

Modeling and Simulation of the Dragonfly Drogue Parachute Opening Loads using POST2

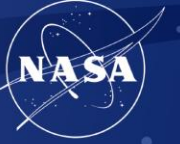
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Prepared for the 28th Aerodynamic Decelerator Systems Conference and Seminar
June 1st – 5th. London, United Kingdom



Overview

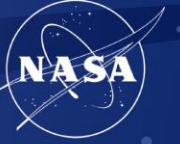


- Dragonfly is a New Frontiers Program mission that will deliver a rotorcraft lander to Saturn's moon, Titan for the first time since Huygens Probe landed in 2005
 - Currently set to launch in 2028 and arrive in Dec. 2034
- The entry, descent, and landing (EDL) sequence is approximately 2 hours, with most of it spent under a two single canopy parachute system (drogue and then main)
- This mission is led by The Johns Hopkins University Applied Physics Laboratory (APL) and the EDL Phase is led by NASA Ames and Langley Research Center
- This presentation gives an overview of the analysis completed to assess opening loads of the drogue parachute to inform hardware risks and ensure that the parachute inflation will meet requirements



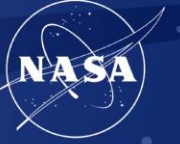
Credit: APL

Table of Contents

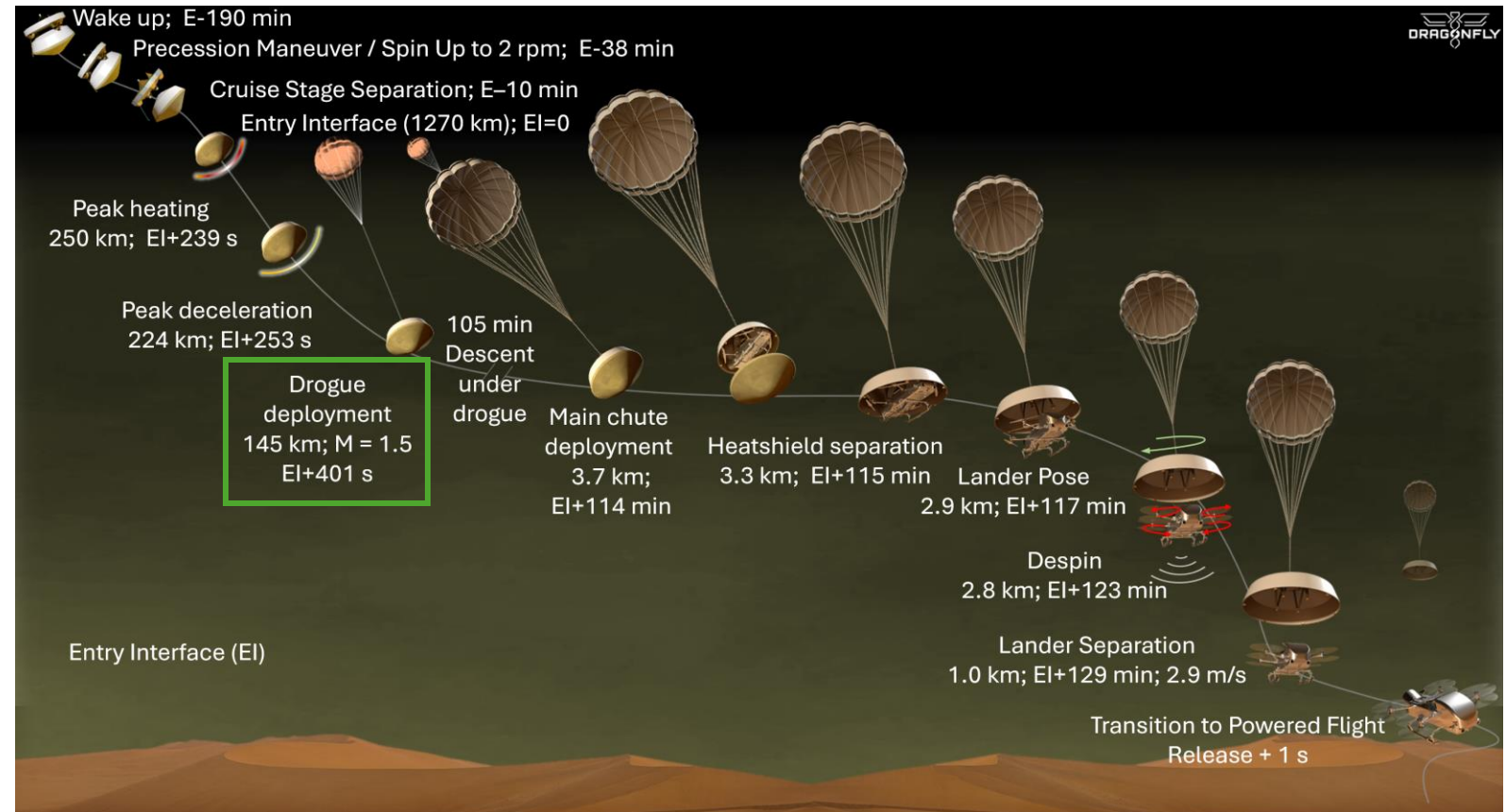


- EDL Background
- Modeling Methodology
 - Modeling and Simulation Overview
 - Multi-body Simulation
 - Drogue Parachute Opening Loads
- Results
 - Elastic Load – Time History
 - Monte Carlo Results
- Sensitivities
 - Correlation Analysis
 - Elastic Riser
 - Drogue Deployment Release Sensitivity
- Conclusions
- Acknowledgements

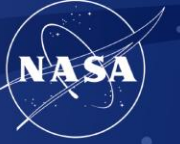
Background



- Parachute Decelerator Subsystem (PDS) Requirement: The PDS shall provide a drogue parachute capable of sustaining opening loads up to 32.0 kN (95%-tile).
- Heritage method to estimate peak opening loads uses a momentum-based method that may not sufficiently capture dynamic amplification
- Dynamic amplification refers to the phenomena whereby a dynamic load applied to an elastic systems results in a higher load than the equivalent static load



Multi-body Simulation



- The EDL sequence was modeled using Program to Optimize Simulated Trajectories II (POST2)
- Parachute and entry vehicle are simulated as two-rigid bodies connected by three flexible bridles

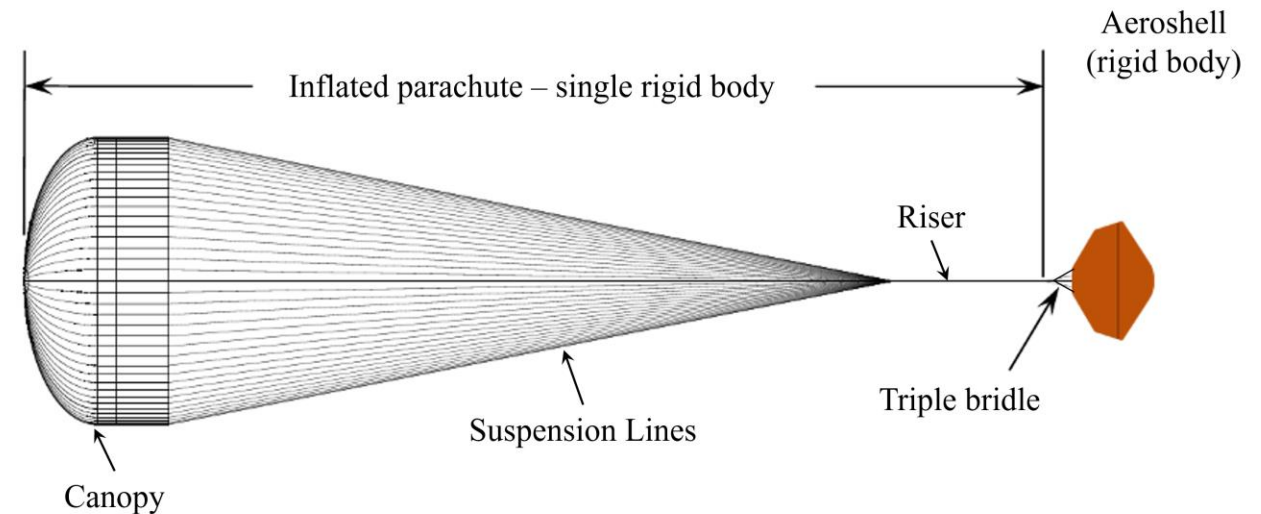


Entry Vehicle Model

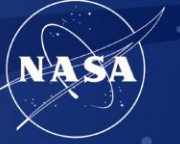
- Genesis derived 4.5 m, 60 deg sphere-cone aeroshell

Parachute Model

- Parachute canopy, suspension lines, and riser are modeled as a single rigid body with 6 degrees-of-freedom
- Bridles are massless, tension-only, linear spring dampers
- Model heritage from Mars Science Laboratory (MSL). Adapted models to Dragonfly Parachute Decelerator Subsystem



Aerodynamics and Peak Opening Loads



Peak Opening Load

$$F_{\text{peak}} = 2k_p q_{\infty} S_P$$

Drogue Parachute Aerodynamics

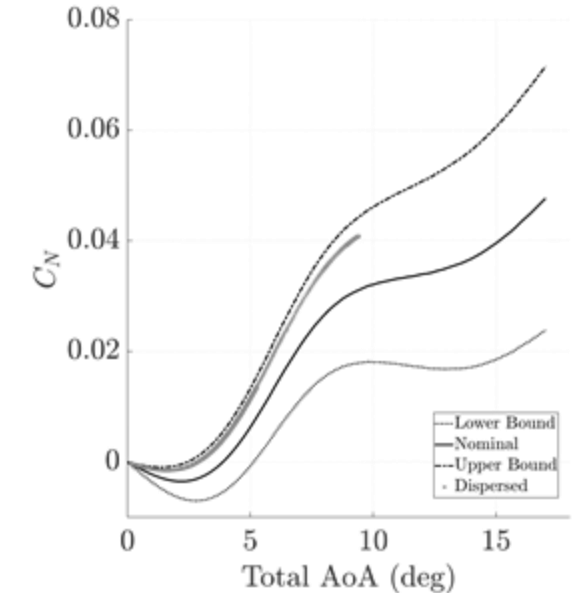
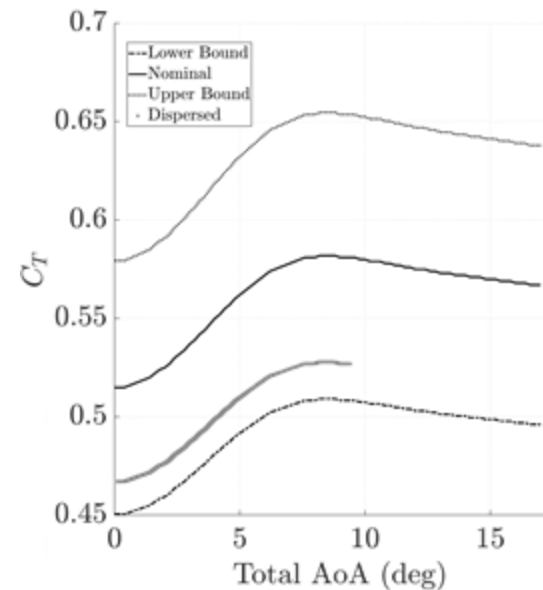
- At full-inflation ($t = t_{\text{FI}}$)

$$C_{X,\text{out}} = C_X(\alpha_T) \frac{F_{\text{peak}} MEF}{q_{\infty} S_0 \sqrt{(C_T(\alpha_T))^2 + (C_N(\alpha_T))^2}}$$

where $C_X = C_T, C_N$

- After full inflation ($t > t_{\text{FI}}$)

$$C_{X,\text{out}} = MEF C_X(\alpha_T)$$



Legend

C_N	normal force coefficient
C_T	tangential force coefficient
C_X	placeholder force coefficient
k_p	momentum peak opening load factor
F_{peak}	parachute peak opening load
MEF	Mach Efficiency Factor
q_{∞}	dynamic pressure of the entry vehicle
S_P	projected parachute area
S_0	nominal parachute area
t_{FI}	time at full inflation
α_T	total angle of attack (AoA)



Total Elastic Loads

- $\Sigma F_{BL} = F_{BL_1} + F_{BL_2} + F_{BL_3}$
- $F_{BL} = k_{BL}\Delta L_B + c_{BL} \frac{d(\Delta L_B)}{dt}$
 - if $F_{BL} \leq 0$, $F_{BL} = 0$

Test Cases

1. Heritage method (k_{BL} & c_{BL} are constant)
2. Experimentally derived stiffness and damping coefficients (k_{BL} & c_{BL} are dispersed and uncorrelated) (See Shafner, J.: ADS-03)
3. **Load independent stiffness and correlated damping**
4. Load dependent stiffness and correlated damping

Load Independent

$$k_{BL} = k_{\text{nom}} \cdot (1 + U_k^M) \frac{\text{N}}{\text{m}}$$

Correlated Damping

$$\zeta = \zeta_{\text{nom}} \cdot (1 + U_\zeta^M)$$

$$f_n = f_{n,\text{nom}} \cdot (1 + U_{f_n}^M) \text{ Hz}$$

$$c_{BL} = \frac{\zeta}{\pi \times f_n} k_{BL}$$

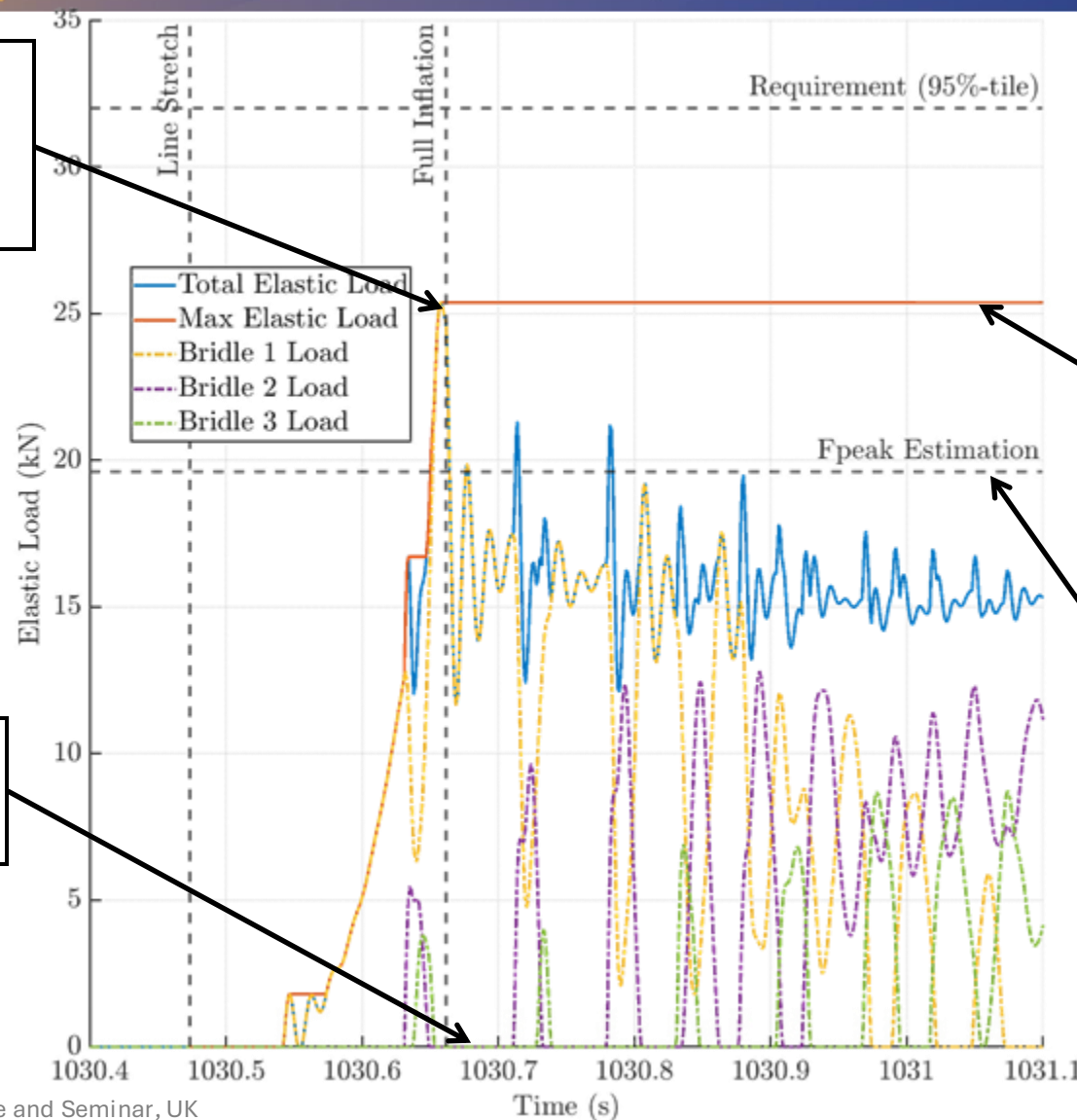
Legend

c_{BL}	coefficient of viscous damping (each bridle leg)
k_{BL}	spring constant (each bridle leg)
F_{BL}	force on the triple bridle leg
f_n	natural frequency (each bridle leg)
U^M	uncertainty multipliers
ΔL_B	change in length of a bridle leg
ζ	damping ratio (each bridle leg)

Elastic Load – Time History



Peak elastic load occurs at full inflation

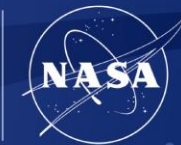


Monitor tracks max value which is used for Monte Carlo assessment

Indicates line 2 & 3 are slacked

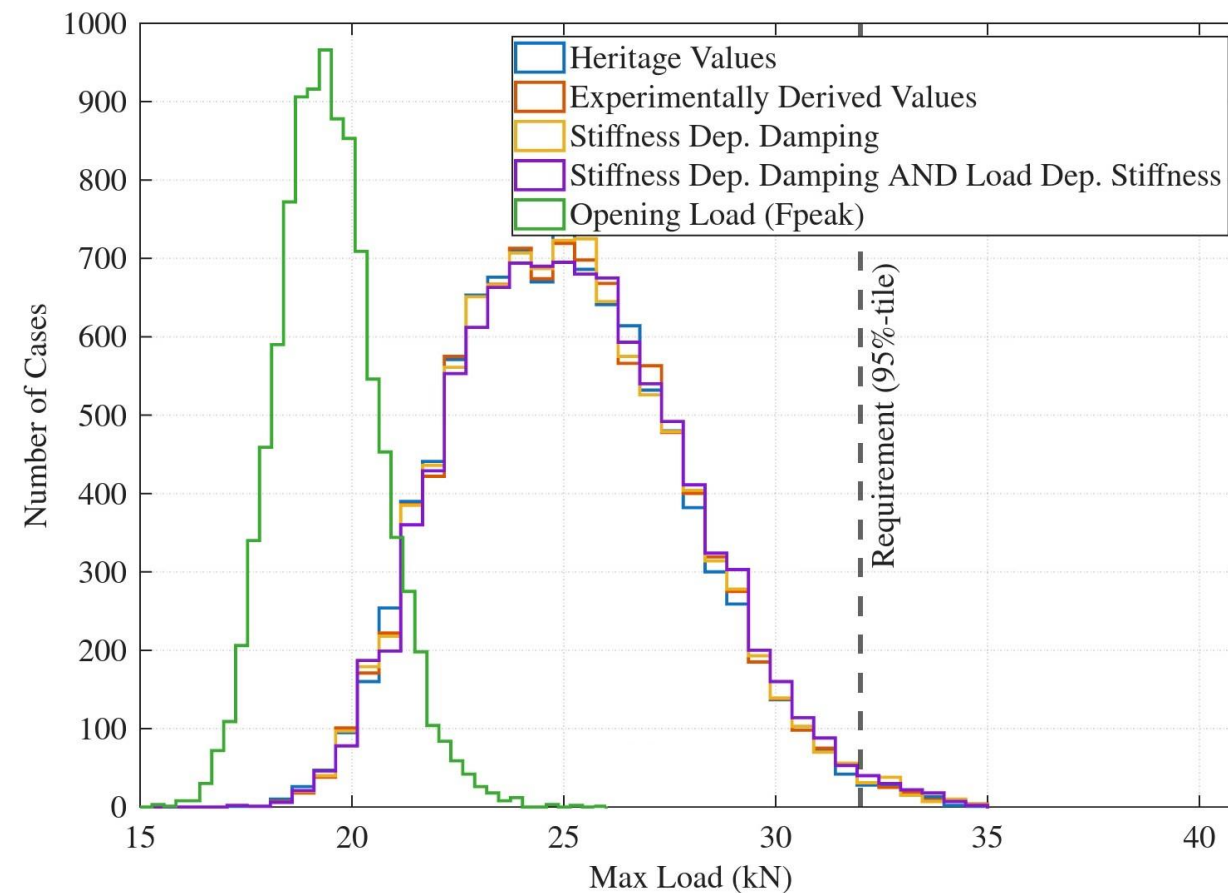
F_{peak} method underpredicts relative to elastic loads

Monte Carlo Results

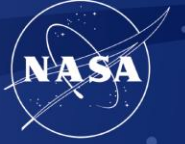


- Monte Carlo consists of 10,000 cases
- Elastic load statistics are insensitive to the elastic bridle parameters and models
- Peak aerodynamic opening load method underpredicts relative to the elastic loads by ~9 kN

Case	95%-tile (kN)
Peak Aerodynamic Opening Load (F _{peak})	21.57
Heritage Values (undispersed)	29.75
Exp. Derived Values (dispersed/uncorrelated)	29.80
Load Indep Stiffness and Correlated Damping	29.83
Load Dep Stiffness and Correlated Damping	30.00



Correlation Analysis



- Evaluating correlation between Monte Carlo outputs and inputs by calculating the Pearson Correlation Coefficients
 - Sorted by strongest linear relationship
- Correlations on full Monte Carlo
 - Mach Efficiency Factor (MEF), Momentum Peak Opening Load Factor (k_p), and the entry vehicle supersonic C_A Multiplier are the dominant trends
 - Max elastic load correlations specified
- To test the sensitivity, Monte Carlos were run with ONLY elastic properties dispersed
 - What is the direct effect of the elastic dispersions when they aren't being washed out by the MEF, KP, etc.
 - Elastic dispersions induce varying levels of dynamic amplification between 1.0x (no overload) and 1.40x the aerodynamic load specified by the inflation model

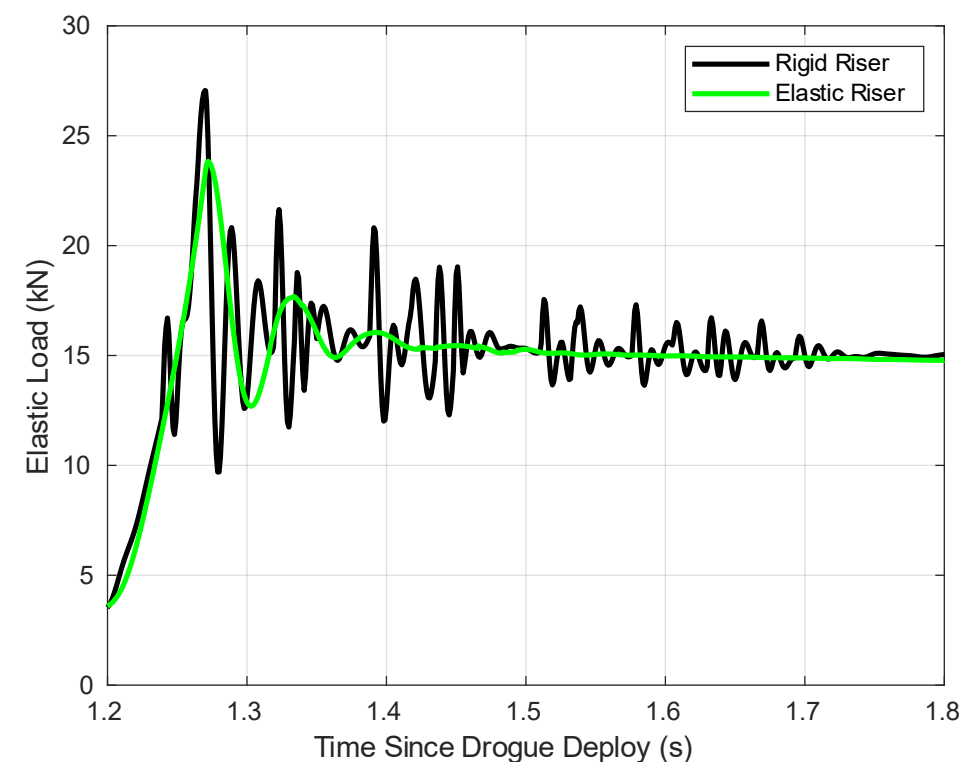
Identified Variable from Full Monte Carlo	Correlation Coefficient
MEF Dispersion	0.72336
k_p Dispersion	0.37578
Supersonic C_A Multiplier	-0.29649
Bridle Damping Ratio Dispersion	-0.04007
Bridle Stiffness Dispersion	Not in Top 20

Elastic Riser

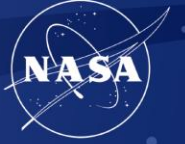


- Revisiting assumptions
 - Are there missing dynamic amplification from modeling the riser as a rigid element?
- The elastic riser acts as a low-pass filter of the drogue inflation dynamics and the max elastic load was in family with the baseline rigid riser case
- Adding the elastic riser dramatically increased the simulation time and is infeasible to baseline for Monte Carlo analysis

Case (Max Load)	Rigid Riser (kN)	Elastic Riser (kN)	Rigid/Elastic Ratio
Heritage – Nominal	27.1	23.8	1.14
Heritage – Max k_p and MEF	29.9	30.1	0.99
Exp. Derived – Nominal	25.4	24.7	1.03
Exp. Derived – Max k_p and MEF	31.5	31.2	1.01



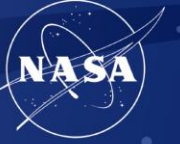
Drogue Deployment Sensitivity



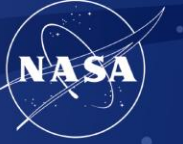
- Deployment conditions are driven by several requirements, primarily two critical ones are:
- The total angle of attack at drogue parachute deployment is less than 15 deg (99%-tile)
- The maximum of aerodynamic and elastic loads are less than 32 kN (95%-tile)
- Tuning the sensed acceleration drogue trigger can be used to reduce peak elastic loads to meet requirements

99 %-tile Mach @ Trigger, -	99 %-tile Total AoA @ Deploy, deg	95 %-tile Peak Elastic Load, kN
1.37	17.27	24.20
1.43	15.63	25.93
1.47	15.74	27.50
1.51	14.13	29.05
1.55	13.13	30.58
1.59	12.21	32.02

Conclusions



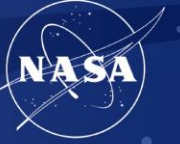
- Monte Carlo results indicate that:
 - Elastic loads and downstream system dynamics show **little sensitivity to the bridle elastic properties**
 - The elastic parameters, determined by test and conservatively dispersed, **induce acceptable elastic loads at drogue inflation**
 - Modeling the elastic riser shows that we **carry some conservatism modeling it as a rigid element**
 - The 95th-percentile elastic loads at drogue deploy are currently at **~30 kN and meets requirement**
- We recommend for future projects to include elastic loads in assessing peak load requirements
- Two other papers on this topic are being presented at AIAA ADS 2026:
 - Characterization of Elastic Elements of the Dragonfly Parachute Decelerator System Through Full-Scale Testing (J. Shafner et al.) AIAA-2026-3802
 - Dynamic Overloading of a Parachute Triple Bridle (C. O'Farrell et al.) AIAA-2026-3811



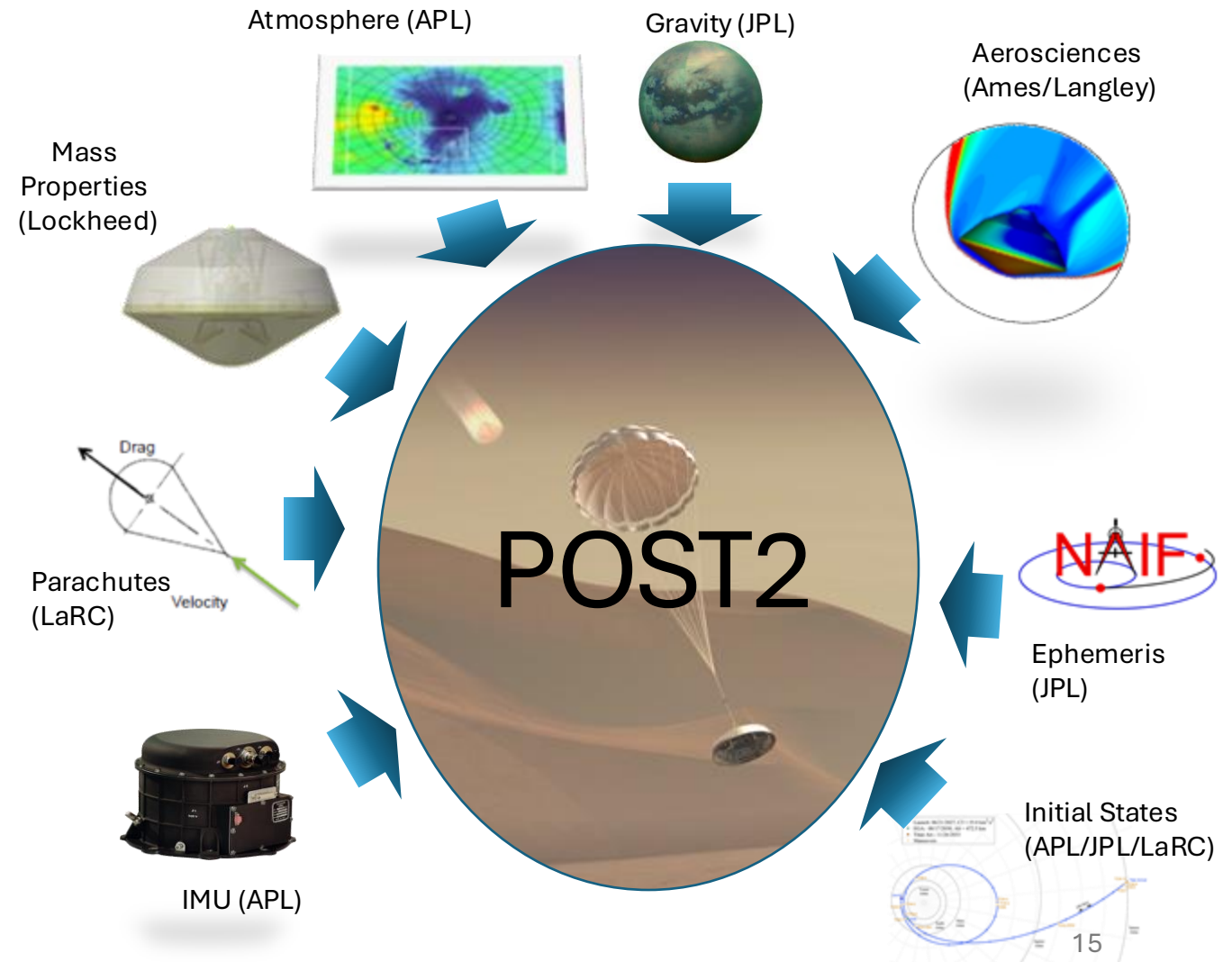
Questions?

POST2 Simulation Overview

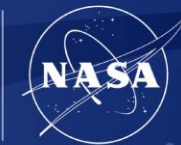
National Aeronautics
and Space Administration



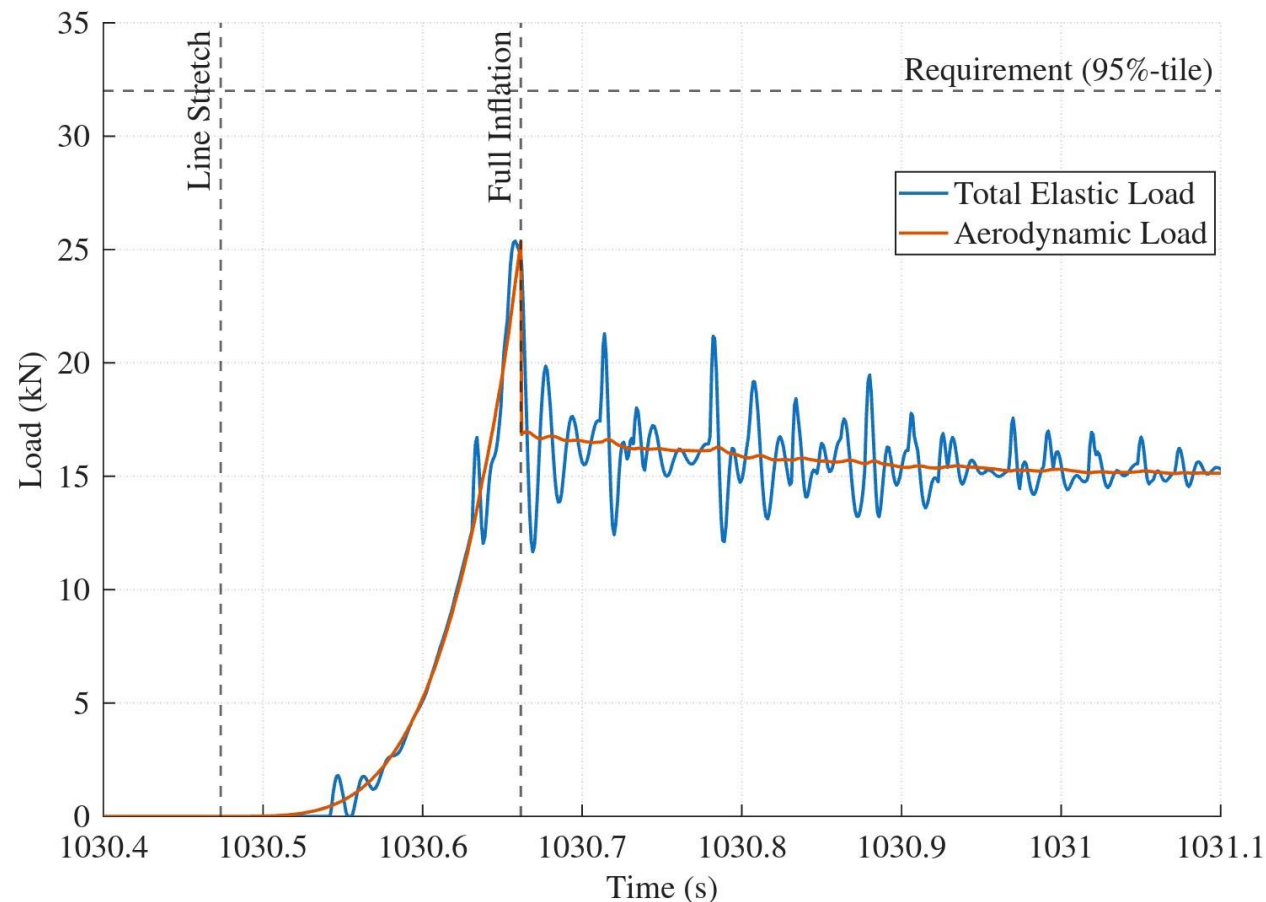
- The EDL sequence was modeled using Program to Optimize Simulated Trajectories II (POST2)
- System performance is assessed through augmented cluster computing scripts that enable Monte Carlo and sensitivity analyses
- Collaboration:
 - LaRC – NASA Langley Research Center
 - APL – Applied Physics Laboratory
 - JPL – Jet Propulsion Laboratory
 - Ames – NASA Ames Research Center
 - Lockheed – Lockheed Martin Space Company



Aerodynamic Load vs Elastic Load



- Elastic Loads follow the aerodynamic forces from the drogue parachute with higher frequency content because of the spring-damper model



Mach Efficiency Factor

