Dragonfly Entry and Descent Flight Mechanics Modeling and Analysis

AIAA SciTech Forum

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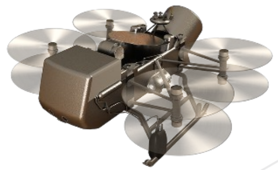
AMA, Inc.

NASA Langley

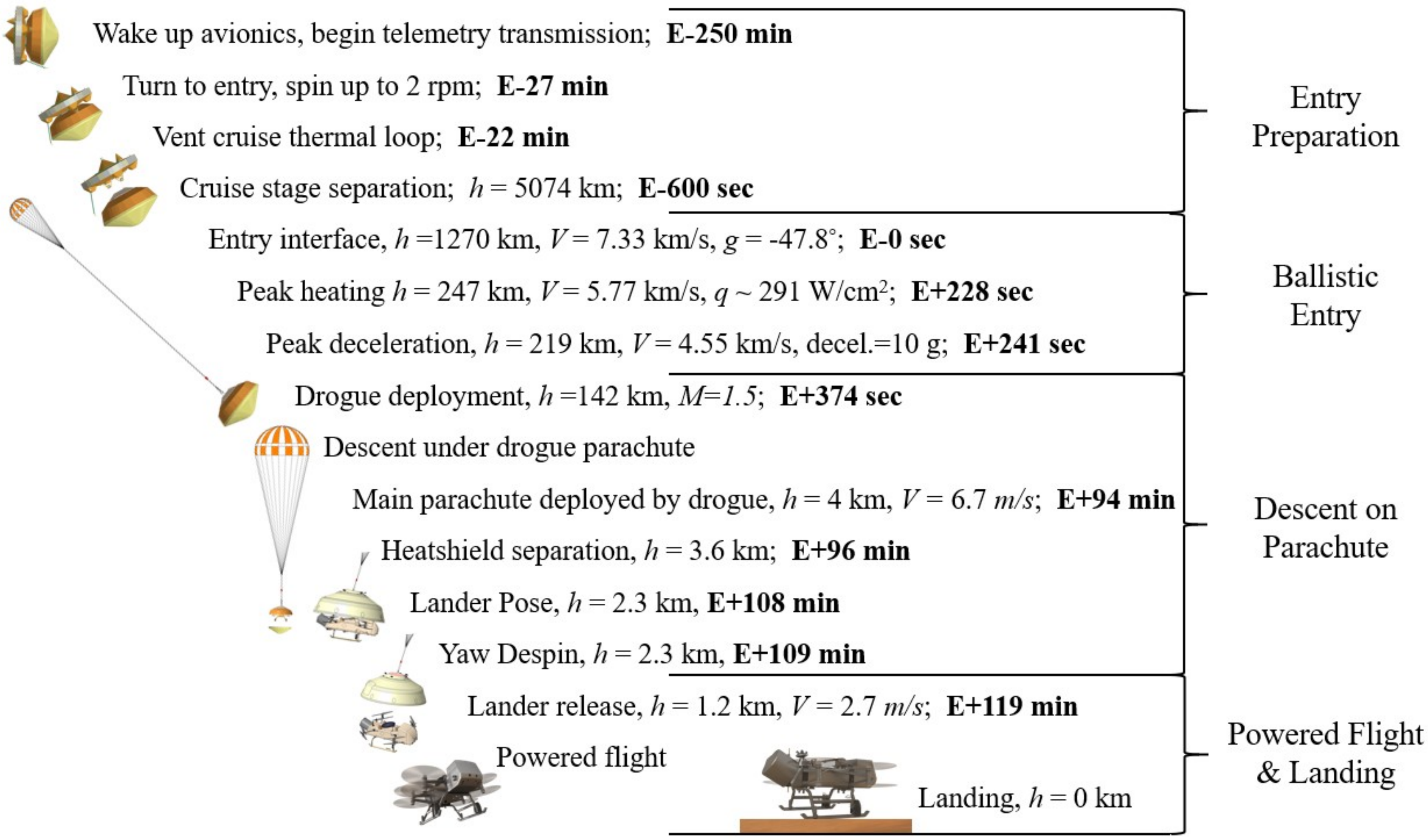
DRAGONFLY

A relocatable lander to explore Titan's prebiotic chemistry and habitability

Overview

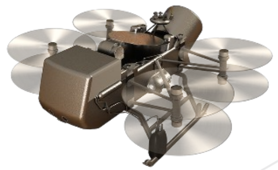


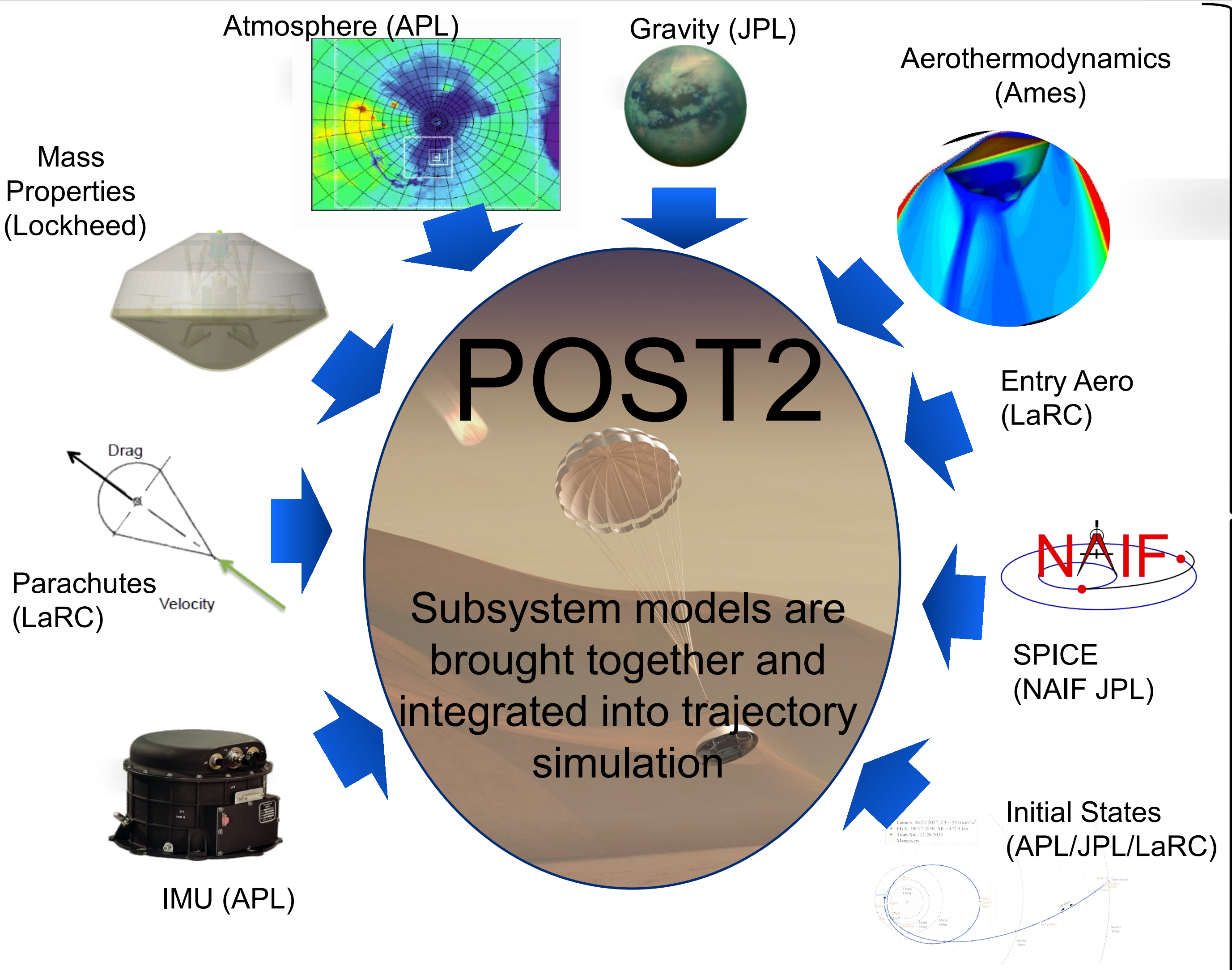
- Dragonfly is a New Frontiers Program mission that will deliver a rotorcraft lander to Saturn's moon, Titan.
- This mission is designed to explore diverse locations to characterize the habitability of Titan's environment.
- The purpose of this presentation is to give an overview of the status of Dragonfly flight mechanics modeling as of the preliminary design review (PDR).



POST2 Entry & Descent Simulation

LaRC – NASA Langley Research Center
APL – Applied Physics Laboratory
JPL – Jet Propulsion Laboratory
Ames – NASA Ames Research Center
Lockheed – Lockheed Martin Space Company



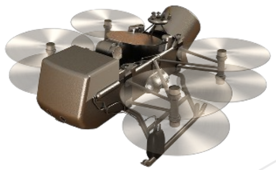


System performance is assessed through augmented cluster computing scripts that enable Monte Carlo and sensitivity analyses

- **POST2 Input File**
- **Config Control Input File**
- **Monte Carlo Input Files**

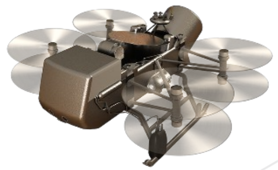
POST2 – Program to Optimize Simulated Trajectories II, developed at NASA Langley
"Enabling Thread Safety and Parallelism in the Program to Optimize Simulated Trajectories II" Williams, et al., AIAA SciTech 2023

Table of Contents



- POST2 Entry & Descent Simulation
- Titan EDL
- Vehicle and Parachute Design
- Baseline Analysis
  - MPV Primary/Backup, CBE Primary/Backup scenarios
- Future Work
- Summary

Titan EDL Compared to Mars EDL

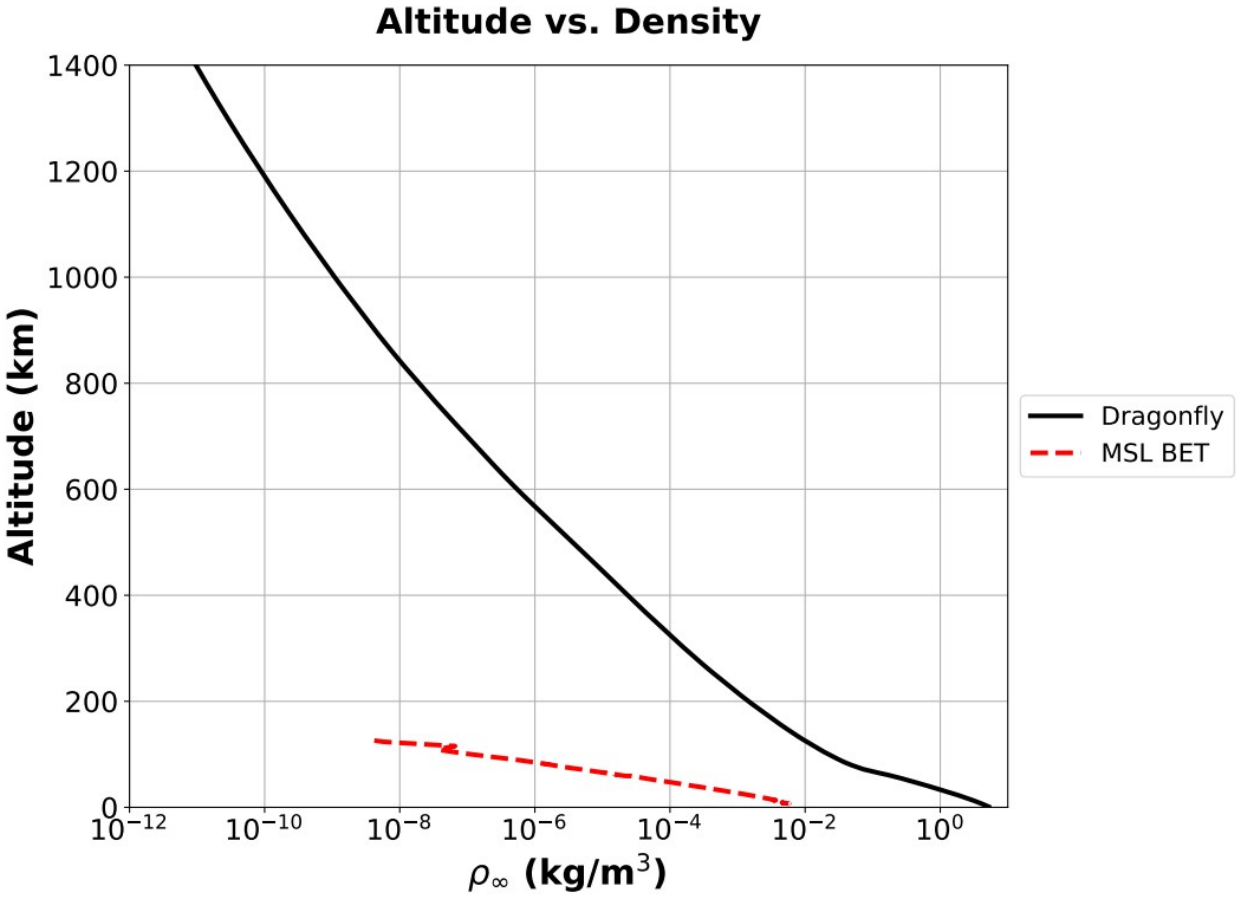


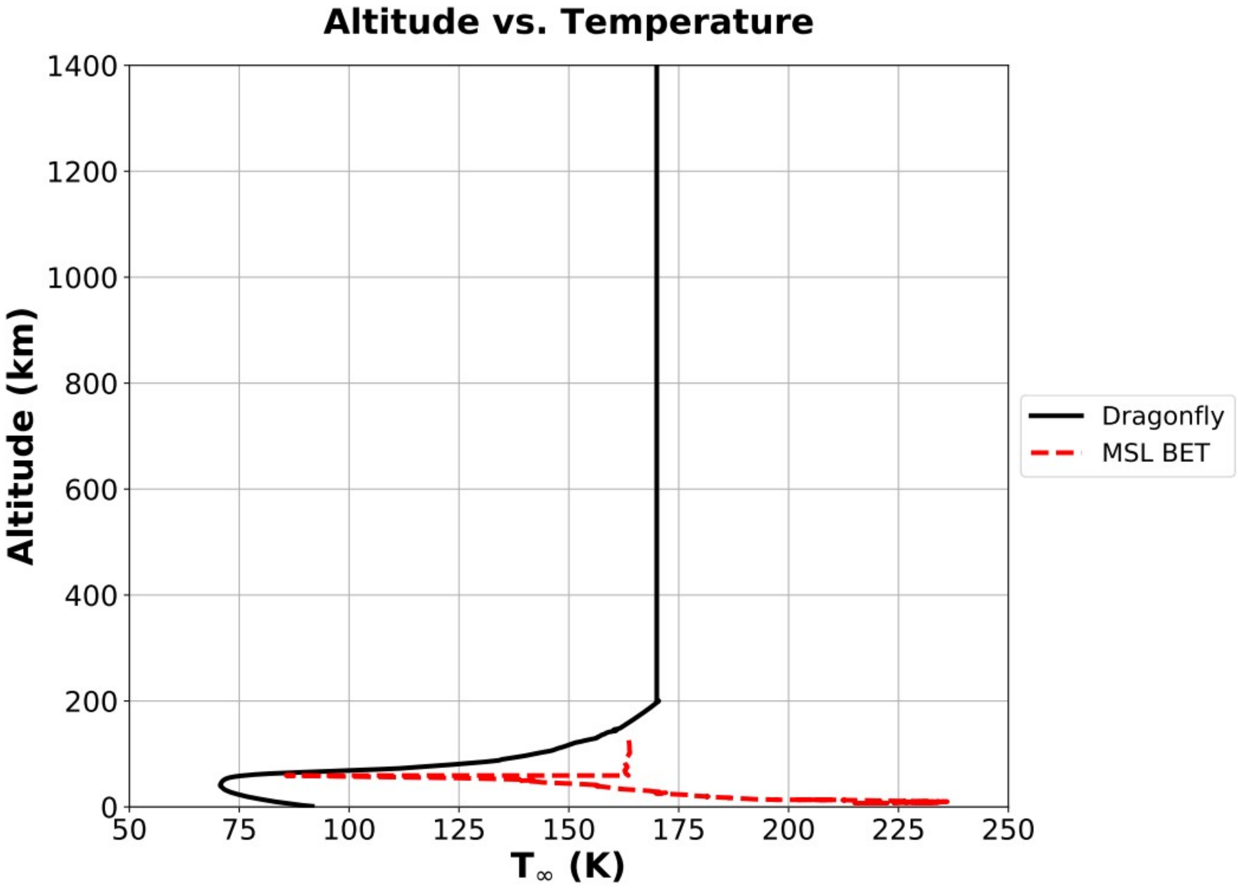
- Titan: Taller/denser atmosphere and lower gravity leads to much longer descent time under parachute(s), > 1.5 hours versus ~2 minutes for Mars
  - Results in thermal and power challenges
- Dragonfly: supersonic (drogue) parachute diameter is slightly larger than capsule diameter, unlike Mars (4-5X)
  - Results in descent system dynamics challenges over a long duration
- Titan: larger scale height leads to insensitivity of aeroheating environments to entry flight path angle range, unlike Mars

	Titan	Mars
Height of Atmosphere (km)	~1270	~125
Density at surface (compared to Earth)	4X	<0.02X
Temperature at surface (K)	~94	~200
Scale Height (km)	~40	~7
Surface gravity (Earth g)	0.14	0.38
Atmosphere (by mass)	98% N_2 + 2% CH_4	96% CO_2 + 2% N_2 + 2% Ar
Avg. distance to Earth (millions of mi)	800	140

Titan environment leads to EDL challenges due to atmosphere height/density/composition and lower gravity compared to Mars

Titan Atmosphere Compared to Mars

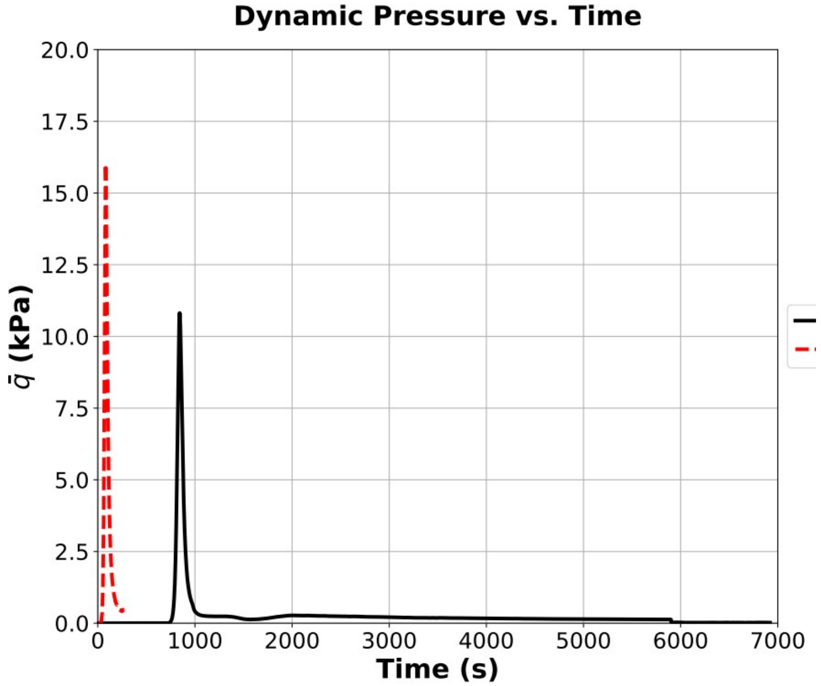


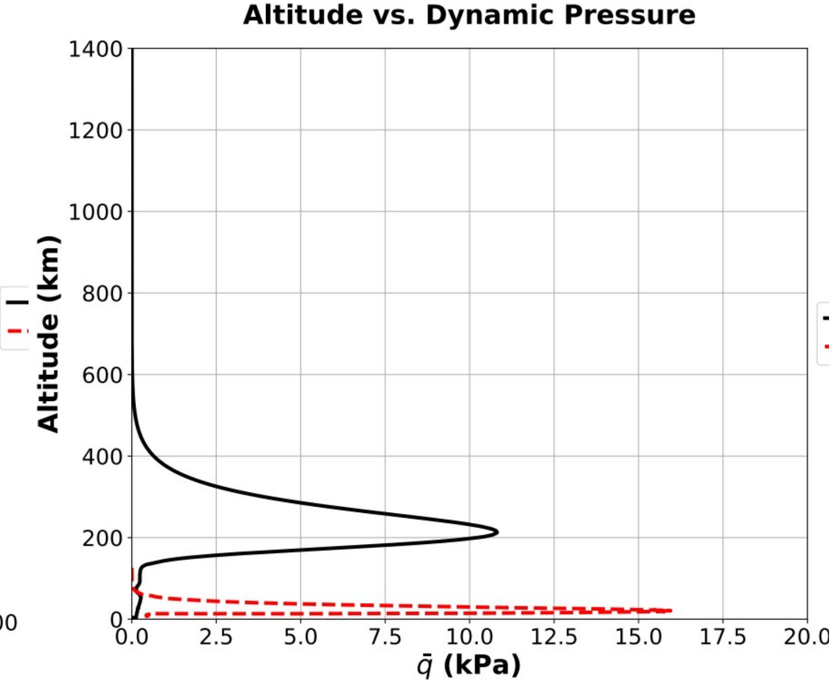


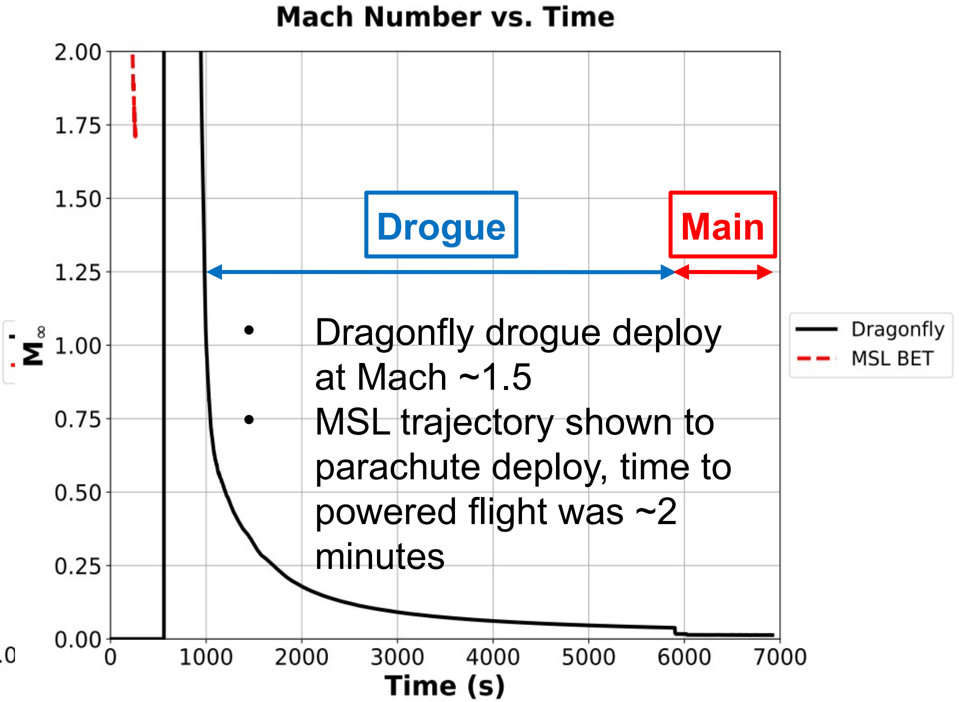
MSL BET = Best Estimated Trajectory from onboard IMU + flush air data system

Titan atmosphere: taller/denser/colder atmosphere with larger scale height compared to Mars

Sample Dragonfly Trajectory Compared to MSL



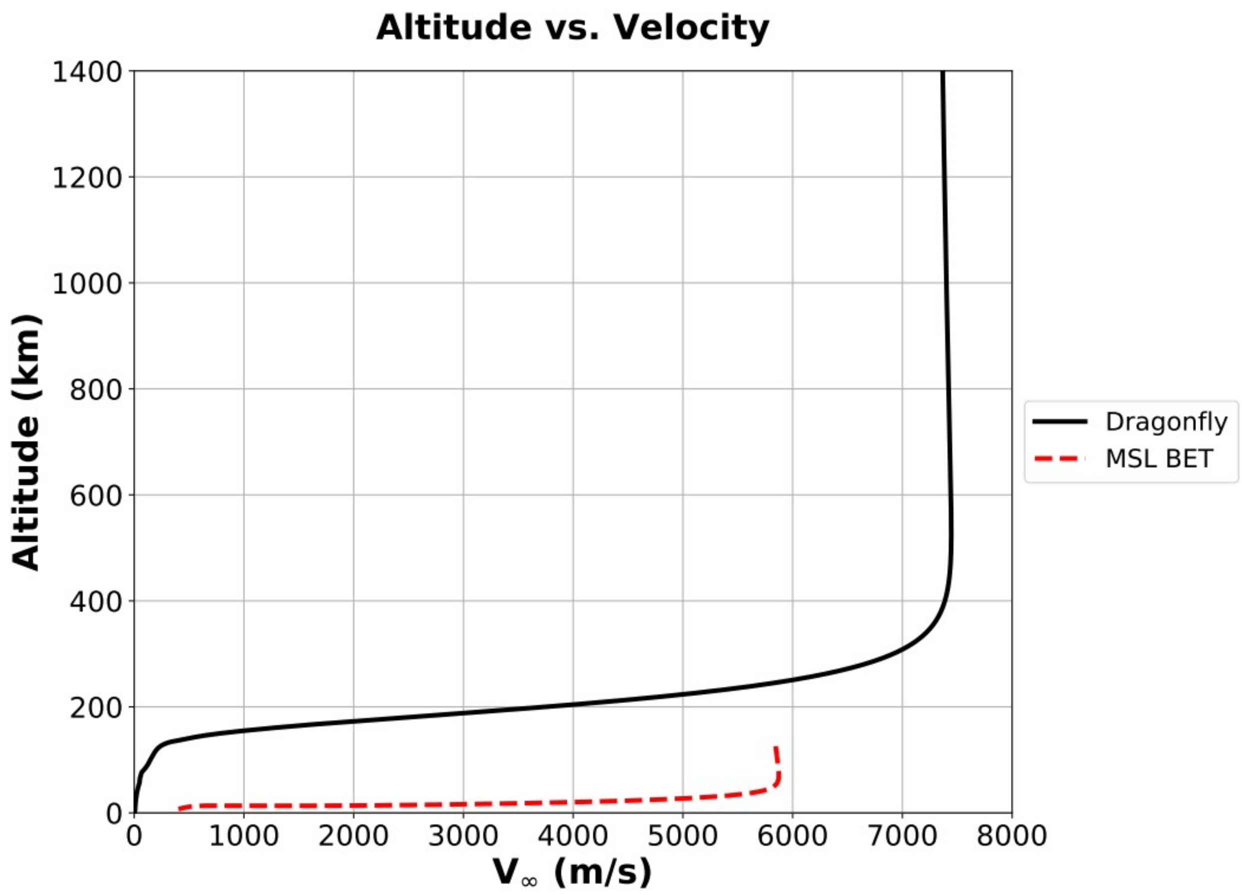


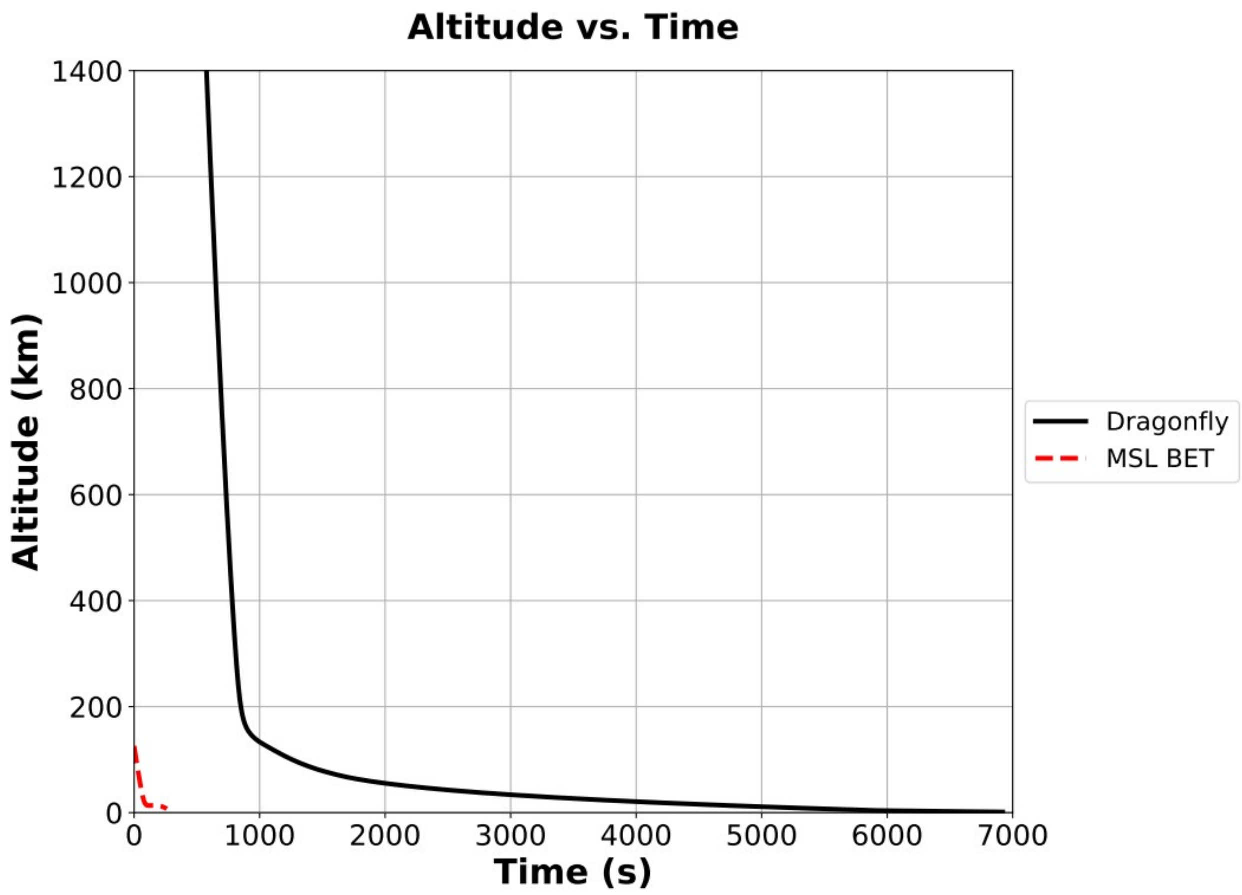


- Dragonfly drogue deploy at Mach ~1.5
- MSL trajectory shown to parachute deploy, time to powered flight was ~2 minutes

Dynamic pressure max. is similar to Mars, but peak occurs at much higher altitude. Much longer time at subsonic conditions for Titan.

Sample Dragonfly Trajectory Compared to MSL



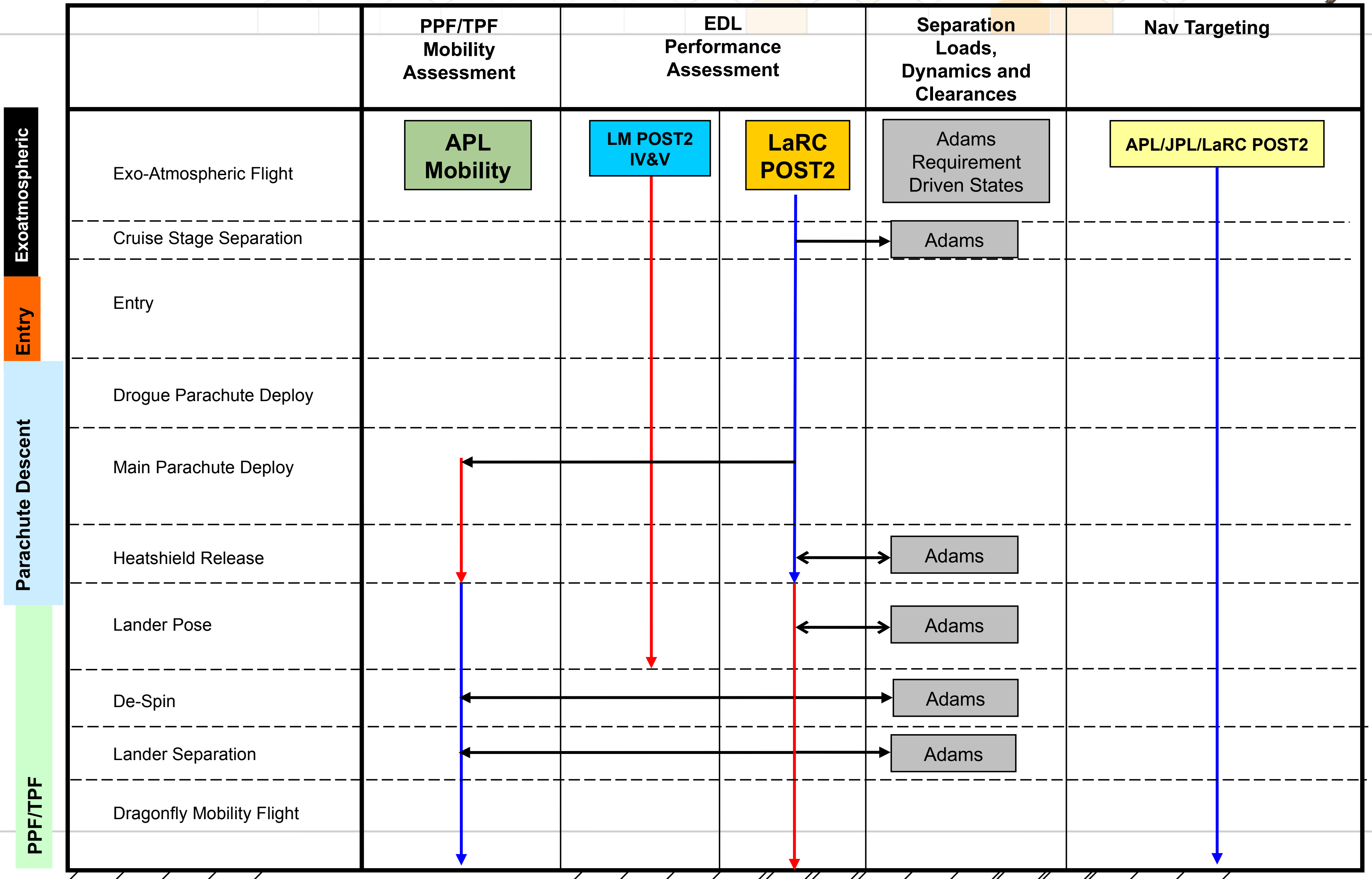


Titan EDL sequence is almost 2 hours compared to Mars "7 minutes of terror"

Modeling and Simulations

Primary Analysis Path

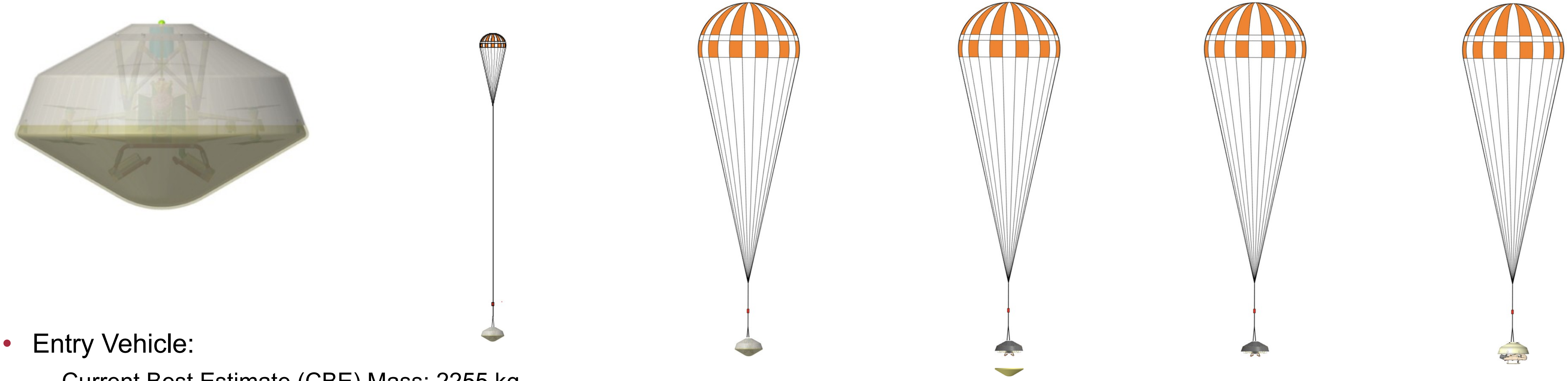
Confirming Analysis Path



Aerodynamic Configurations

* EI = entry interface
* Scales and times are approximate

Capsule	Capsule on Drogue	Capsule on Main	Heatshield Separation	**Stowed Lander in Backshell**	**Posed Lander in Backshell**
Entry to Mach 1.5	Mach 1.5 to 7 m/s	Mach < 0.04	3.6 km		2.7 m/s
EI – 10 min to EI + 6 min	90 min	2 min	Main + 2 min	12 min	11 min



- Entry Vehicle:
  - Current Best Estimate (CBE) Mass: 2255 kg
  - Maximum Possible Value (MPV) Mass: 2500 kg
  - Diameter: 4.5 m
  - Sphere Cone Angle: 60
  - Based on Genesis Sample Return Capsule
  - Aerodatabase uses computational fluid dynamics (CFD), the Langley 12’ low speed wind tunnel, and the Langley Transonic Dynamic Tunnel (TDT).
- Drogue Parachute
  - 5.4m Disk Gap Band (DGB)
  - Deployed via mortar fire using a smart trigger to minimize the total angle off attack
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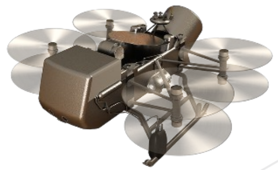
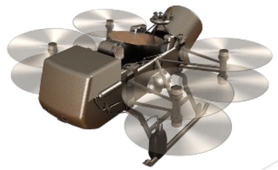
  - 16.55 m DGB
  - Deployed using Drogue parachute at a specified altitude

CEA in POST2



- Chemical equilibrium with applications (CEA) is a NASA code that computes chemical equilibrium conditions and thermodynamic states for various scenarios, including processes occurring in a rocket engine and in a shock tube. CEA has been integrated with POST2 to provide thermodynamic and mass properties of an equilibrium reaction at every time step
- Source: NASA Glenn documentation and software release “Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications II. Users Manual and Program Description” McBride, Gordon. 1996. NASA-RP-1311.
- Implementation: POST2 interface to CEA Fortran code (source code)
- Verification: Comparison of POST2 outputs with stand alone CEA code
- Uncertainties: None for CEA
- Inputs: Freestream properties, atmospheric composition, atmospheric relative velocity
- Outputs: Post-shock properties density, temperature, Mach, inputs to aeroheating calculations.
- Future improvements: Possible CEA future updates

Aerothermal Indicators



- Implementation: C source code of curve fits for convective and radiative heating; incorporated with CEA
- Inputs:
  - Free stream velocity and density
  - Post shock Density, Temperature, and CN Mass Fraction (CEA)
- Outputs:
  - Convective and radiative heating at 4 body points (Stagnation Point, Fore Shoulder, Aft Shoulder, and Edge of Aft Cover).
- Verification: Comparison against DPLR/NEQAIR results. Compared heating results and compared CEA values with A. Brandis
- Uncertainties: Dragonfly aerothermal design margins included into the fit
- Gaps: Anchored on 2100 and 2700 kg trajectories, not current design mass
- Improvements: Additional body points as needed, and updates to indicators based on DAC1b aerothermal simulations. The radiative heating margin may also be updated based on analysis of current EAST testing.

DAC1 Indicator Form

$$q_{conv} = A \times \left(10^3 \times \rho_\infty\right)^B \times \left(\frac{v_\infty}{10^3}\right)^C \times \left(\frac{T_2}{10^3}\right)^D$$

Updated DAC1 CFD Fit Coefficients

Location	A	B	C	D
Stagnation Point	0.29649	0.46144	2.80644	0.74544
Forebody Shoulder	9.96533E-2	0.83002	4.60919	-0.17372
Aft Shoulder	0.11543	0.49693	1.48421	1.38858
Aft Lid	0.13921	0.56549	1.02911	1.54841

DAC1B Indicator Form

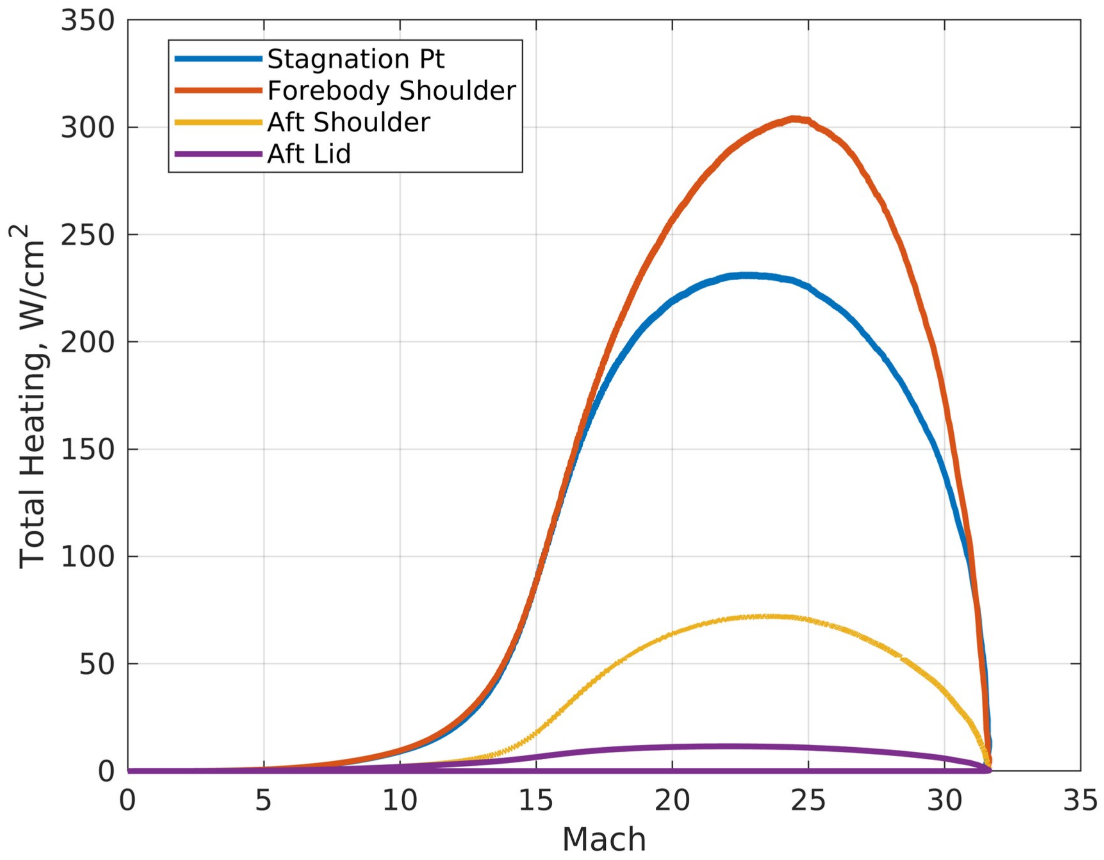
$$q_{rad} = A \times \left(10^7 \times \frac{\rho_2 \times CN_2}{\left(\frac{\rho_2}{\rho_\infty} - 1\right)^3}\right)^B \times \left(\frac{T_2}{10^3}\right)^C$$

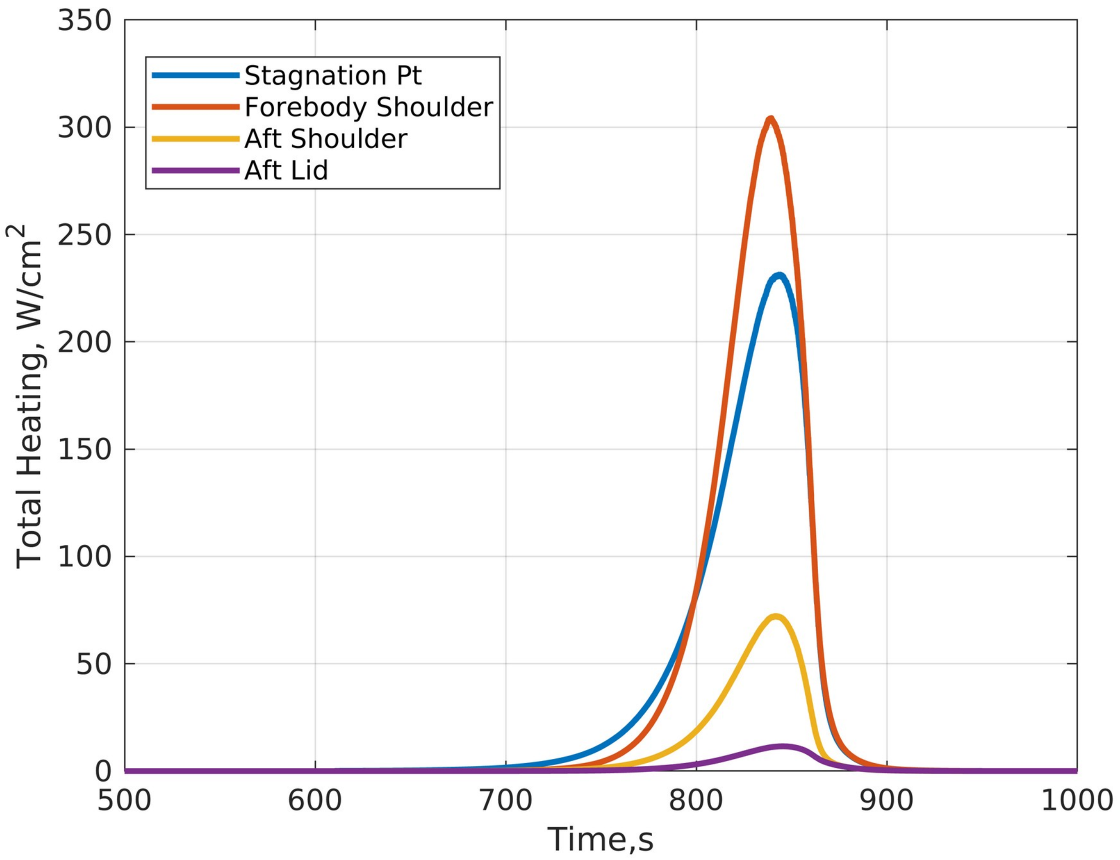
New term to account for shock-layer thickness

Updated DAC1 CFD Fit Coefficients

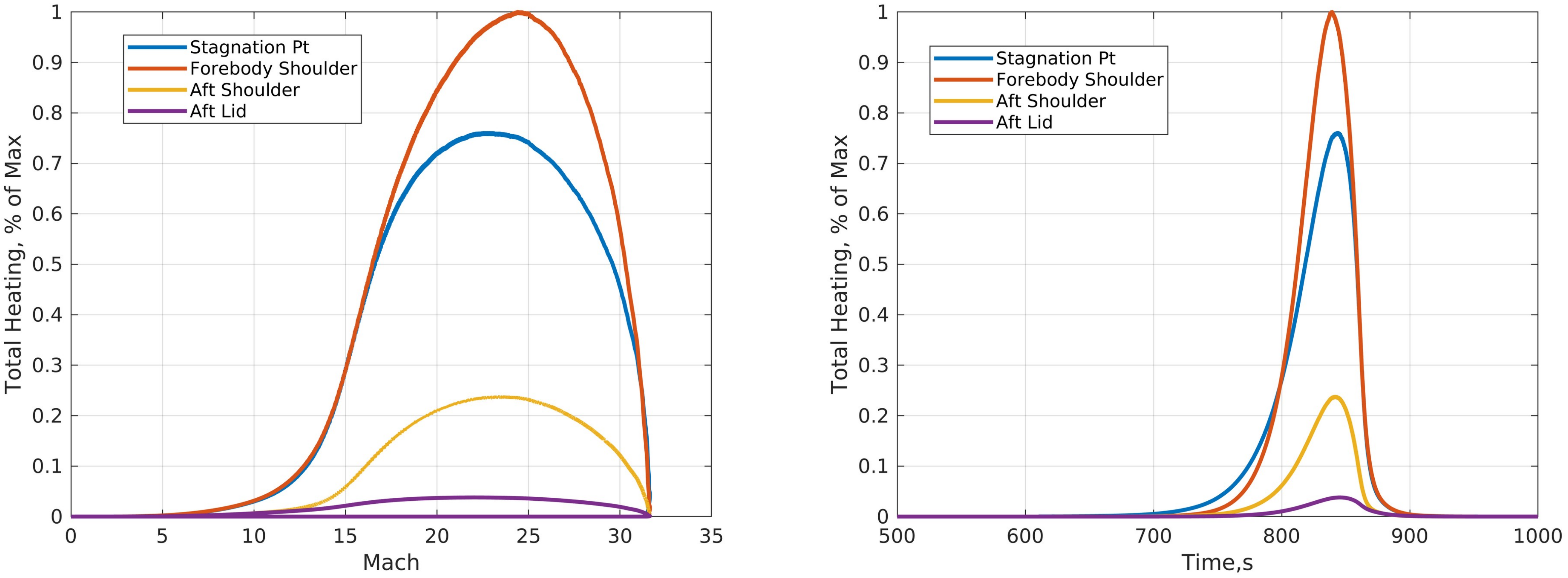
Location	A	B	C
Stagnation Point	2.08619E-3	0.45819	6.83797
Forebody Shoulder	2.59984E-3	0.35411	6.76723
Aft Shoulder	2.12678E-4	0.32056	7.56926
Aft Lid	3.17503E-4	0.35465	5.47184

Representative Heating

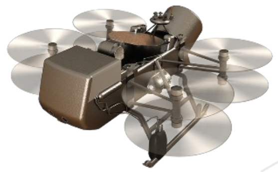




Representative Heating

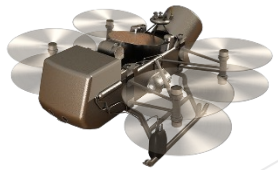


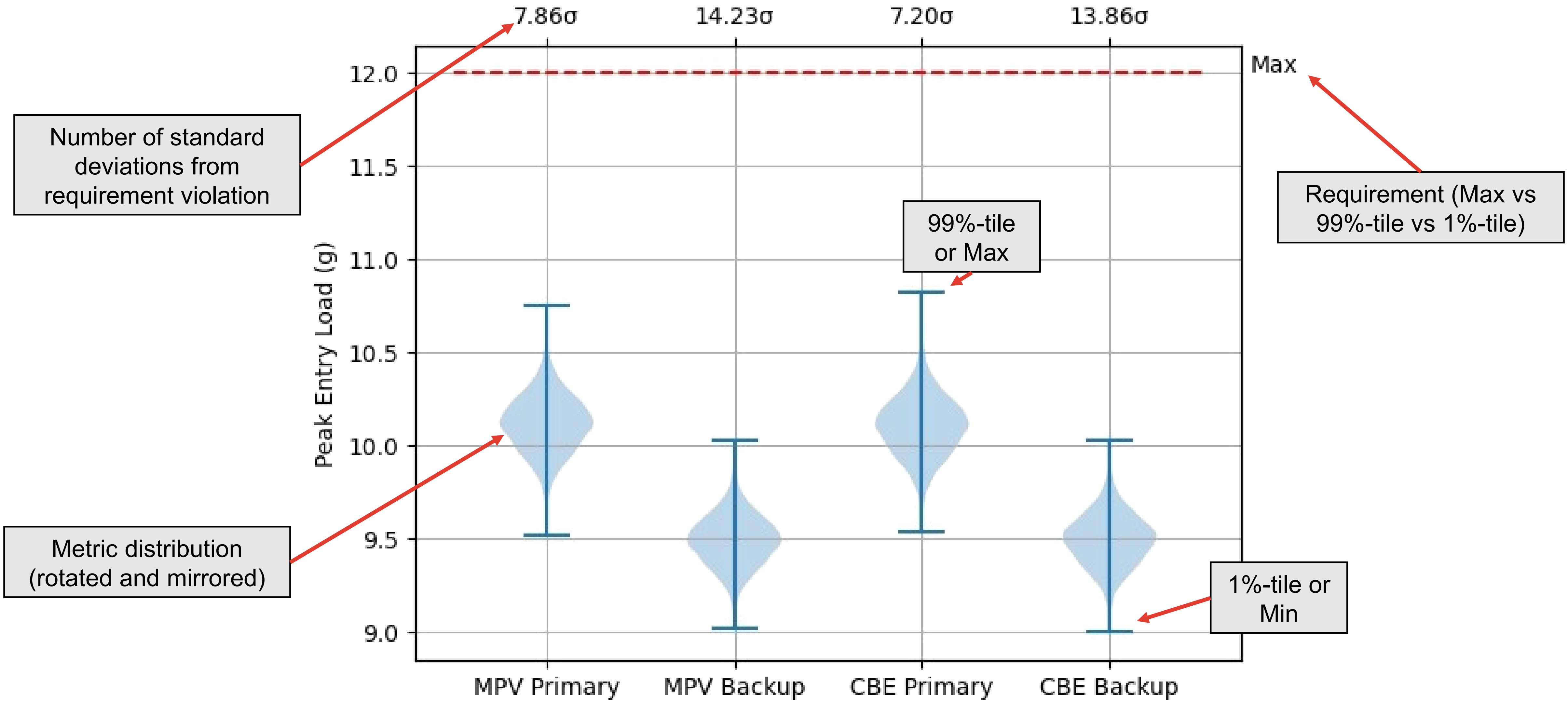
Requirements and EDL Metrics



Requirement Description	Requirement Phase	Requirement Type	Requirement Comparison/Units	
Lateral Tipoff Rate Magnitude After CS Sep	Entry Prep	max	<3	deg/s
Peak Entry Load	Entry	max	<12	g
Max Peak Heat Rate	Entry	max	<310	W/cm^2
Peak Drogue Opening Load	Drogue Parachute	99%	<14700	N
Total AoA @ Drogue Chute Deploy	Drogue Parachute	99%	<15	deg
Time to Mach 1.4	Drogue Parachute	99%	<10	s
High Altitude @ Main Deploy	Main Parachute	1%	>=3500	m
Low Altitude @ Main Deploy	Main Parachute	99%	<=4500	m
Altitude @ Lander Release	Prep for Powered Flight	1%	>1200	m
Down Atm. Rel. Velocity @ Lander Release	Prep for Powered Flight	99%	<2.9	m/s
Total Descent Time from Atm Interface	Entry	99%	<7200	s

Interpreting EDL Performance Charts



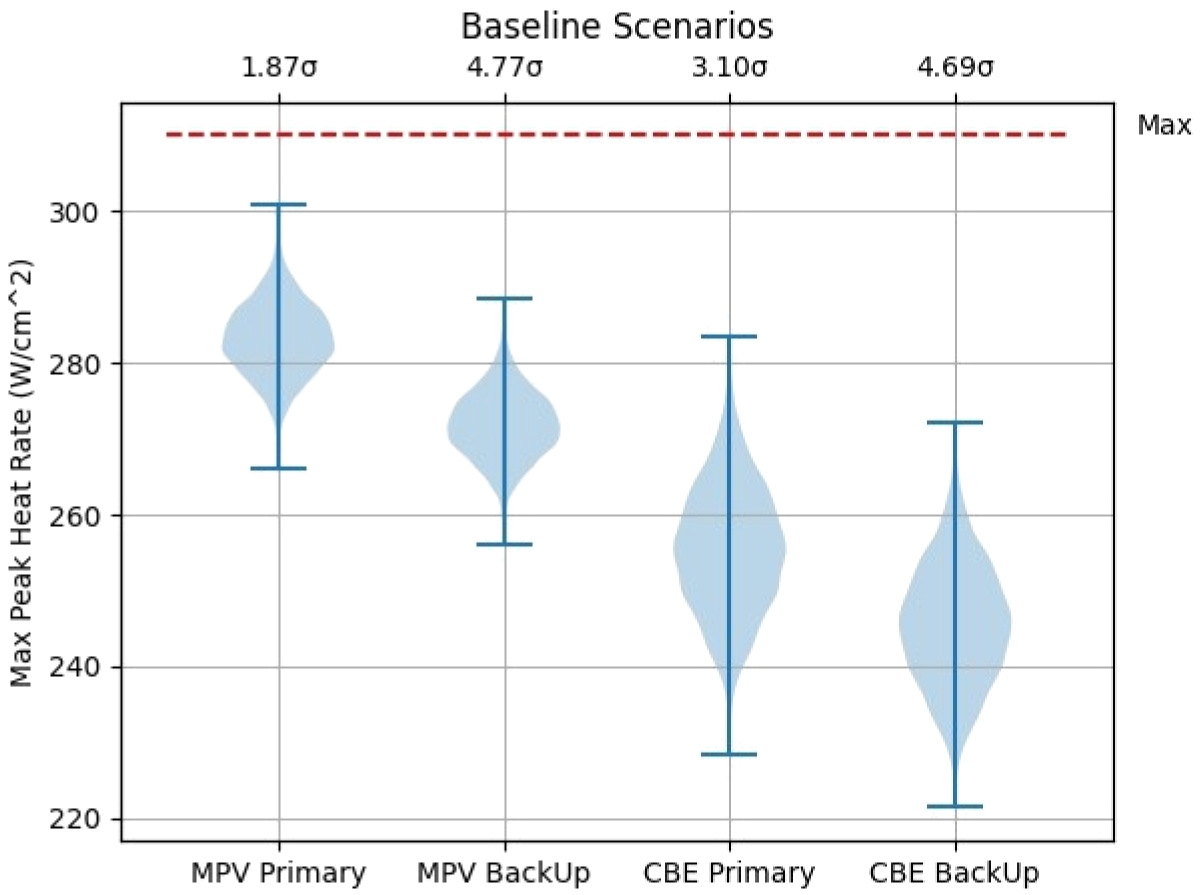


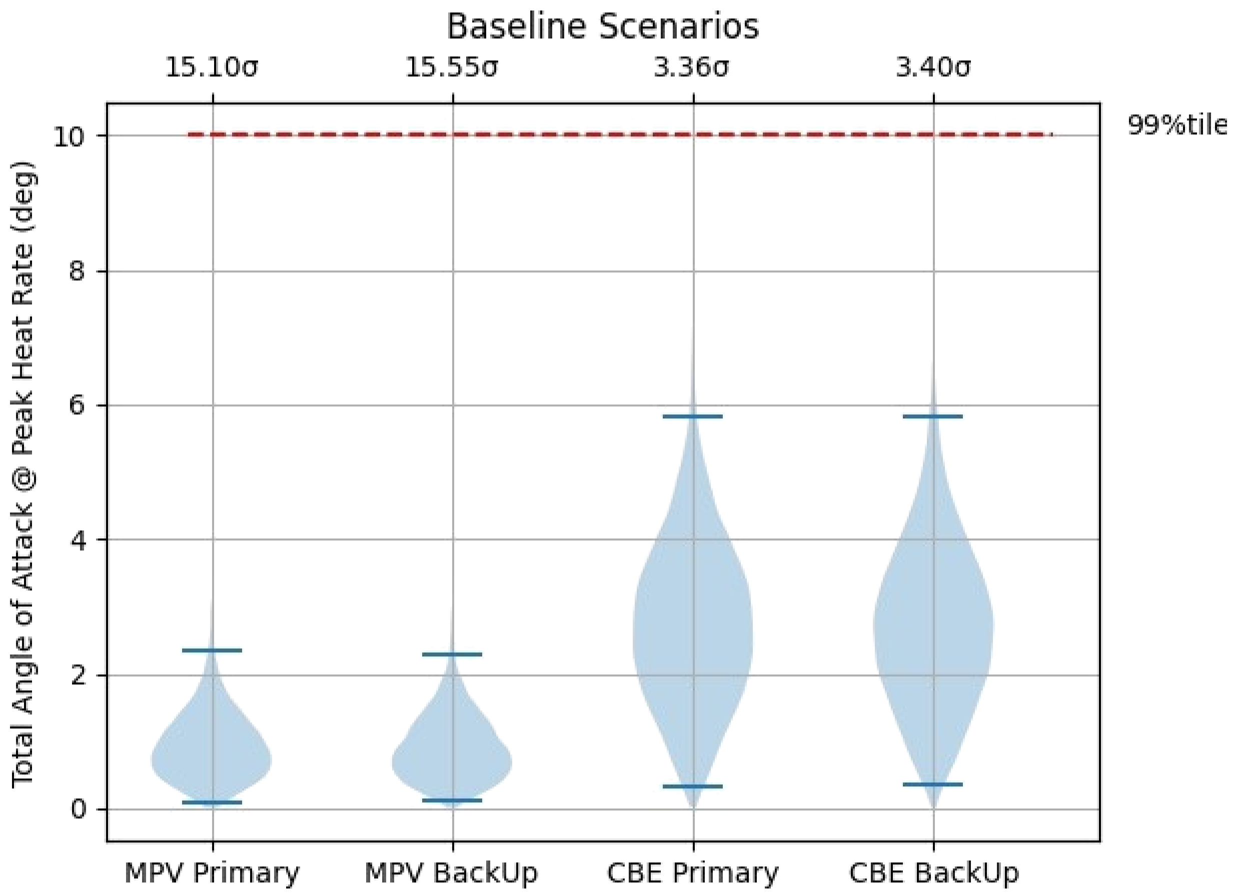
Current Best Estimate (CBE)

Maximum Possible Value (MPV)

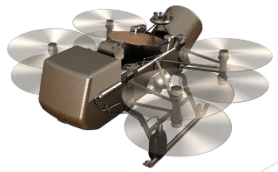
Entry Heating

- **Peak Entry Heating < 310 W/cm² (99%-tile)**





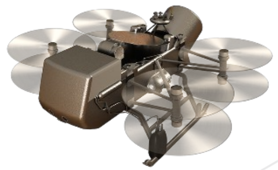
Requirements and EDL Metrics Compliance



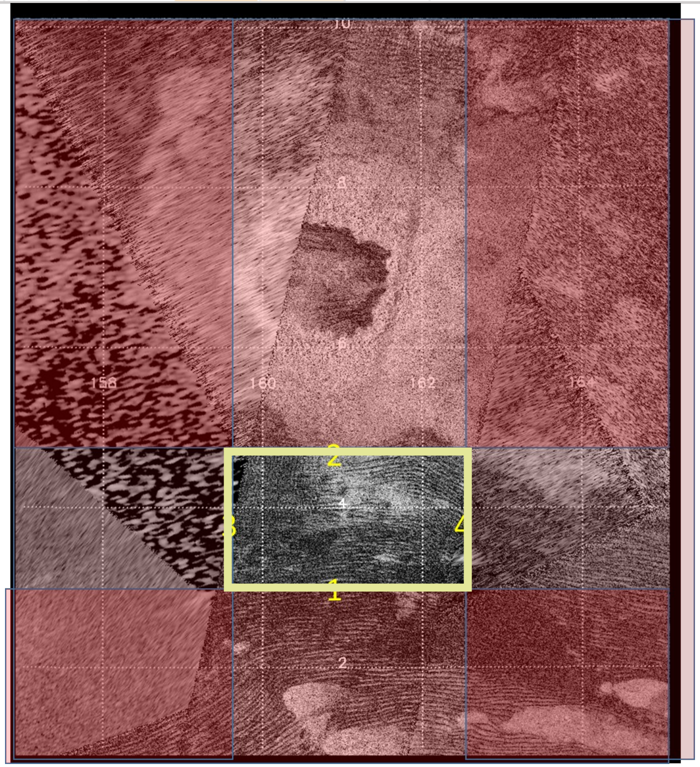
Constraint Name	Requirement Type	Value	Units	MPV Primary	MPV Back Up	CBE Primary	CBE Back Up
Lateral Tipoff Rate Magnitude After CS Sep	max	x <3	deg/s	100%	100%	99.8%	99.8%
Peak Entry Load	max	x <12	g	100%	100%	100%	100%
Max Peak Heat Rate	max	x <310	W/cm^2	100%	100%	100%	100%
Peak Drogue Opening Load	99%	x <14700	N	100%	100%	100%	100%
Total AoA @ Drogue Chute Deploy	99%	x <15	deg	99.9%	100%	99.9%	99.9%
Time to Mach 1.4	99%	x <10	s	100%	99.9%	99.9%	99.4%
Low Altitude @ Main Deploy	1%	x >=3500	m	98.5%	98.5%	98.5%	98. 5%
High Altitude @ Main Deploy	99%	x <=4500	m	99.3%	99.4%	99.4%	99.4%
Altitude @ Lander Release	1%	x >1200	m	99.92%	99.9%	99.9%	99.9%
Down Atm. Rel. Velocity @ Lander Release	99%	x <2.9	m/s	100%	100%	100%	100%
Total Descent Time from atm interface	99%	x <7200	s	100%	100%	94.6%	92.3%

- Both cruise stage separation and total descent time for CBE will be designed based on updated mass properties – expect no failures as MPV and CBE converge in Phase C

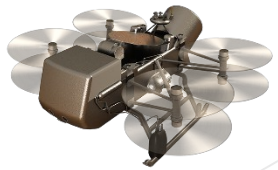
Landing Site Targeting



- Mission Design and EDL teams work to design reference trajectory “center point” of lander separation target at the EDL handoff point
  - Titan lat/long = 3.7N, 161.8E at a reference altitude of 1200 m.
- Target region is defined as follows: 95% of lander separation points shall be in the box (95% is advocated as criterion rather than 99% since boundaries are not ‘sudden death’, but merely degraded scenarios/higher risk)
  1. Lat > 3.0 N (further south requires >176km traverse to Selk center. Could waive this limit if traverse range were not a concern)
  2. Lat < 4.5 N (further north entails high probability of ejecta blanket/rough terrain)
  3. Lon > 159.5 E (further West takes us into terra incognita. Most probably dunes, but no useful radar data to confirm)
  4. Lon < 162.5 E (further East goes into poorer radar data, and increases required traverse range)

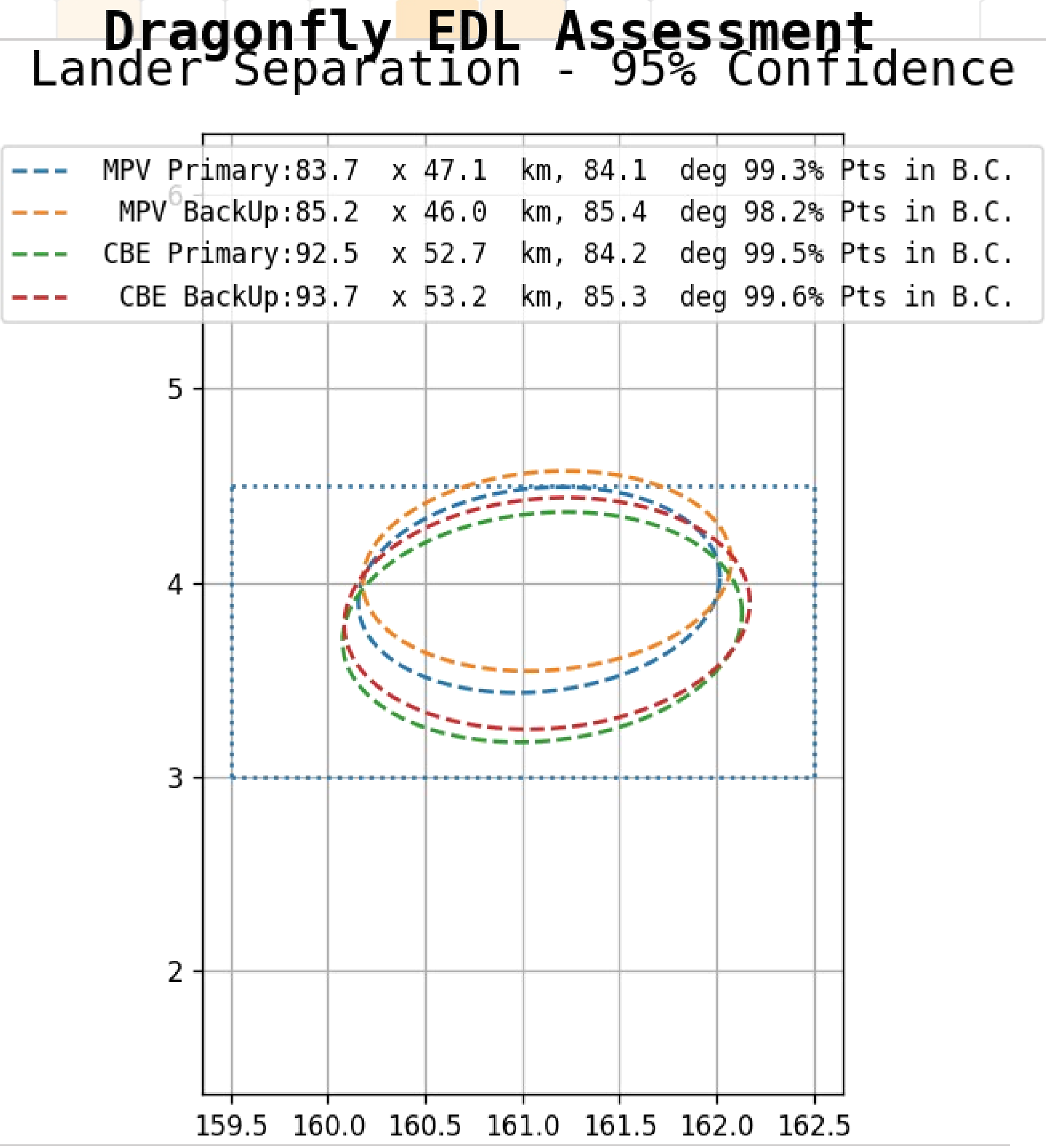


Lander Separation Footprint

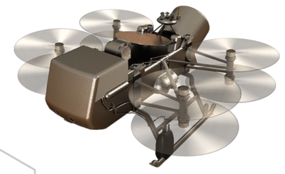


- Requirement:
  - The Ground System shall be designed such that 95% of the lander separation points are within a box on Titan's surface defined by: 3.0 N < latitude < 4.5 N, 159.5 E < longitude < 162.5 E.

- All four baseline scenarios meet this requirement



Summary & Future Work

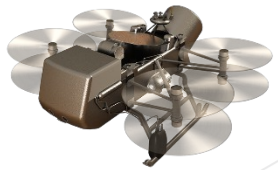


- Current trajectory design meets all aerothermal requirements with margin against all uncertainties modeled through Monte Carlo analysis

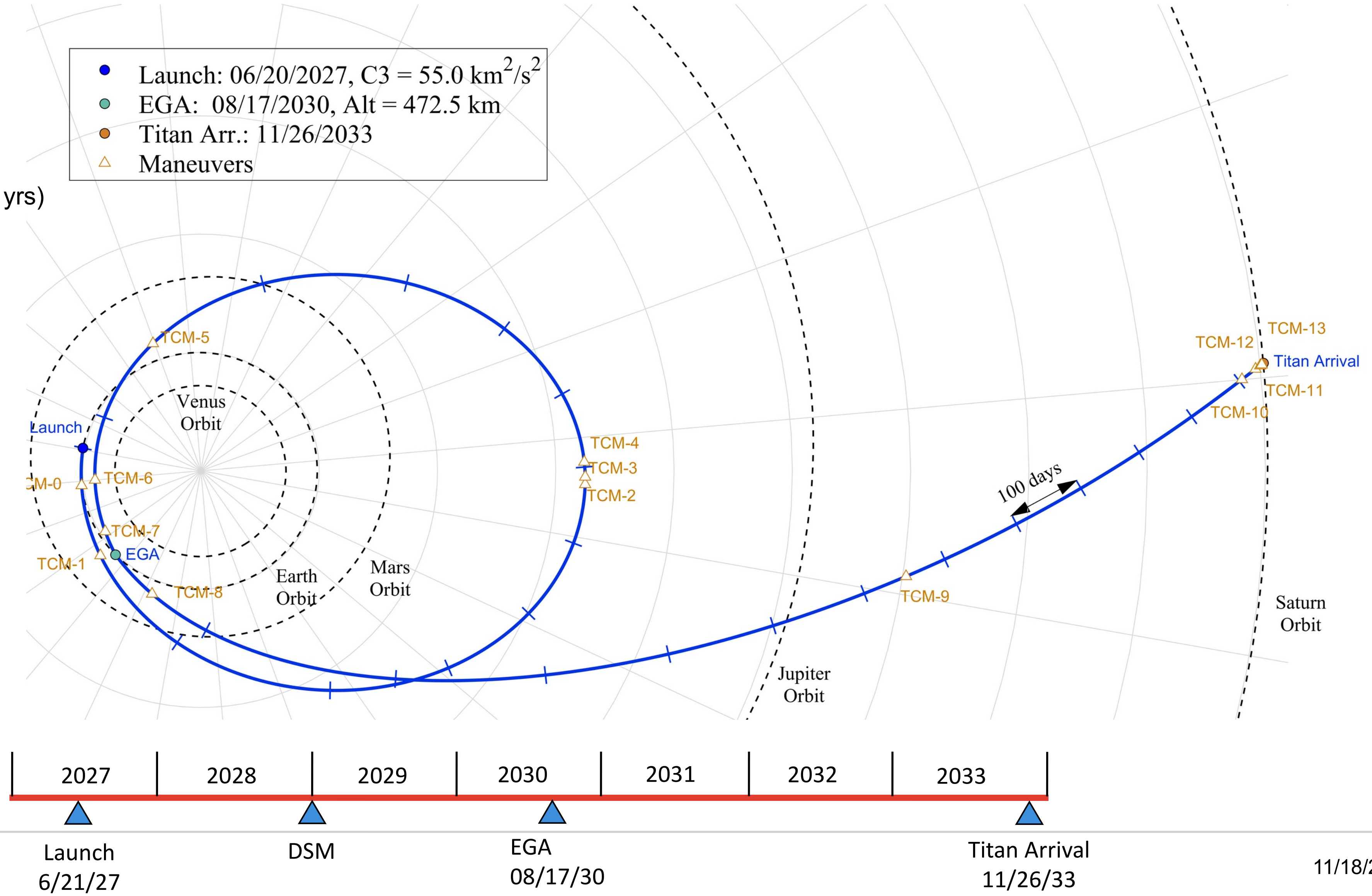
- Expected new model deliveries
  - Yaw-despin controller from APL mobility
  - Low subsonic aerodynamics from TDT testing
  - Capsule drop test data
  - Parachute models from subcontractor
  - IMU and Flight software from APL G&C
- Model verification
- New analysis
  - Investigation of lander separation trigger update
  - Incorporation of despin controller and actuation in POST2

DRAGONFLY

2027 ΔV-EGA^{3+} (First Day of Prime Launch Period)



ΔV = Deep Space Maneuver (DSM)
EGA = Earth Gravity Assist
3 = Near 3:1 resonance with Earth (3 yrs)
+ = post perihelion EGA



Launch Period
Prime: 6/20/27 -- 7/10/27
Backup: 7/4/28 -- 7/24/28

Vehicle

- Entry Vehicle:
  - Current Best Estimate (CBE) Mass: 2255 kg
  - Maximum Possible Value (MPV) Mass: 2500 kg
  - Diameter: 4.5 m
  - Sphere Cone Angle: 60
  - Based on Genesis Sample Return Capsule
  - Aerodatabase is updated using computational fluid dynamics (CFD), the Langley 12’ low speed wind tunnel, and the Langley Transonic Dynamic Tunnel (TDT).
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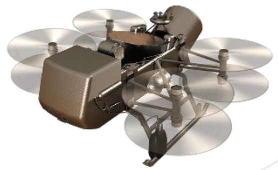
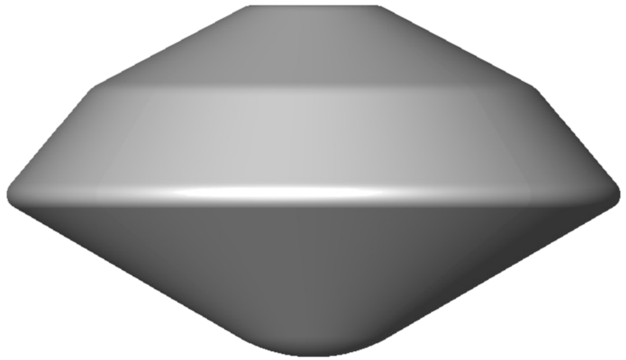
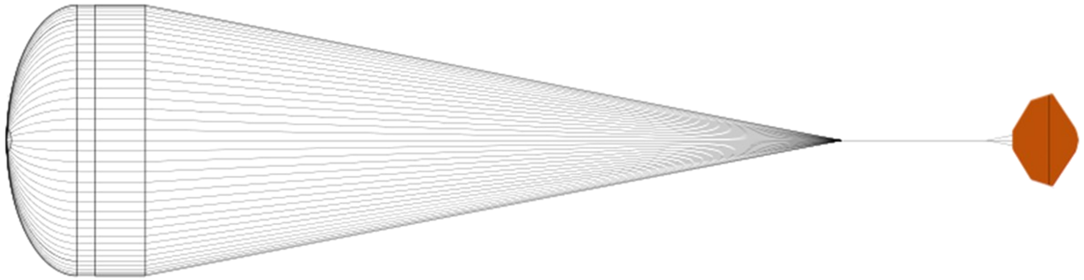
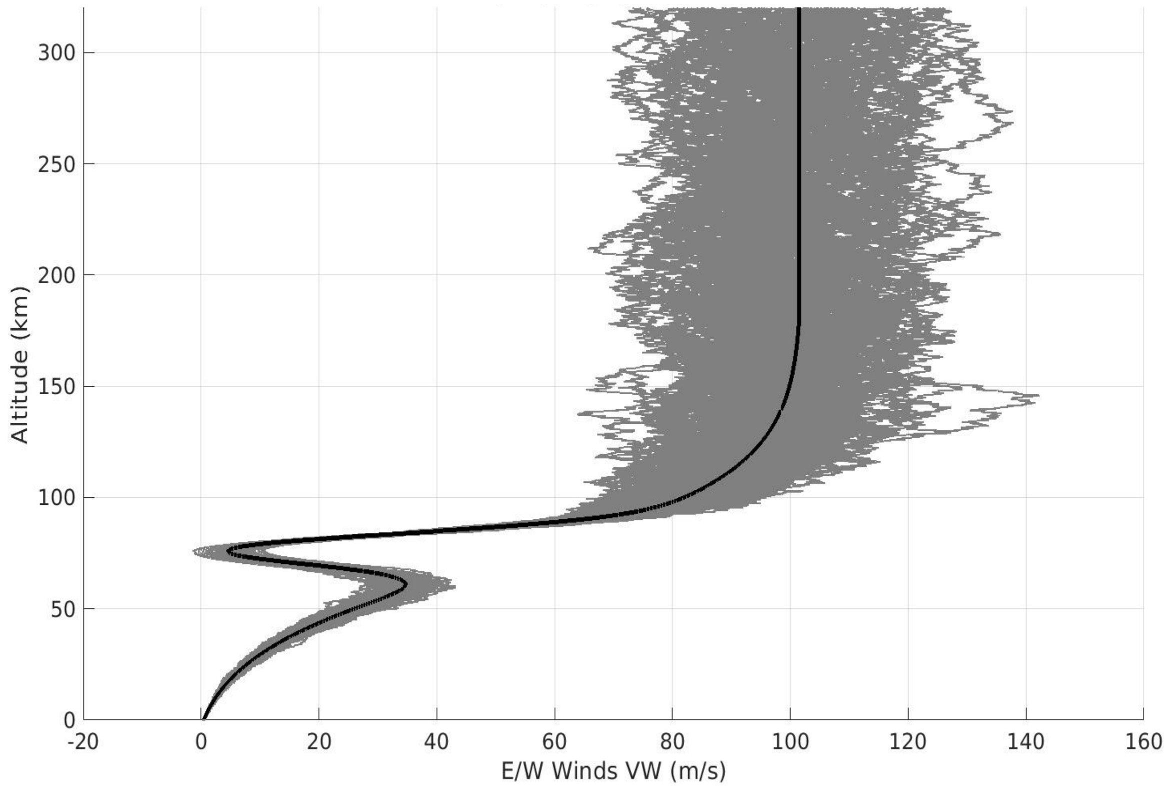






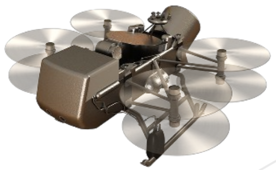
Titan Modeling

- Gravity Modeling
  - 4x4 spherical harmonics provided by JPL/APL
- Atmosphere and Wind Modeling
  - Using Yelle Model [1] based on Hyugens data
  - Wind and Gust models provided by Mission Architect based on Hyugens data.
  - Titan’s atmospheric density scale height is much larger (~40 km) than Earth and Mars (~7 km) which makes the aerothermal story unique.



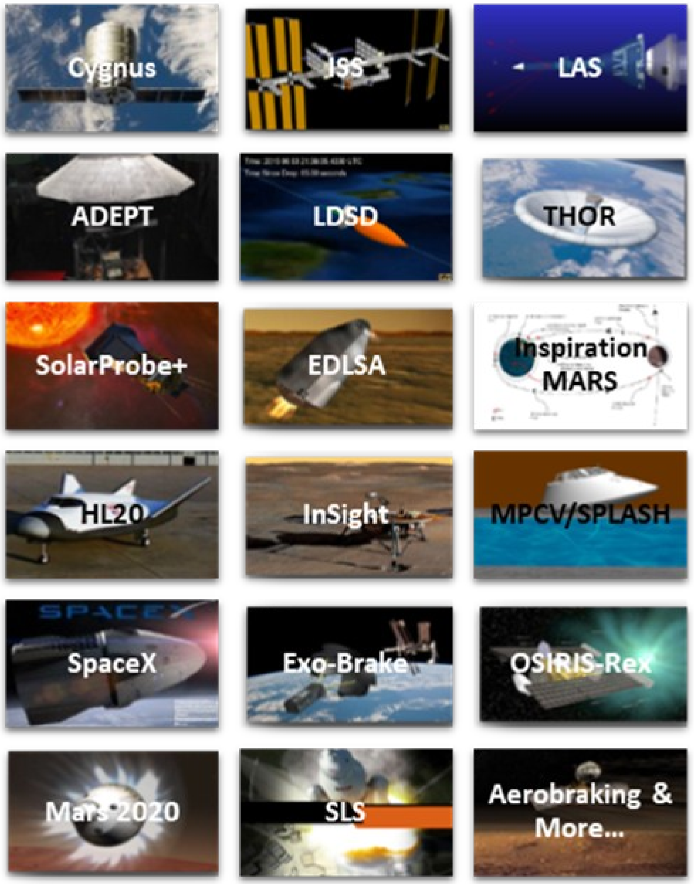
[1] Yelle, Roger V. et al. “Engineering Models for Titan ' s Atmosphere.”, 1998.

POST2 Background

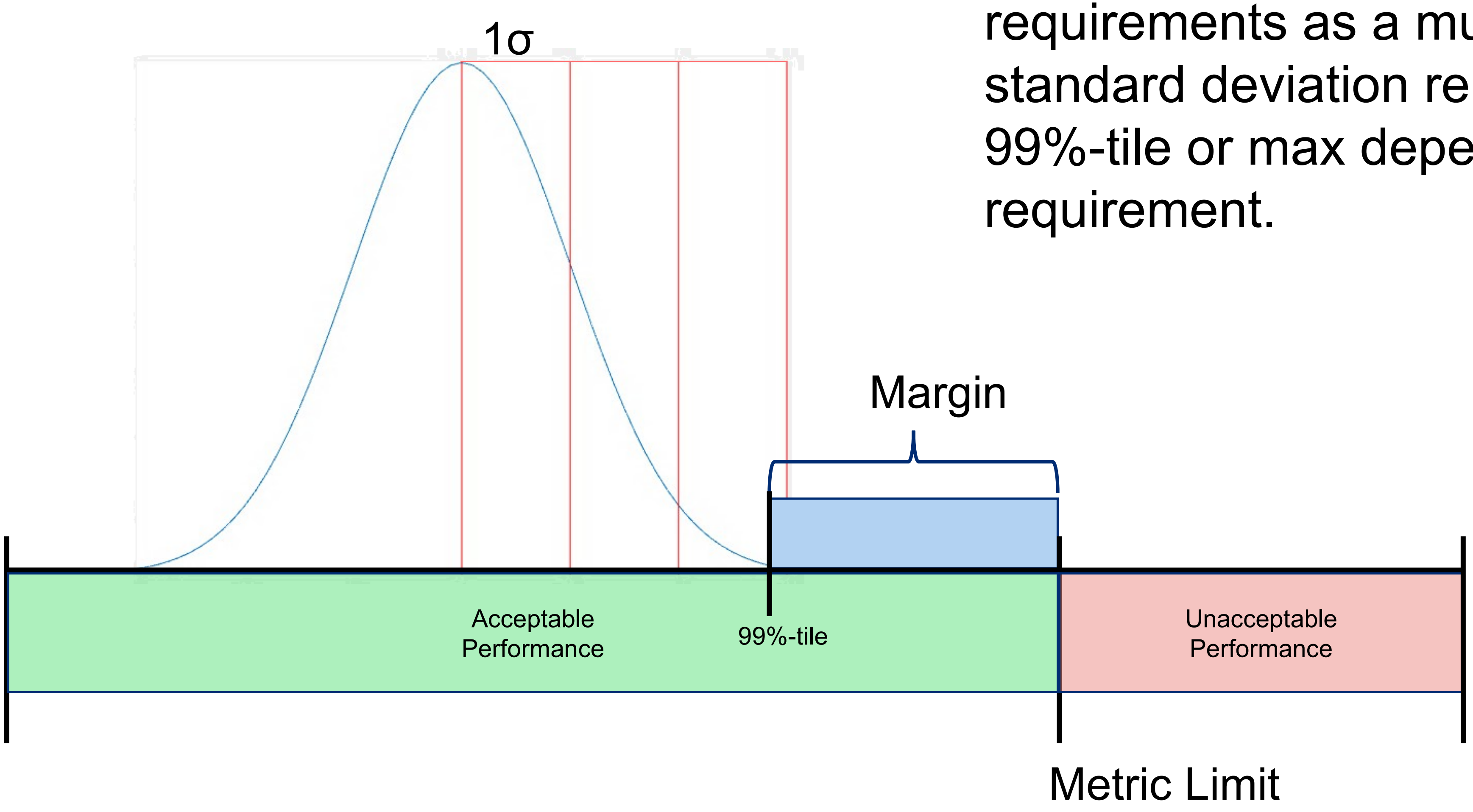


- The Program to Optimize Simulated Trajectories II (POST2) is a generalized point mass, discrete parameter targeting and optimization program. POST2 provides the capability to target and optimize point mass trajectories for multiple powered or un-powered vehicles near an arbitrary rotating, oblate planet. POST2 has been used successfully to solve a wide variety of atmospheric ascent and entry problems, as well as exo-atmospheric orbital transfer problems. The generality of the program is evidenced by its multiple phase simulation capability which features generalized planet and vehicle models. This flexible simulation capability is augmented by an efficient discrete parameter optimization capability that includes equality and inequality constraints. POST2 supports NASA's Strategic Goal to expand the frontiers of knowledge, capability, and opportunity in space by directly contributing to expanding our human and robotic presence into the solar system and to the surface of Mars as well as other planetary bodies.

- https://www.nasa.gov/post2



Margin Relative to Requirements



- Expressing margin to requirements as a multiple of the standard deviation relative to 99%-tile or max depending on requirement.

Peak Entry Deceleration

- Metric
  - **Peak Entry Deceleration < 12 g's (99%)**