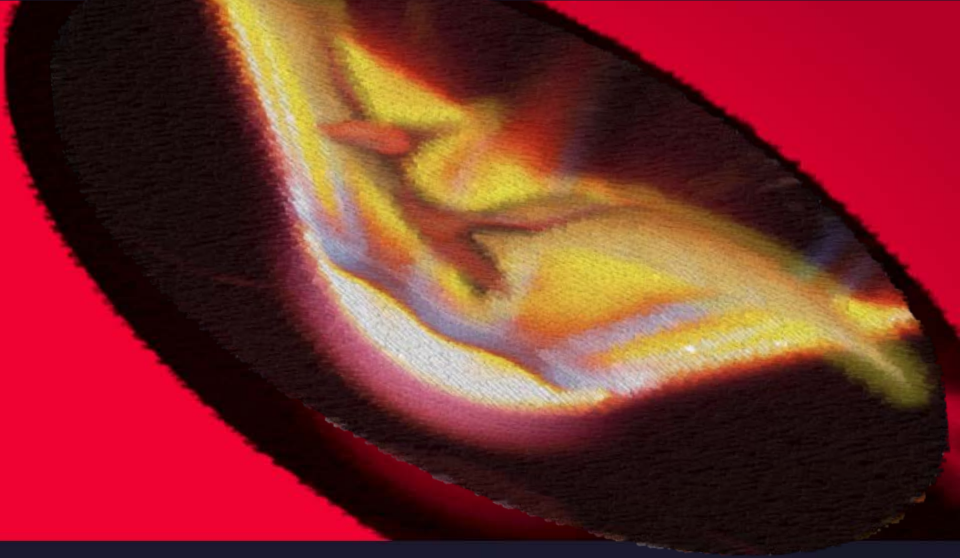


NASA SPACE TECHNOLOGY MISSION DIRECTORATE EARLY CAREER INITIATIVE

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

Breanna Johnson
NASA Johnson Space Center
Flight Mechanics and Trajectory Design Branch EG5

What is Pterodactyl?

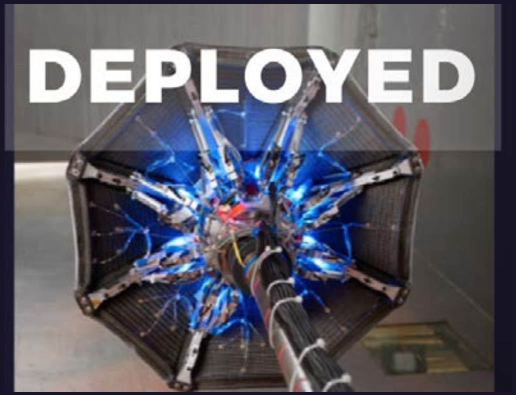
A design, build, and test capability for finding optimal, scalable Guidance & Control (G&C) solutions for Deployable Entry Vehicles (DEVs) to enable precision targeting

MOTIVATION

Feasibility study such that the solution closes

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

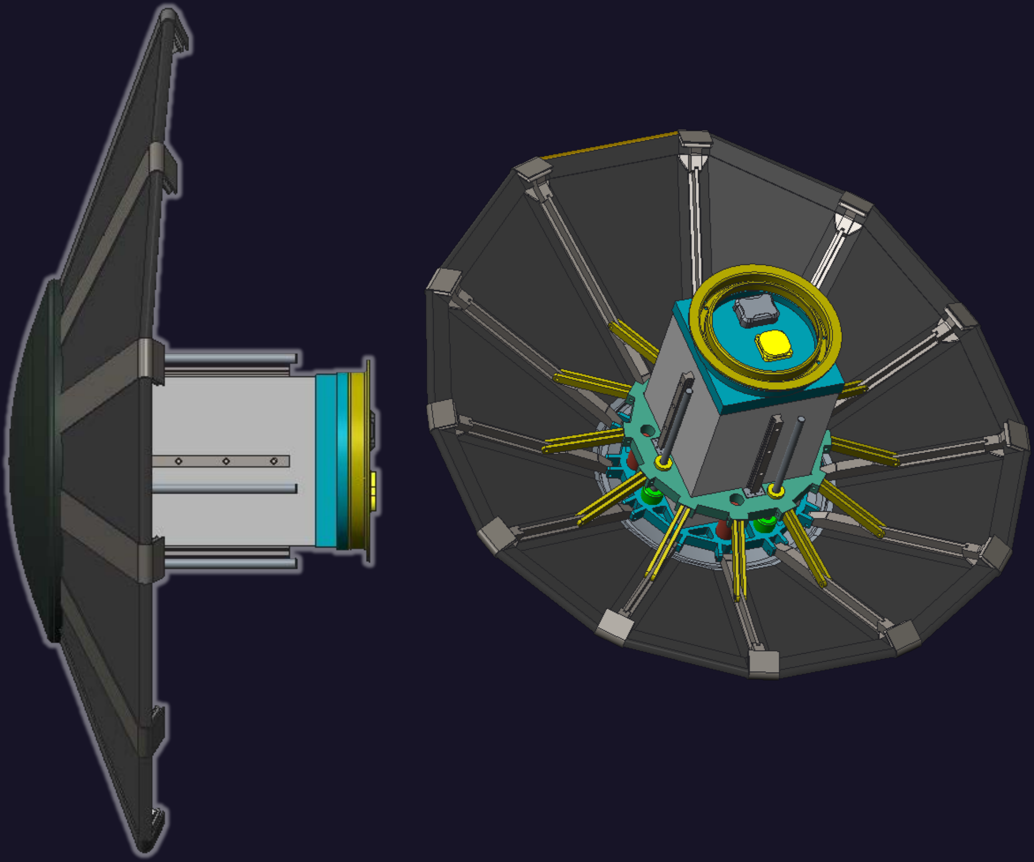
Selected Lunar Return mission parameters to stress design for precision targeting and future scalability



BASELINE MODELS AND PARAMETERS

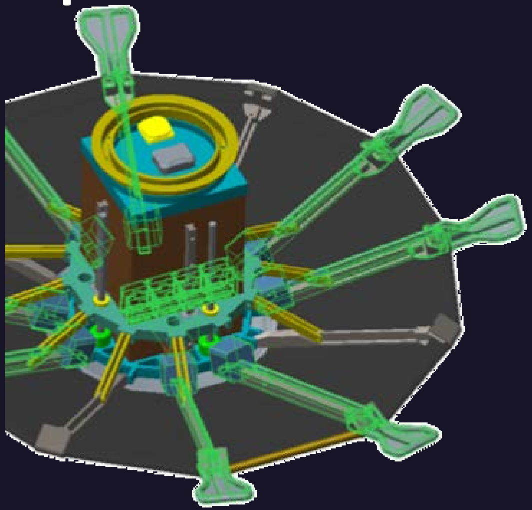
Baseline vehicle (Aeroshell is fixed)
Lifting Nano-ADEPT (LNA)
1 m diameter
Mass = 54 kg

Loading Constraints
Heating Rate $\leq$ 250 W/cm^2
G-load $\leq$ 15g's

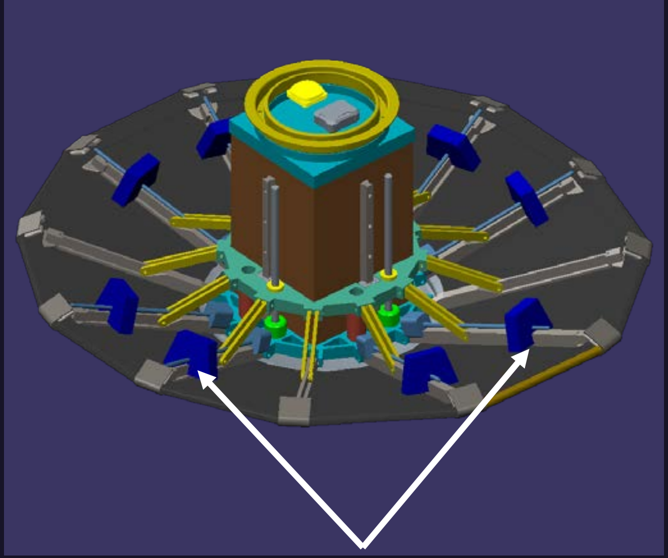


CONTROL SYSTEM TRADE STUDY

Flaps

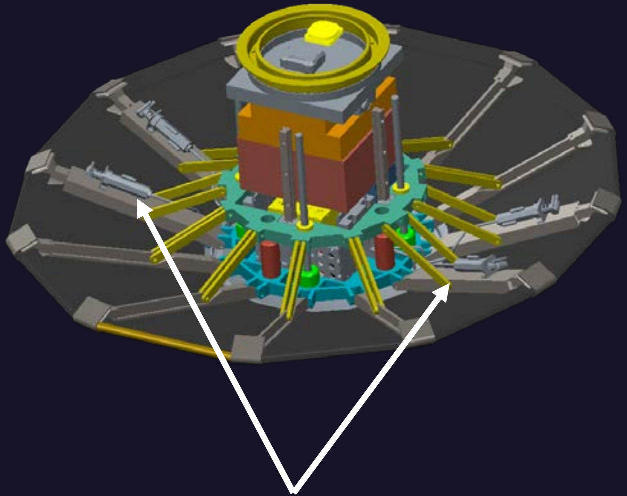


Mass Movement



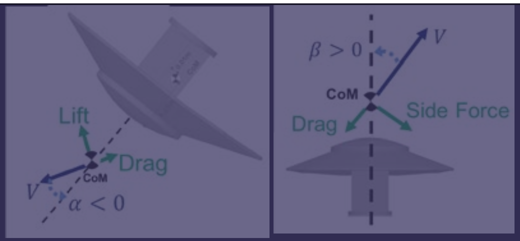
Independent
Moveable Masses

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 α/β control	Precision targeting by reducing down range and cross range errors
Control Algorithm	Identify flap deflections to track guidance commands	- 6DOF simulation development - Define control requirements for mechanical design
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 α/β control for targeting in the Fully Numerical Predictor-corrector Entry Guidance (FNPEG[1])

WHY? It is robust and adaptable to different configurations

α–command method

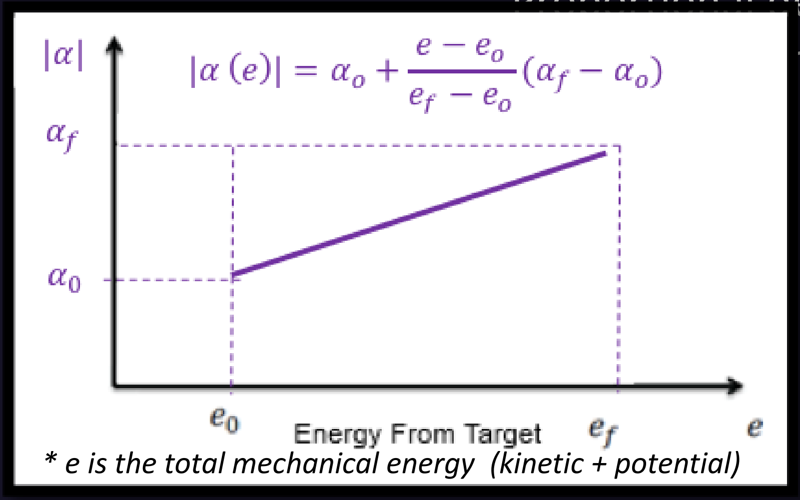
INITIAL GUESS – Linear function of mechanical energy

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

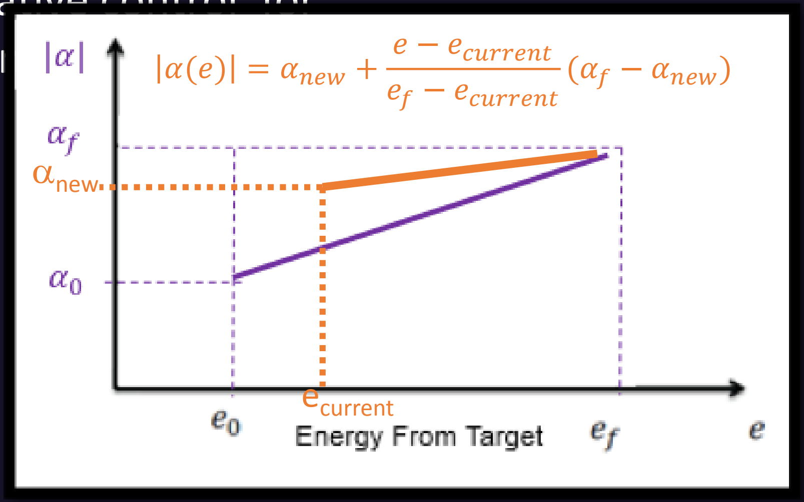
β–command method

Proportional derivative control, for

ng a



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



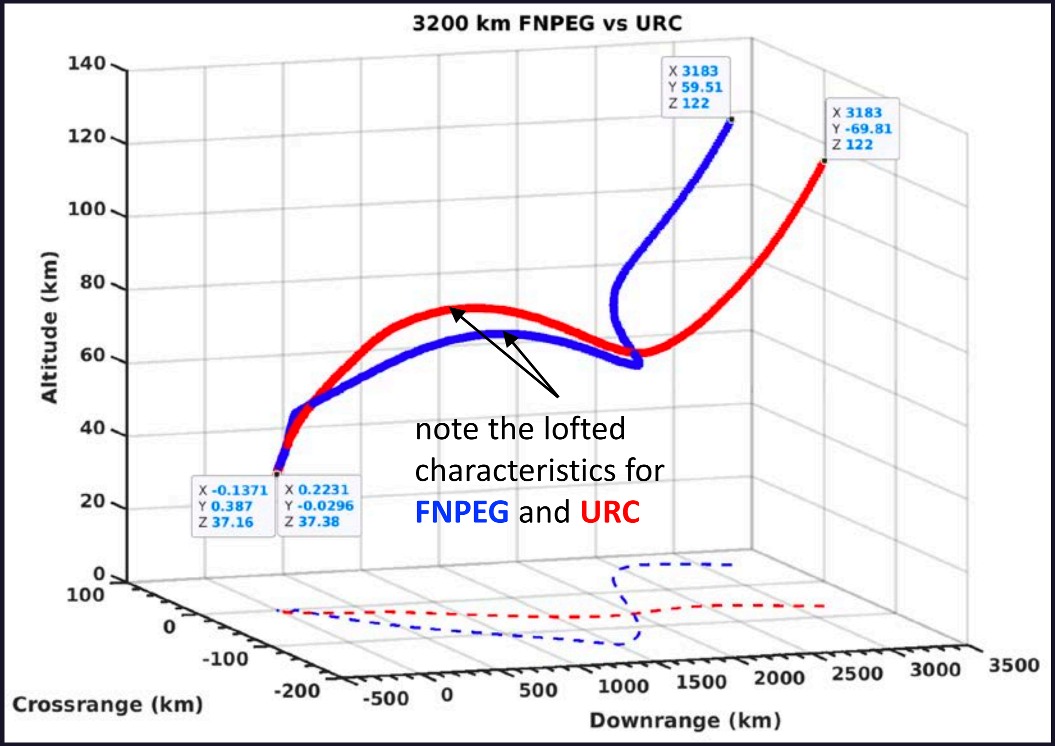
[1]Lu, P. Entry Guidance: A Unified Method. Journal of Guidance, Control, and Dynamics, Vol. 37, No. 3, 2014, pp. 713- 728.

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



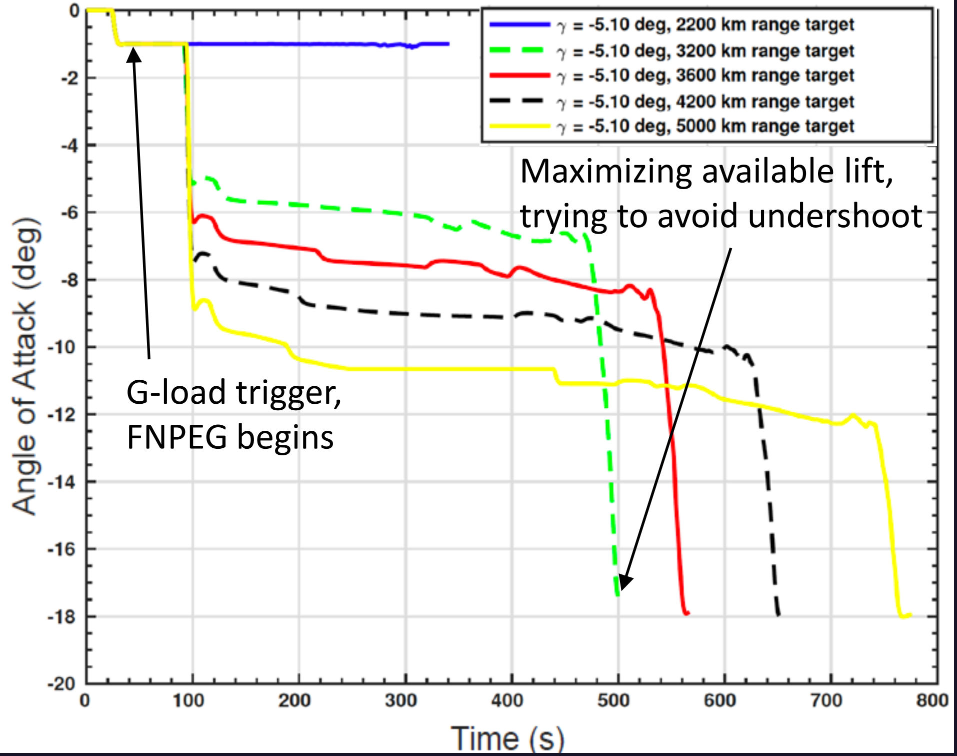
note the lofted characteristics for **FNPEG** and **URC**

*Comparable profiles between the two algorithms are observed, ≤5km miss distance is desired

URC TARGETING PERFORMANCE

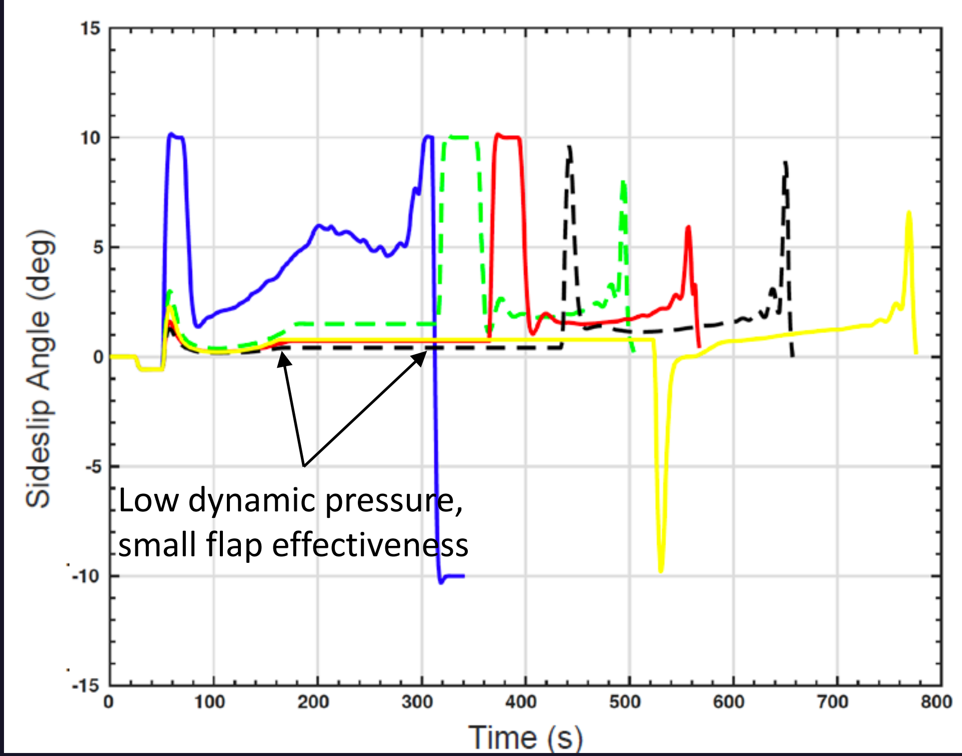
These guidance profiles resulted in:

- 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



Maximizing available lift, trying to avoid undershoot

G-load trigger, FNPEG begins



Low dynamic pressure, small flap effectiveness

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 (<5 km) desired limits

Monte Carlo Variables	Standard Deviation σ
Initial Velocity	±3.33 m/s
Initial FPA	±0.03 °
Initial Azimuth	±0.1°
Initial Lat	±0.1°
Initial Lon	±0.1°
Initial Altitude	±100 m
Initial Mass	±1% 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**):
  - 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

- **Mass Movement** 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	0.154 km	0.426 km
Peak Heat Rate	232 W/cm^2	245 W/cm^2
Peak G-load	7.7 g	8.1 g

γ_{EI}=-5.8°, Range to target = 4200 km

- **Flaps** 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	W/cm^2	217 W/cm^2
Peak G-load	g	7.49 g

γ_{EI}=-5.2°, 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**):
  - α_{trim} = -16.9°
  - L/D_{trim} = 0.27
  - $\beta_{ball\ coef}$ = 58 kg/m^2

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

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

- **Altered** Performance Statistics (**FNPEG**):
  - α_{trim} = -14°
  - L/D_{trim} = 0.23
  - $\beta_{ball\ coef}$ = 58 kg/m^2

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

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

- **Example** 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	0.154 km	0.426 km
Peak Heat Rate	232 W/cm^2	245 W/cm^2
Peak G-load	7.7 g	8.1 g

γ_{EI}=-5.8°, Range to target = 4200 km

- **Altered** Performance Statistics (**URC**):
  - $[\alpha_{range}]$, $[\beta_{range}]$ = [- 9 °,-17°] , [±4.5 °]
  - L/D_{range} = [0.15, 0.29]
  - $[\beta_{ball\ coef}]$ = 64 kg/m^2

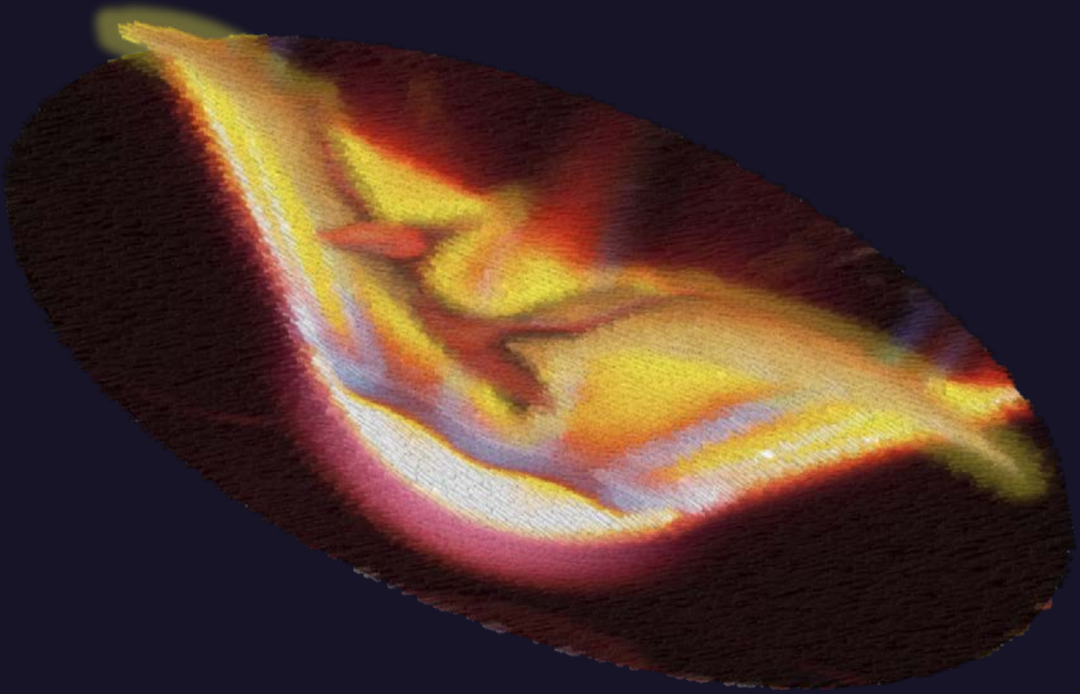
1000-case MC	Mean	Max
Miss Distance	0.76 km	3.58 km
Peak Heat Rate	243 W/cm^2	260 W/cm^2
Peak G-load	8.12 g	8.81 g

γ_{EI}=-5.8°, 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?



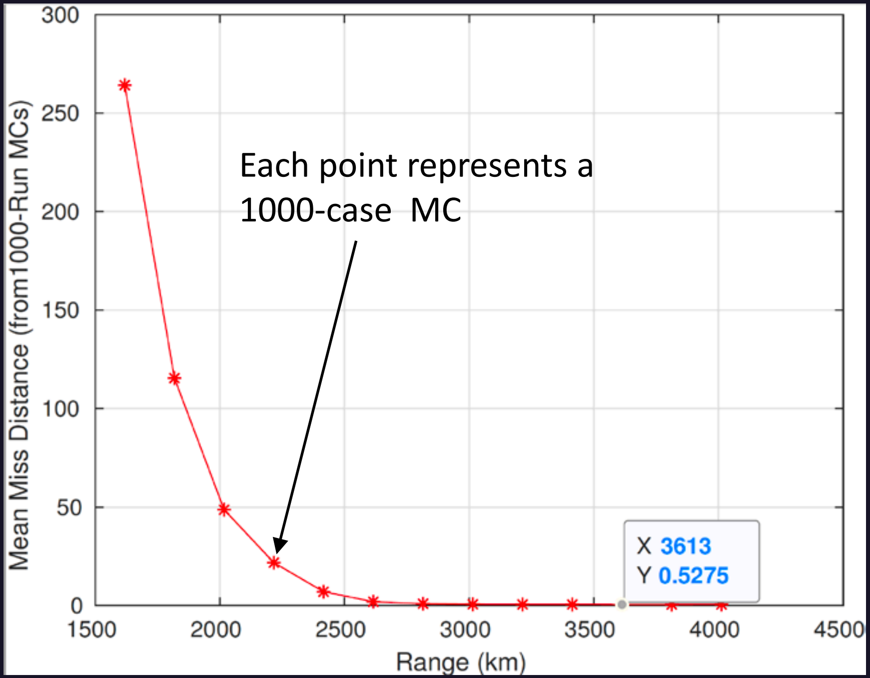
BACK UP SLIDES

URC TARGETING PERFORMANCE

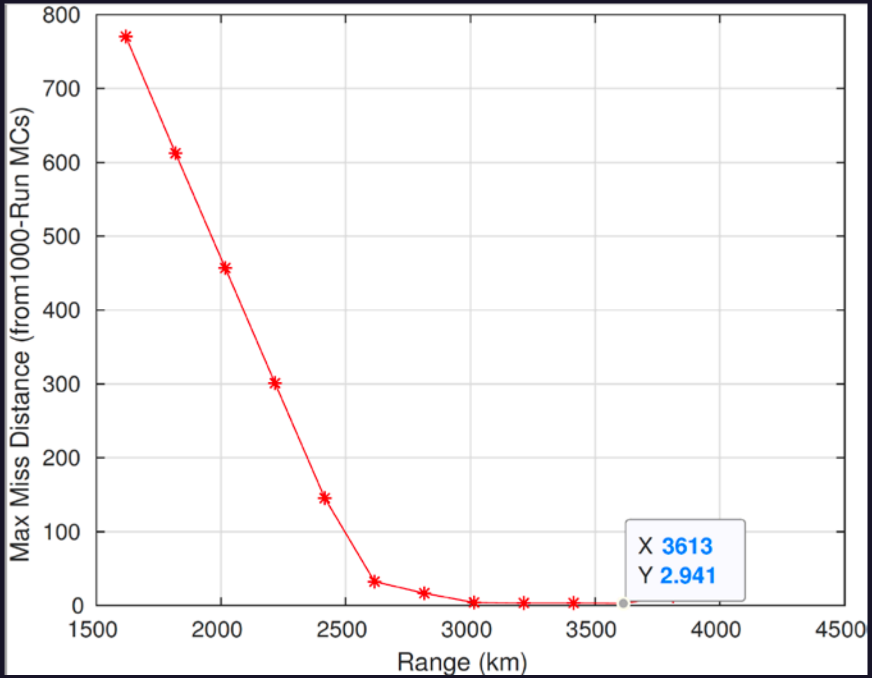
- Monte Carlos (MCs) were run with typical dispersions for a lunar entry mission
- All runs for example FNPEG-URC case satisfy heating (<250 W/cm^2), g-load (<15 g’s), and miss distance (<5 km) desired limits

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

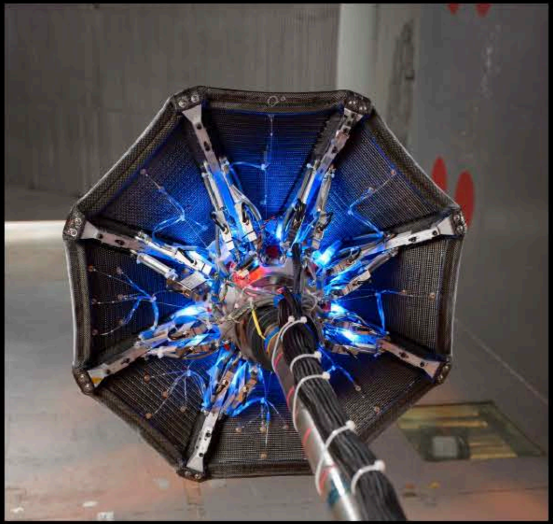
Monte Carlo Variables	Multiplier
EARTH GRAM iopr	N/A
CD, CL, CS	0.9-1.1



Each point represents a 1000-case MC



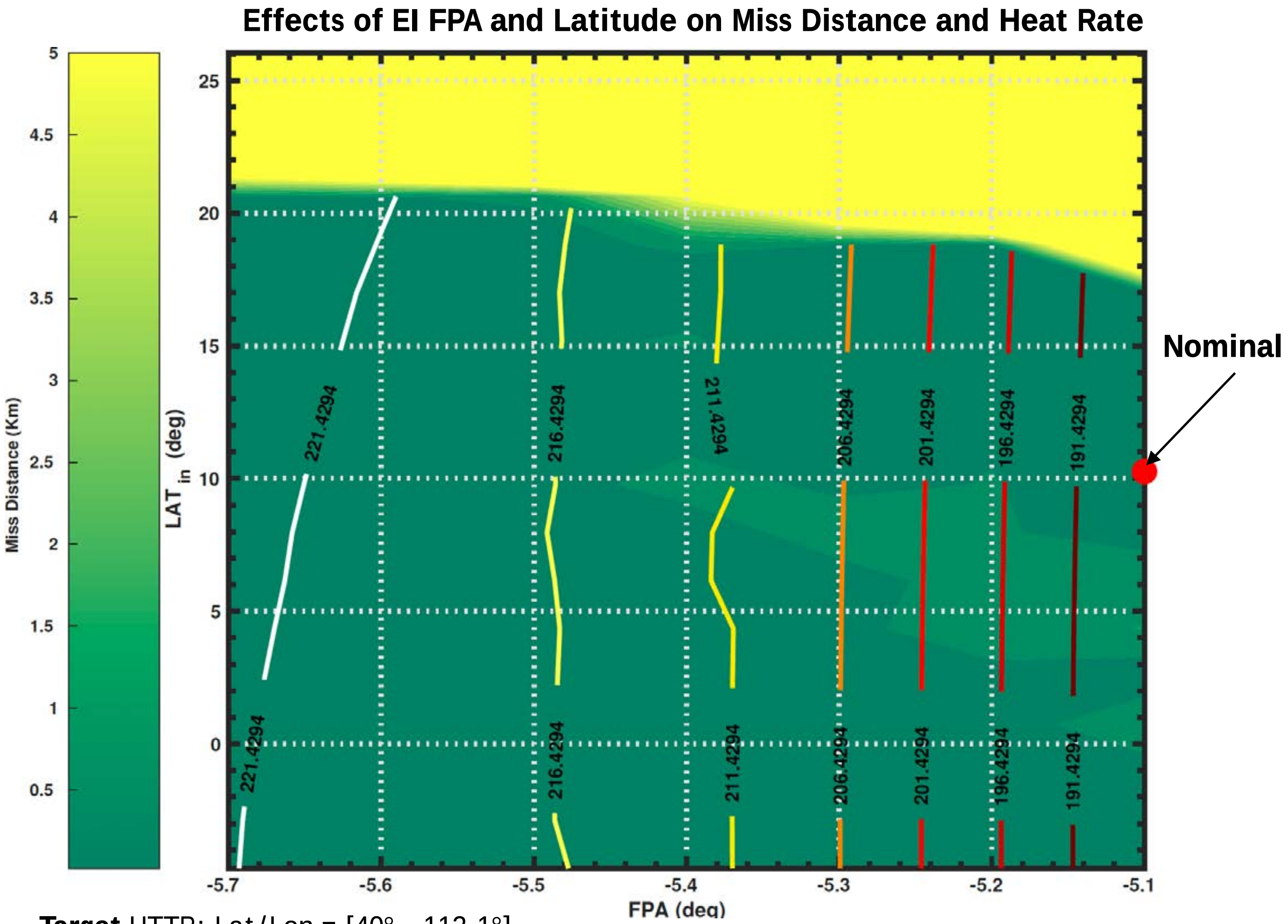
Large to Small Mass Missions are driving the development of DEVs!



Adaptable, Deployable Entry Placement Technology (ADEPT)

Hypersonic Inflatable Aerodynamic Decelerator (HIAD)

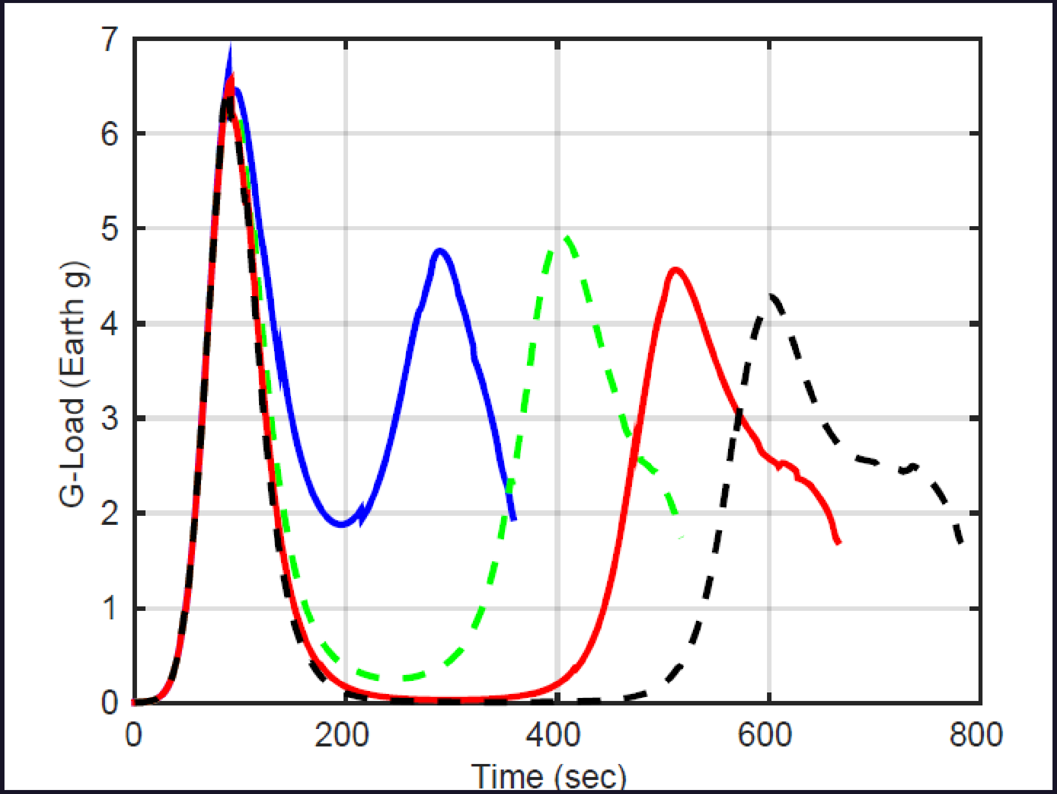
EI STUDY : IN SEARCH OF CONVERGENCE



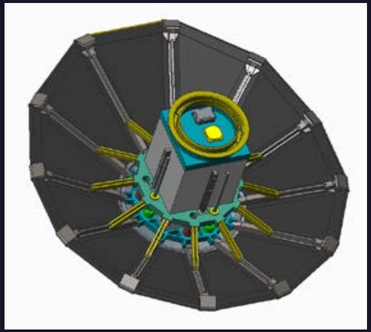
Target UTTR: Lat/Lon = [40°, -112.1°]

*Daniela Rocca-Bejar's Contributor

FNPEG URC G-LOAD CURVES

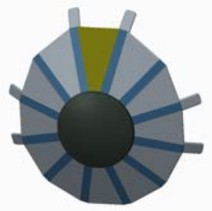


Pterodactyl Design Process Overview



Lifting Nano-ADEPT
Asymmetric, 1+ meter diameter

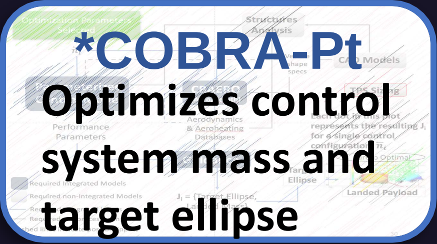
Identify Potential Control Systems
Tabs, RCS, etc.



- CAD Models
- Aerodynamics
  Aerothermodynamics
- Guidance & Control
- Structures Analysis
- TPS Sizing

Develop Vehicle and Control System Simulations
Varied Fidelity

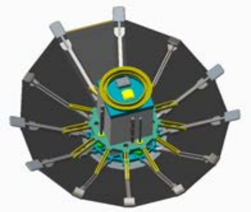
Integrate Models into MDAO Framework
Multi-disciplinary, Design, Analysis and Optimization



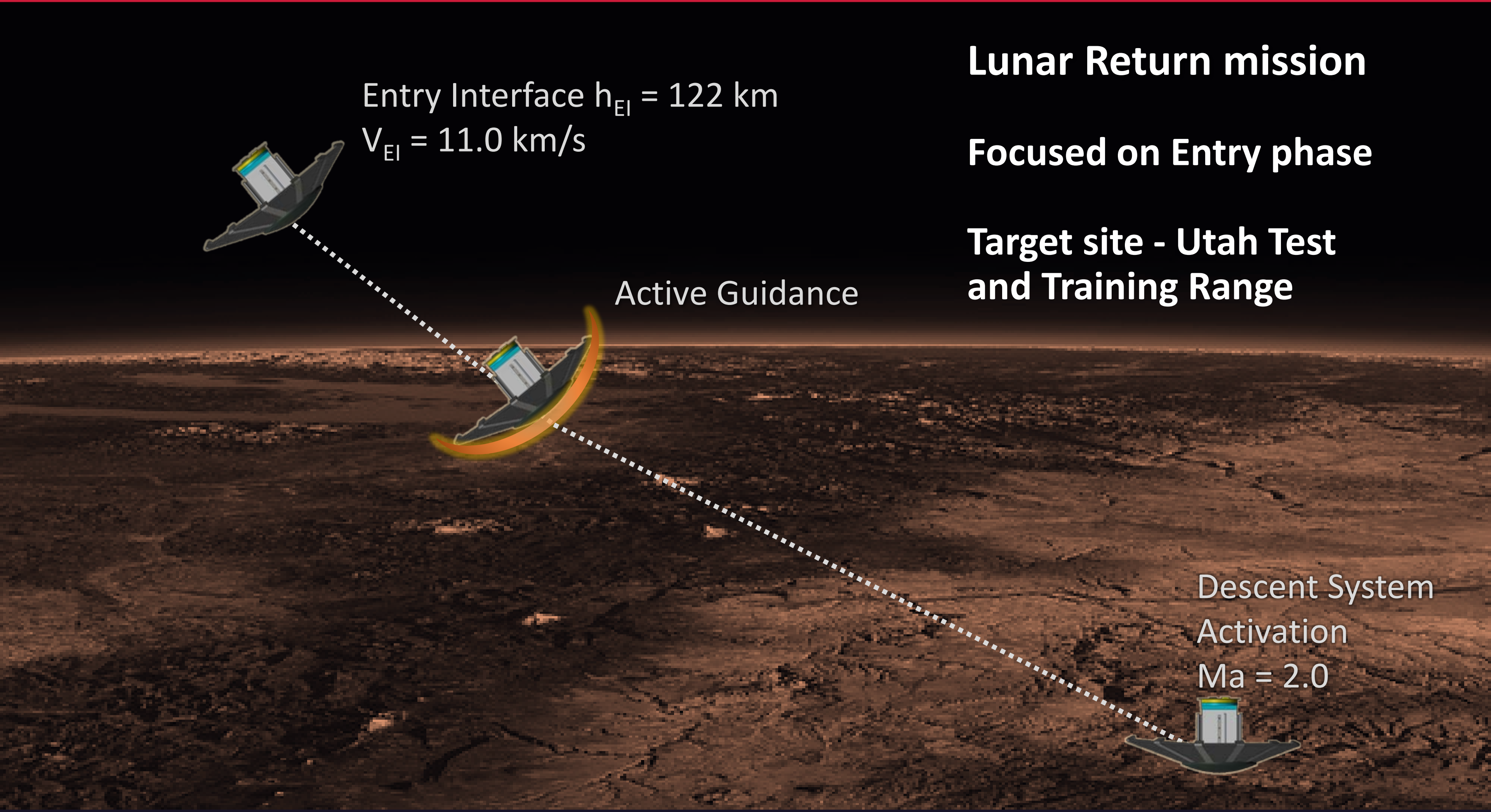
***COBRA-Pt**
Optimizes control system mass and target ellipse

*Garcia et al., AIAA 2010-5052

Select Optimal Design
MDAO output, SMEs



BASELINE MODELS AND PARAMETERS
(CONT'D)

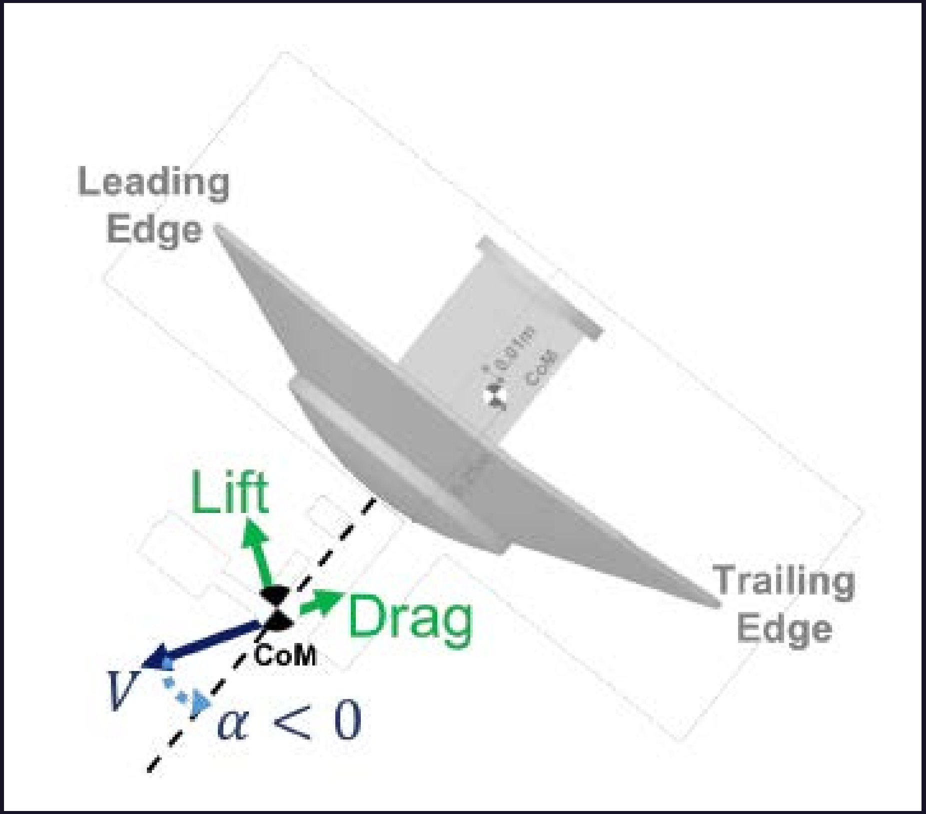


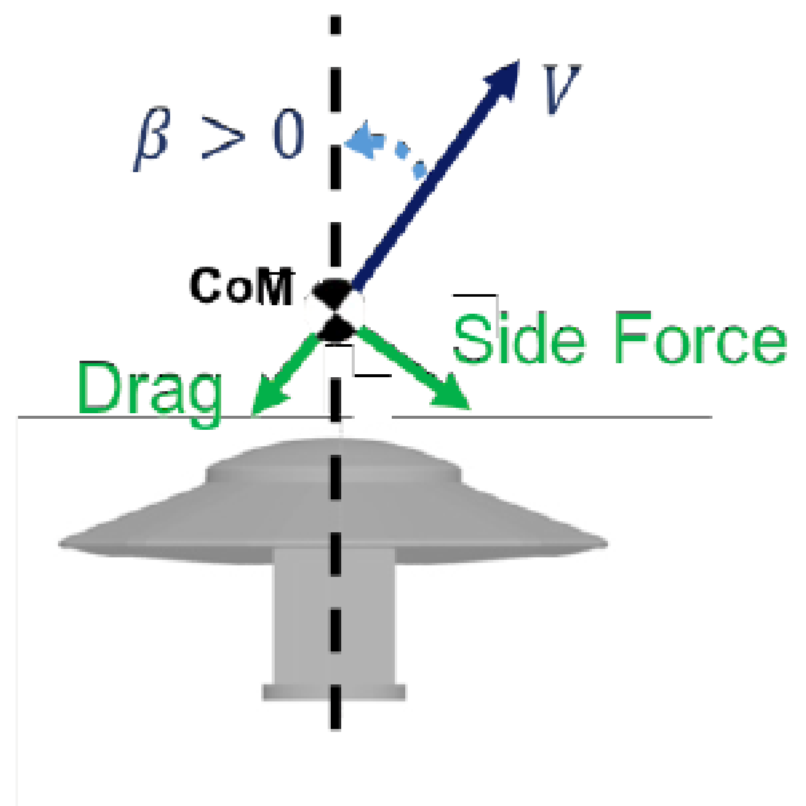
Lunar Return mission

Focused on Entry phase

Target site - Utah Test and Training Range

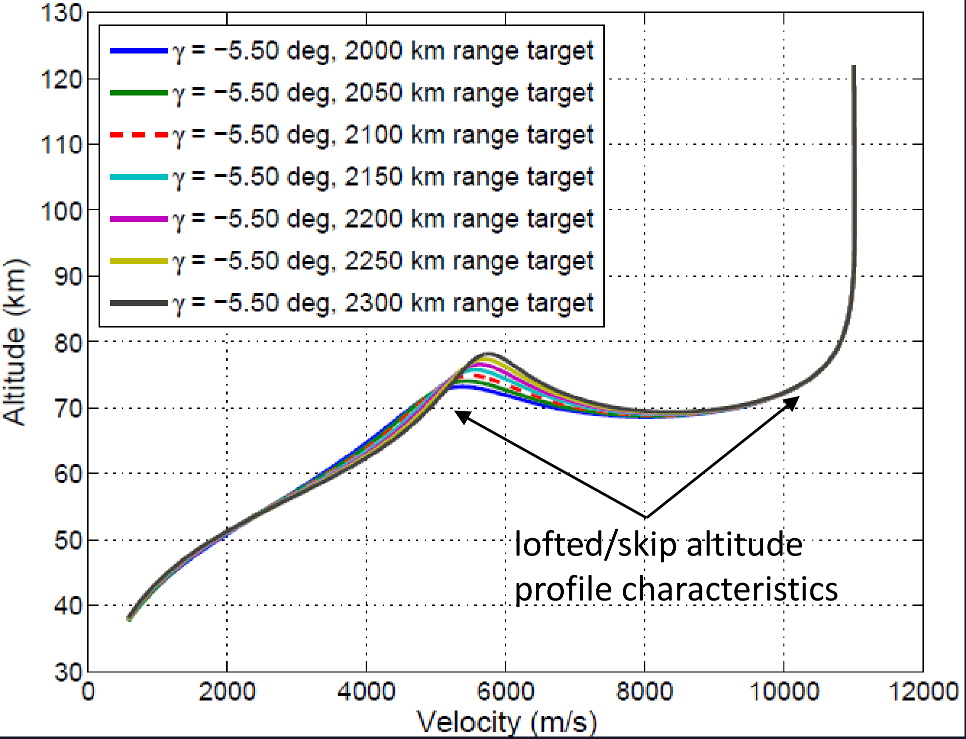
FLAP CONFIGURATION OVERVIEW



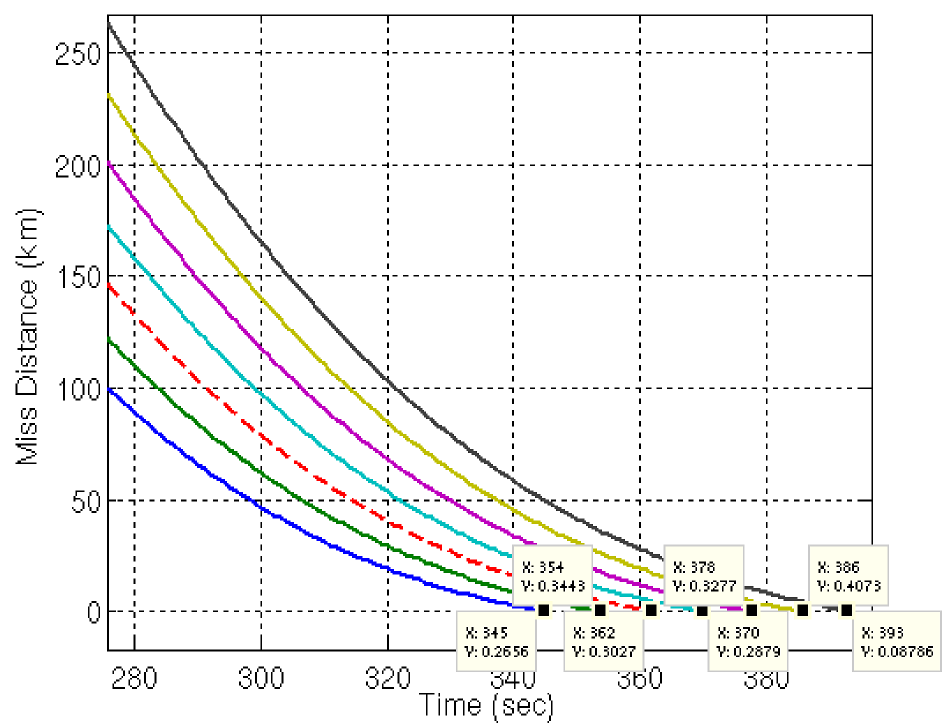


α-β GUIDANCE

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



lofted/skip altitude profile characteristics

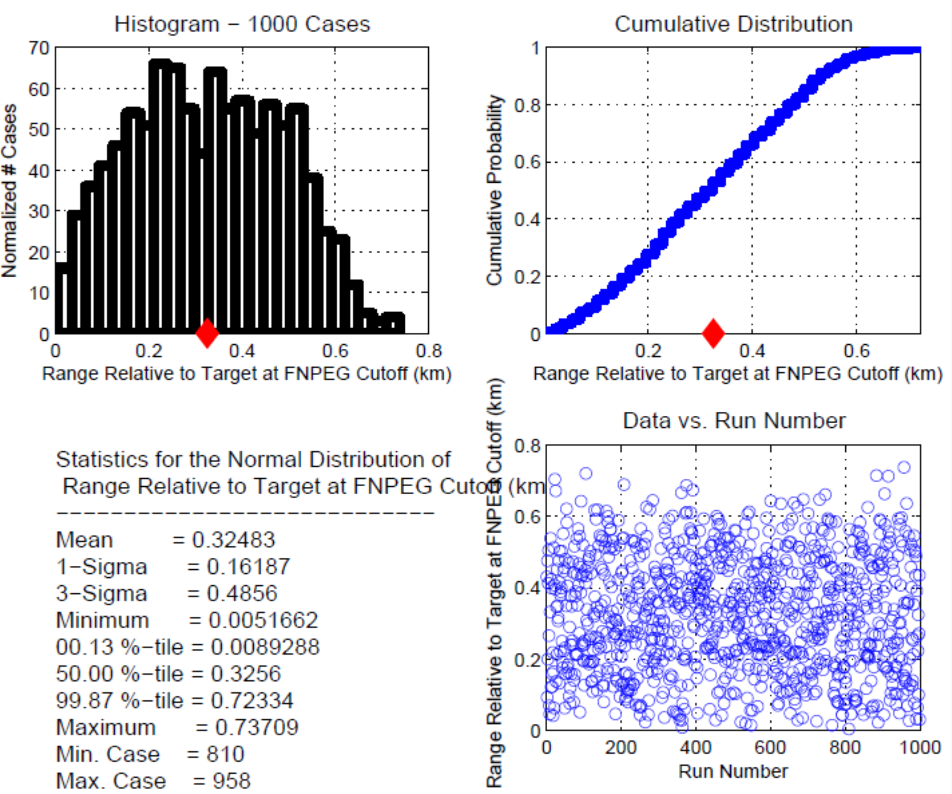


α-β GUIDANCE

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

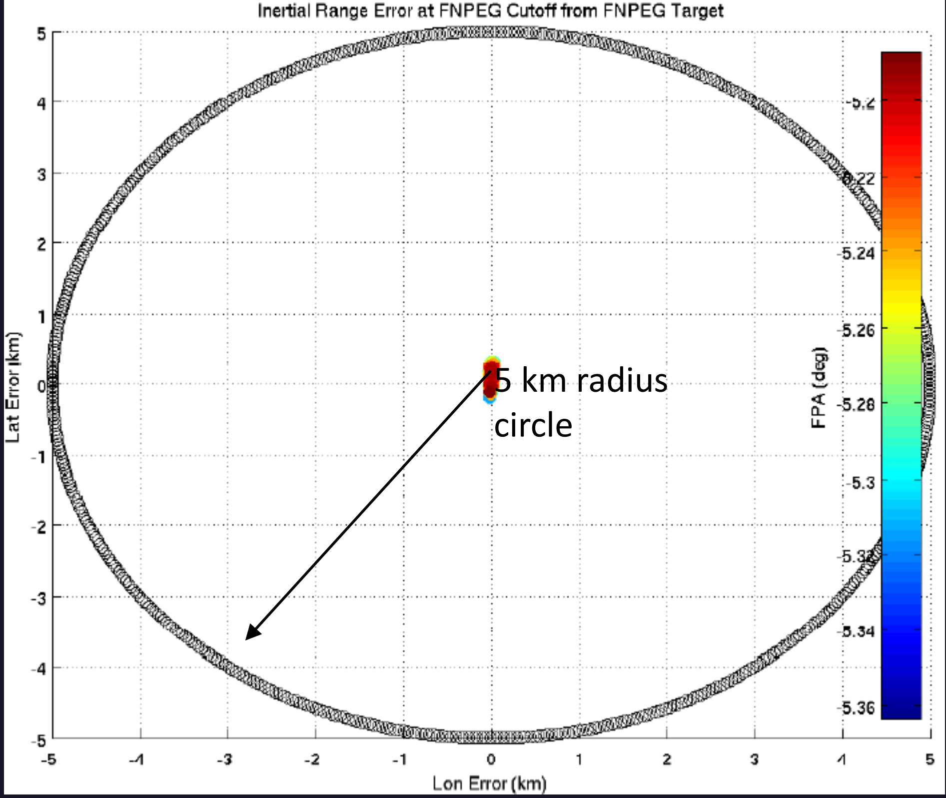
Monte Carlo Variables	Standard Deviation σ
Initial Velocity	±3.33 m/s
Initial FPA	±0.03 °
Initial Azimuth	±0.1°
Initial Lat	±0.1°
Initial Lon	±0.1°
Initial Altitude	±100 m
Initial Mass	±0.4 kg

- 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)



Statistics for the Normal Distribution of
Range Relative to Target at FNPEG Cutoff (km)

Mean = 0.32483
1–Sigma = 0.16187
3–Sigma = 0.4856
Minimum = 0.0051662
00.13 %–tile = 0.0089288
50.00 %–tile = 0.3256
99.87 %–tile = 0.72334
Maximum = 0.73709
Min. Case = 810
Max. Case = 958

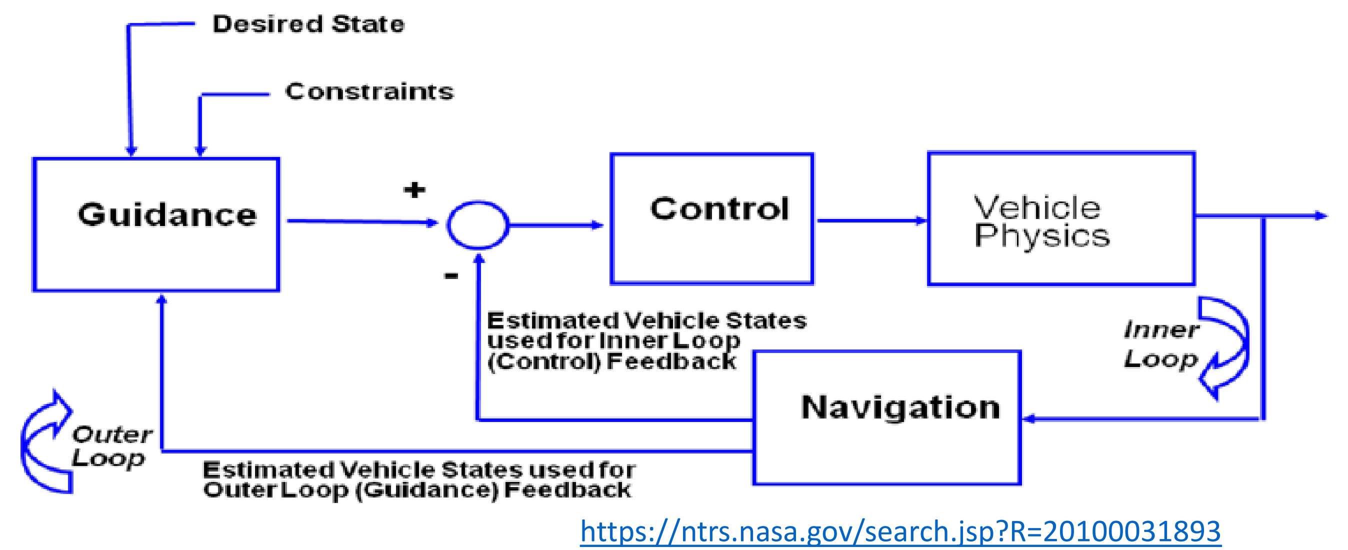


GUIDANCE WORK COMPLETED

- 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

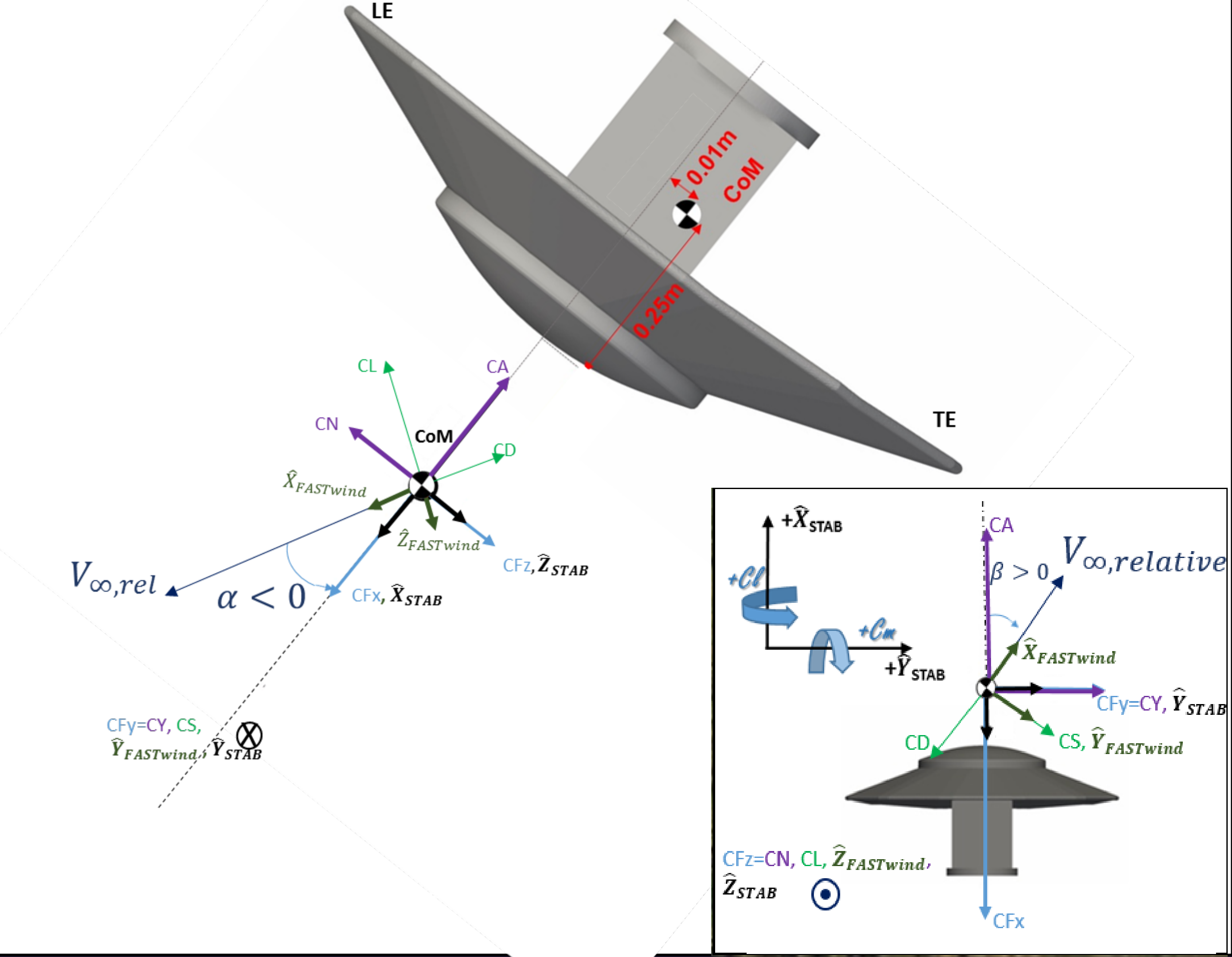


https://ntrs.nasa.gov/search.jsp?R=20100031893

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	θ_{Lat}
Longitude	θ_{Lon}
Flight Path Angle	γ
Heading Angle	σ
Bank Angle	ϕ
Sideslip Angle	β
Angle of Attack	α
Lift	L
Drag	D
Density	ρ
Mass	m
Time	t

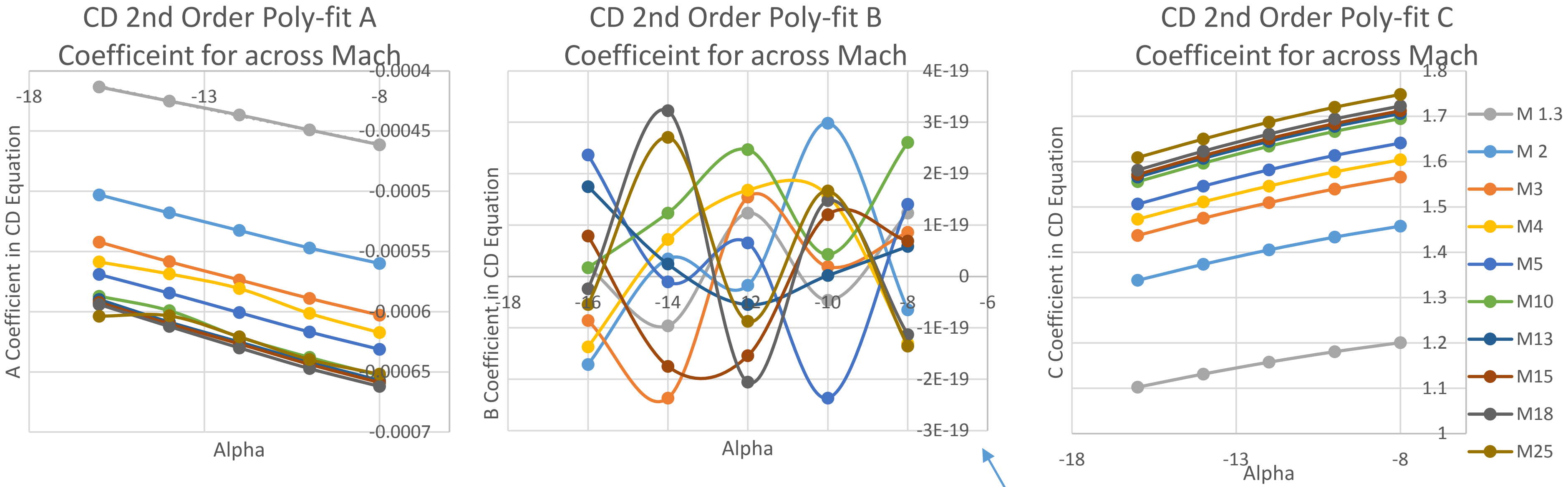


HERITAGE

- 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 Coefficeint for across Mach

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

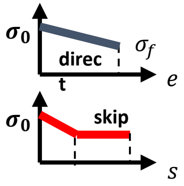
CD 2nd Order Poly-fit C Coefficeint for across Mach

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

appx zero

Introduction to FNPEG

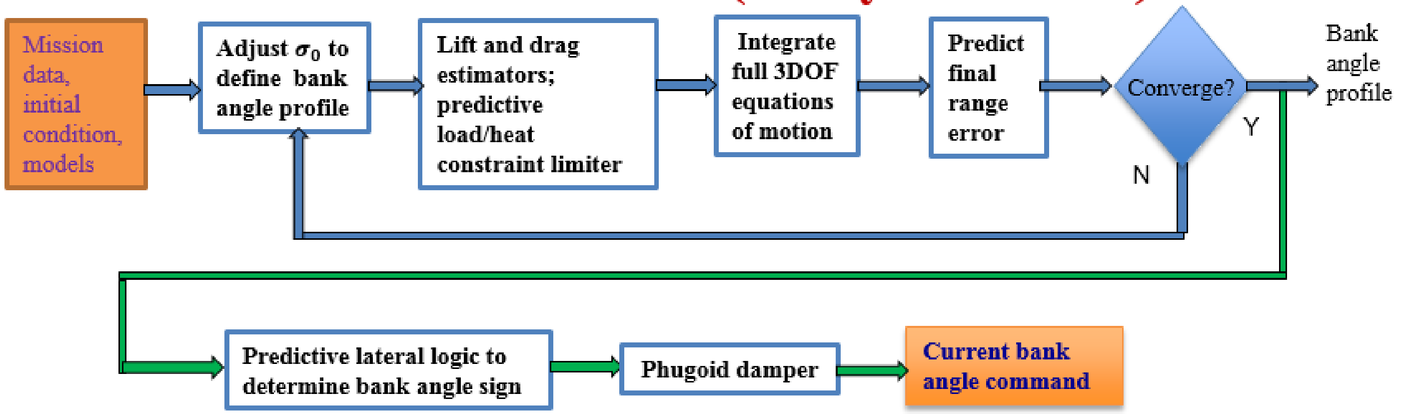
- Features
  - FNPEG is a fully numerical predictor-corrector entry guidance algorithm capable of direct entry guidance and skip entry guidance
  - At each guidance time step, FNPEG uses Newton-Raphson method within its' predictor-corrector to search for the bank angle command σ_0 that creates a bank 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 (σ) 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

Overview of FNPEG (Entry Guidance)



Mission data, initial condition, models

Adjust σ_0 to define bank angle profile

Lift and drag estimators; predictive load/heat constraint limiter

Integrate full 3DOF equations of motion

Predict final range error

Converge?

N

Y

Bank angle profile

Predictive lateral logic to determine bank angle sign

Phugoid damper

Current bank angle command

- Simple and clean structure, free of complex phasing logic
- High precision with guaranteed superlinearly converged solution if one exists
- Fully automated, little tuning required for different missions and vehicles

*from Dr. Ping Lu

The case for FNPEG

- 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

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

Dynamic Equations of Motion Re-derivation in NED Frame

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 β & CS are assumed small.

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

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

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

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

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

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

Using Eqns 13 and 56 yield

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

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

$$\mathcal{V}\dot{\psi} = \frac{1}{m}\frac{\mathcal{N}s(\sigma)}{c(\gamma)} + \boxed{\frac{1}{m}\frac{\mathcal{S}c(\sigma)}{c(\gamma)}} - \frac{\mathcal{V}^2}{r}c(\gamma)c(\psi)t(\phi) + 2\omega\mathcal{V}(t(\gamma)c(\psi)s(\psi) - s(\phi)) - \frac{\omega^2 r}{c(\gamma)}s(\phi)c(\phi)c(\psi) \tag{45}$$