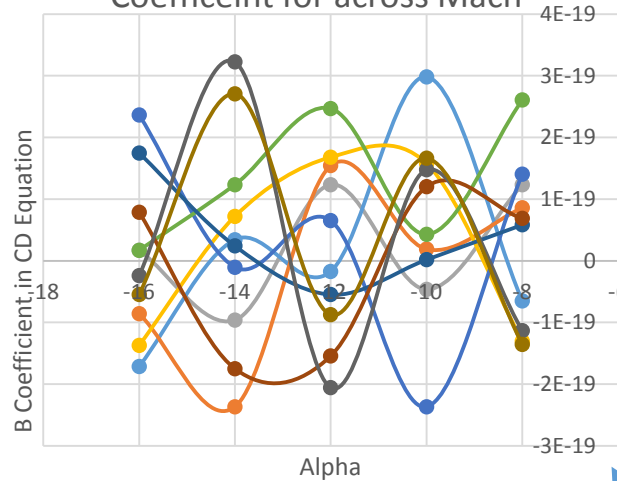
# Updated FNPEG to Include Side Force Contributions

- To reduce computational load, a polynomial fit + 2-step interpolation was used as an approximate to the true CD, CL, and CS coefficients
  - CD and CL required a second-order polynomial fit for each Mach
  - CS required linear polynomial fit
  - Trends were difficult to quantify between alpha and beta leading to a two step interpolation method
- Coefficients were used to define equations useful for automatic lateral logic gain updates based on dynamic pressure ( $\bar{q}$ )

CD 2nd Order Poly-fit A  
Coefficient for across Mach



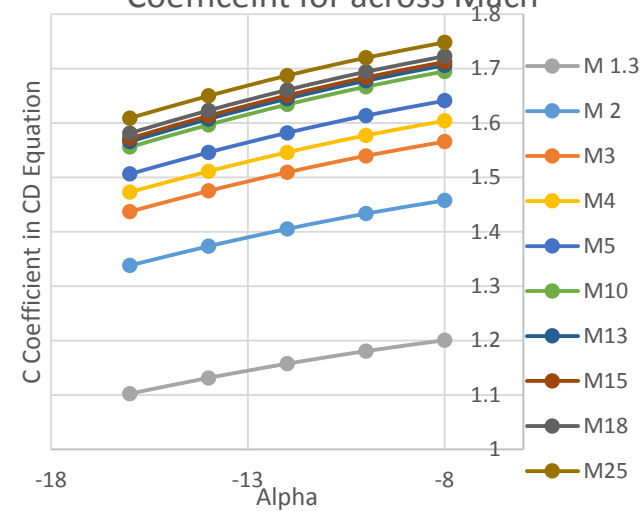
CD 2nd Order Poly-fit B  
Coefficient for across Mach



for example  $CD = A\beta^2 + B\beta + C$

appx zero

CD 2nd Order Poly-fit C  
Coefficient for across Mach



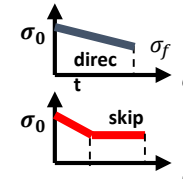


# Introduction to FNPEG



## • Features

- FNPEG is a fully numerical predictor-corrector entry guidance algorithm capable of direct entry guidance and skip entry guidance
- At each guidance time step, FNPEG uses Newton-Raphson method within its' predictor-corrector to search for the bank angle command  $\sigma_0$  that creates a bank angle vs. energy linear profile, resulting in minimal miss distance, where energy is defined as: 
$$e = \frac{\mu}{r} - \frac{V^2}{2}$$
- Inequality path constraint enforcement capability
  - g-Load, heating rate, dynamic pressure,...
  - Constraint enforcement does not interfere with guidance precision

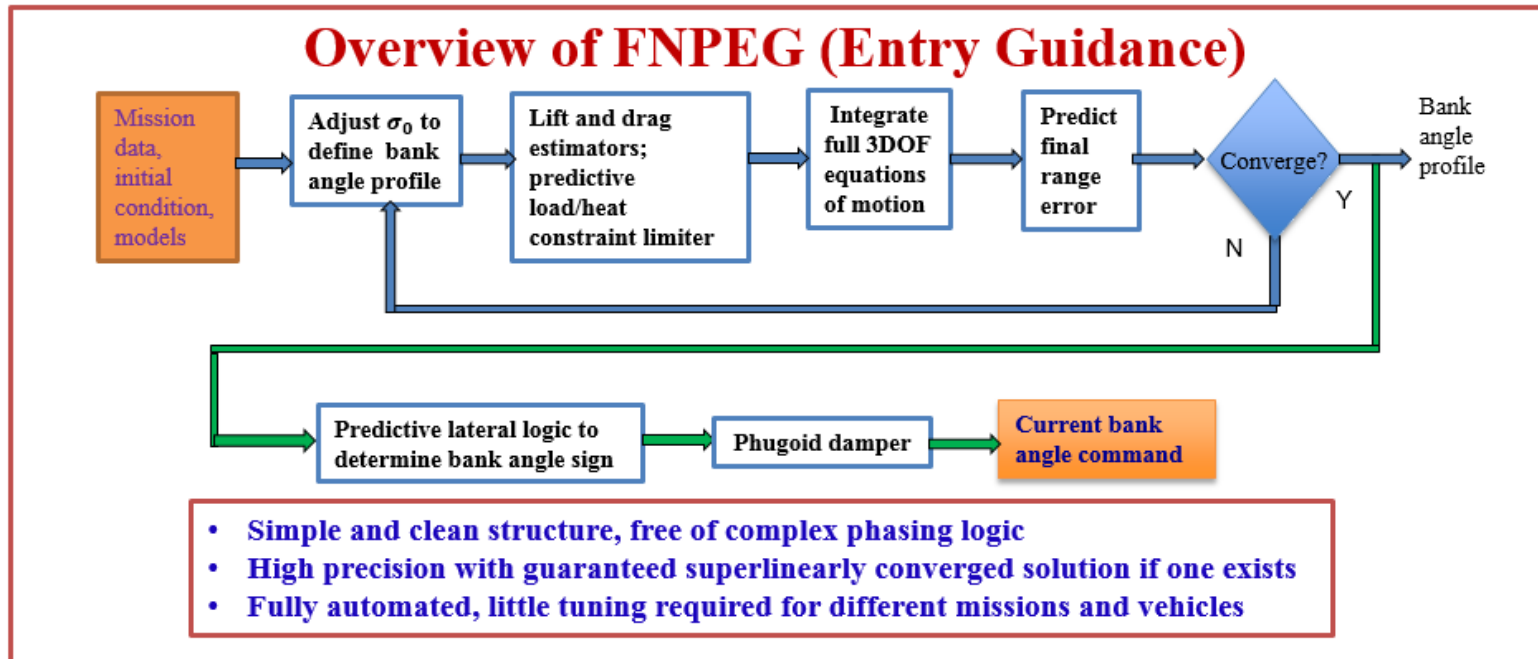


- Deterministic lateral algorithm that allows the user to specify a desired number of bank ( $\sigma$ ) reversals
- Applicability to different vehicles with a wide range of L/D ratios, mission types, and initial conditions, without the need for redesign, tuning, or extensive adjustments to the algorithm
- A variation is available for *optimal* aerocapture guidance (FNPAG)

## • Status

- FNPEG tested and evaluated at JSC in Orion simulation environment; Compared favorably with Orion entry guidance algorithm PredGuid
- FNPAG was in an aerocapture fly-off at Langley in 2016, and extensively used at JSC in aerocapture parametric studies
- Reference: Lu, Brunner, Stachowiak, Mendeck, Tigges, Cerimele, "Verification of a Fully Numerical Predictor-Corrector Entry Guidance Algorithm", *Journal of Guidance, Control, and Dynamics*, Vol. 40, No. 2, 2017

# Fully Numerical Predictor-Corrector Entry Guidance





- 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)
- It 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

$$\dot{Q} = k_Q \sqrt{\rho} V^{3.15} \leq \dot{Q}_{max}$$

$$a = \sqrt{L^2 + D^2} \leq a_{max}$$

$$\bar{q} = (g_0 R_0 \rho V^2) / 2 \leq \bar{q}_{max}$$

Re-derived compared to accepted text from N. Vinh), but should eventually include the side force contribution into the 3 dynamic equations of motion ( $\dot{\gamma}, \dot{\psi}, \dot{V}$ ), which was not included in Vinh and Lu's derivations. They usually aren't important to include for bank guidance where  $\beta$  & CS are assumed small.

$$\underline{\mathcal{F}}_{\rightarrow w}^T(\mathbf{D}_w + \mathbf{L}_w) = \underline{\mathcal{F}}_{\rightarrow w}^T \left( \begin{bmatrix} -D \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -L \end{bmatrix} + \begin{bmatrix} 0 \\ S \\ 0 \end{bmatrix} \right) \quad (53)$$

$$\underline{\mathcal{F}}_{\rightarrow f}^T(\mathbf{A}_f + \mathbf{T}_f) = \underline{\mathcal{F}}_{\rightarrow f}^T(\mathbf{D}_f + \mathbf{R}_{fw}\mathbf{L}_w + \mathbf{R}_{fw}\mathbf{S}_w + \mathbf{R}_{fb}\mathbf{T}_b) \quad (55)$$

$$\underline{\mathcal{F}}_{\rightarrow f}^T(\mathbf{A}_f + \mathbf{T}_f) = \underline{\mathcal{F}}_{\rightarrow f}^T \left( \begin{bmatrix} -D \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ Ls(\sigma) \\ -Lc(\sigma) \end{bmatrix} + \begin{bmatrix} 0 \\ Sc(\sigma) \\ Ss(\sigma) \end{bmatrix} + \begin{bmatrix} Tc(\alpha + \epsilon)c(\beta) \\ Ts(\alpha + \epsilon)s(\sigma) - Tc(\alpha + \epsilon)s(\beta)c(\sigma) \\ -Ts(\alpha + \epsilon)c(\sigma) - Tc(\alpha + \epsilon)s(\beta)s(\sigma) \end{bmatrix} \right) \quad (56)$$

$$\mathcal{T} = Tc(\alpha + \epsilon)c(\beta) - D$$

$$S = Tc(\alpha + \epsilon)s(\beta) - S$$

$$\mathcal{X} = Ts(\alpha + \epsilon) + L$$

Using Eqns 13 and 56 yield

$$\dot{V} = \frac{1}{m}\mathcal{T} - gs(\gamma) + \omega^2rc(\phi)(s(\gamma)c(\phi) - c(\gamma)s(\phi)s(\psi)) \quad (43)$$

$$\mathcal{V}\dot{\gamma} = \frac{1}{m}\mathcal{X}c(\sigma) - \frac{1}{m}Ss(\sigma) - gc(\gamma) + \frac{\mathcal{V}^2}{r}c(\gamma) + 2\omega\mathcal{V}c(\phi)c(\psi) + \omega^2rc(\phi)(c(\gamma)c(\phi) + s(\gamma)s(\phi)s(\psi)) \quad (44)$$

$$\mathcal{V}\dot{\psi} = \frac{1}{m}\frac{\mathcal{X}s(\sigma)}{c(\gamma)} + \frac{1}{m}\frac{Sc(\sigma)}{c(\gamma)} - \frac{\mathcal{V}^2}{r}c(\gamma)c(\psi)t(\phi) + 2\omega\mathcal{V}(t(\gamma)c(\psi)s(\psi) - s(\phi)) - \frac{\omega^2r}{c(\gamma)}s(\phi)c(\phi)c(\psi) \quad (45)$$