

Modeling and Simulation of Parachute Apparent Mass Aerodynamics for the Dragonfly Mission

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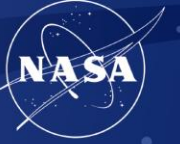
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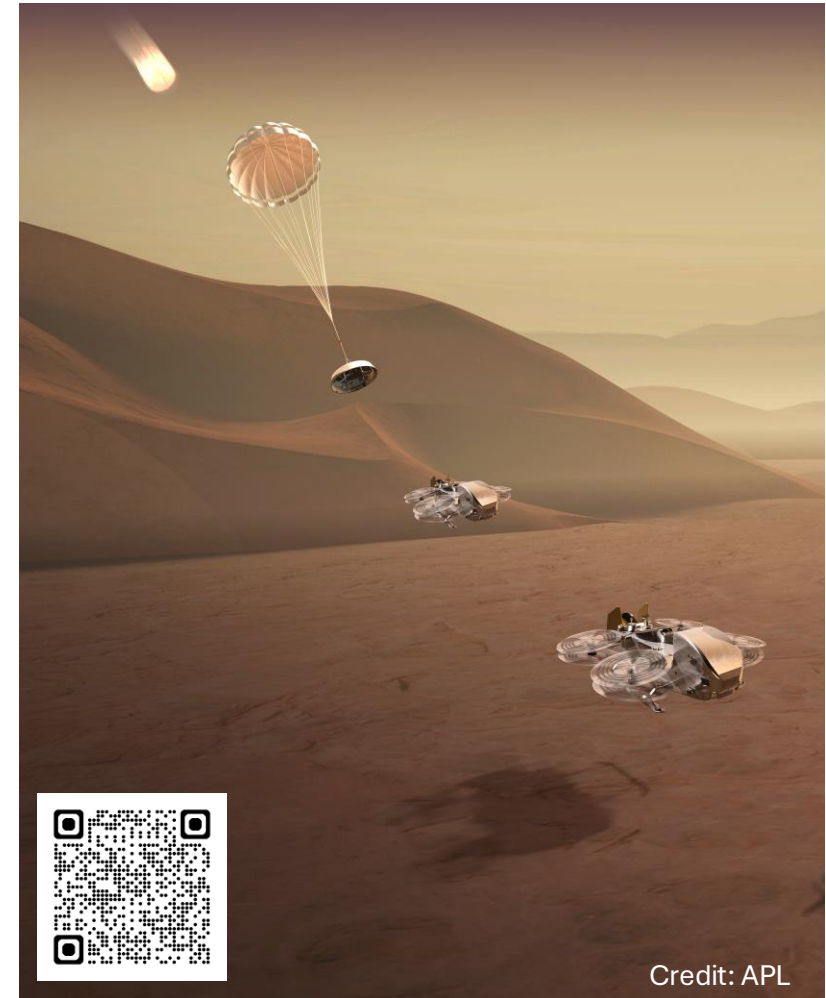


Overview

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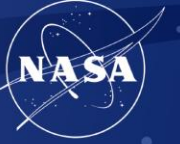


- Dragonfly is a New Frontiers Program mission that will deliver a rotorcraft lander to Saturn's moon, Titan for the first time since Huygens Probe landed in 2005
 - Currently set to launch in 2028 and arrive in Dec. 2034
- The entry, descent, and landing (EDL) sequence lasts approximately 2 hours. The descent phase uses a two-stage parachute system (drogue and main)
- This mission is led by The John Hopkins Applied Physics Laboratory and the EDL Phase is led by NASA Ames and Langley Research Center
- This presentation introduces the apparent mass aerodynamics model used to simulate the parachute and lander system dynamics with the goal of ensuring that staging/separation events are conducted safely



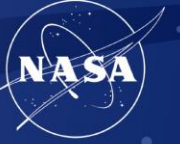
Credit: APL

Contents

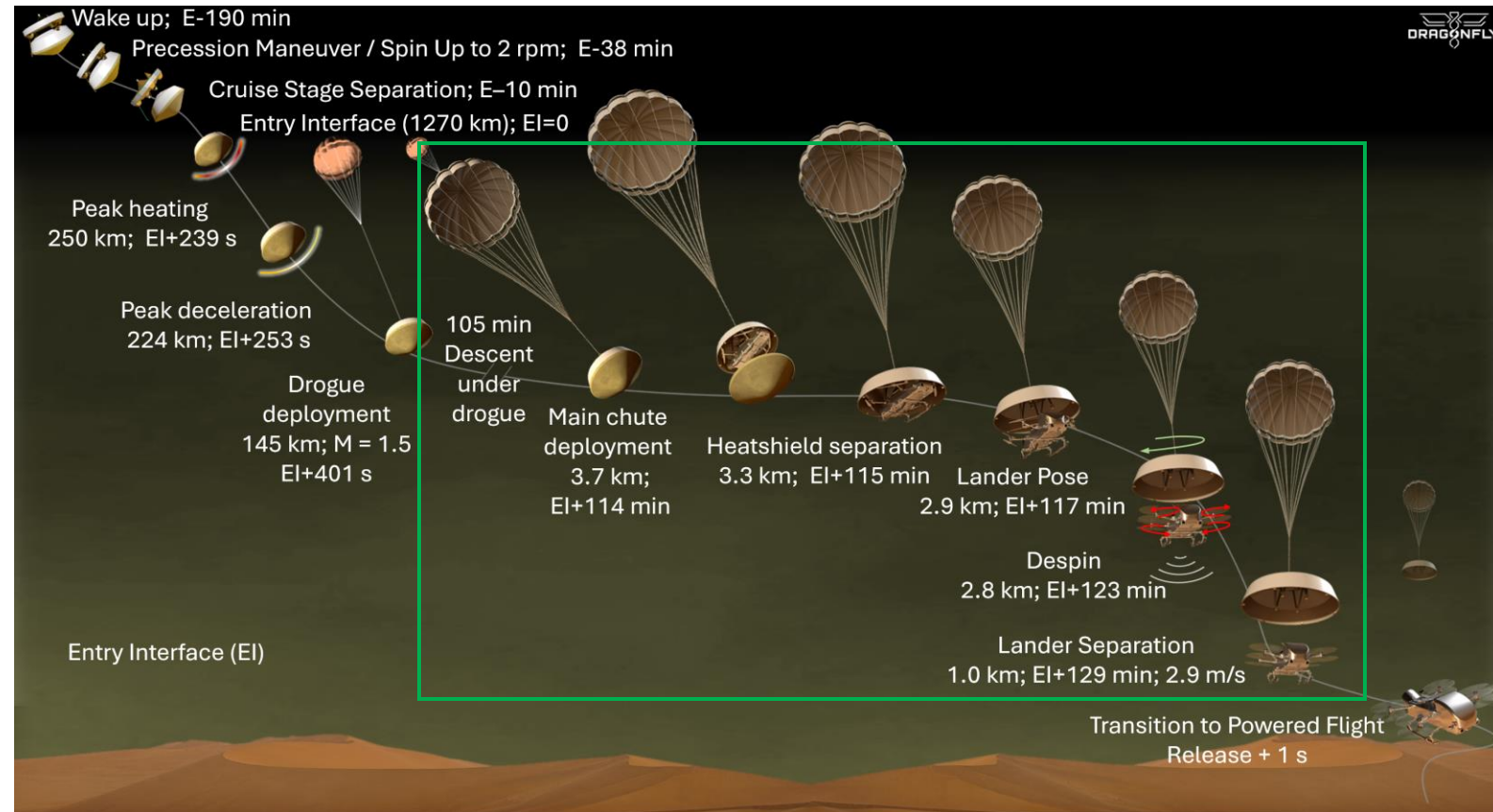


- EDL Phase Overview
- Parachute Decelerator Subsystem (PDS)
- Multi-Body Simulation Background
- Apparent Mass Aerodynamics
- Model Parameters and Implementation
- Results
- Conclusions
- Acknowledgements

EDL Phase Overview

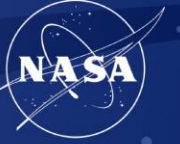


- Dragonfly is contained in a 4.5 m diameter aeroshell with 60 deg sphere-cone
- Drogue parachute descent ~105 min
 - Supersonic deployment & inflation
 - Deploys main parachute
- Main parachute descent ~16 min
 - Allows heatshield separation
 - Ensures terminal descent conditions for lander release
- The atmosphere of Titan is 4 times denser than Earth's at the surface. Heritage apparent mass models used to simulate planetary EDL were updated.



Parachute Decelerator Subsystem

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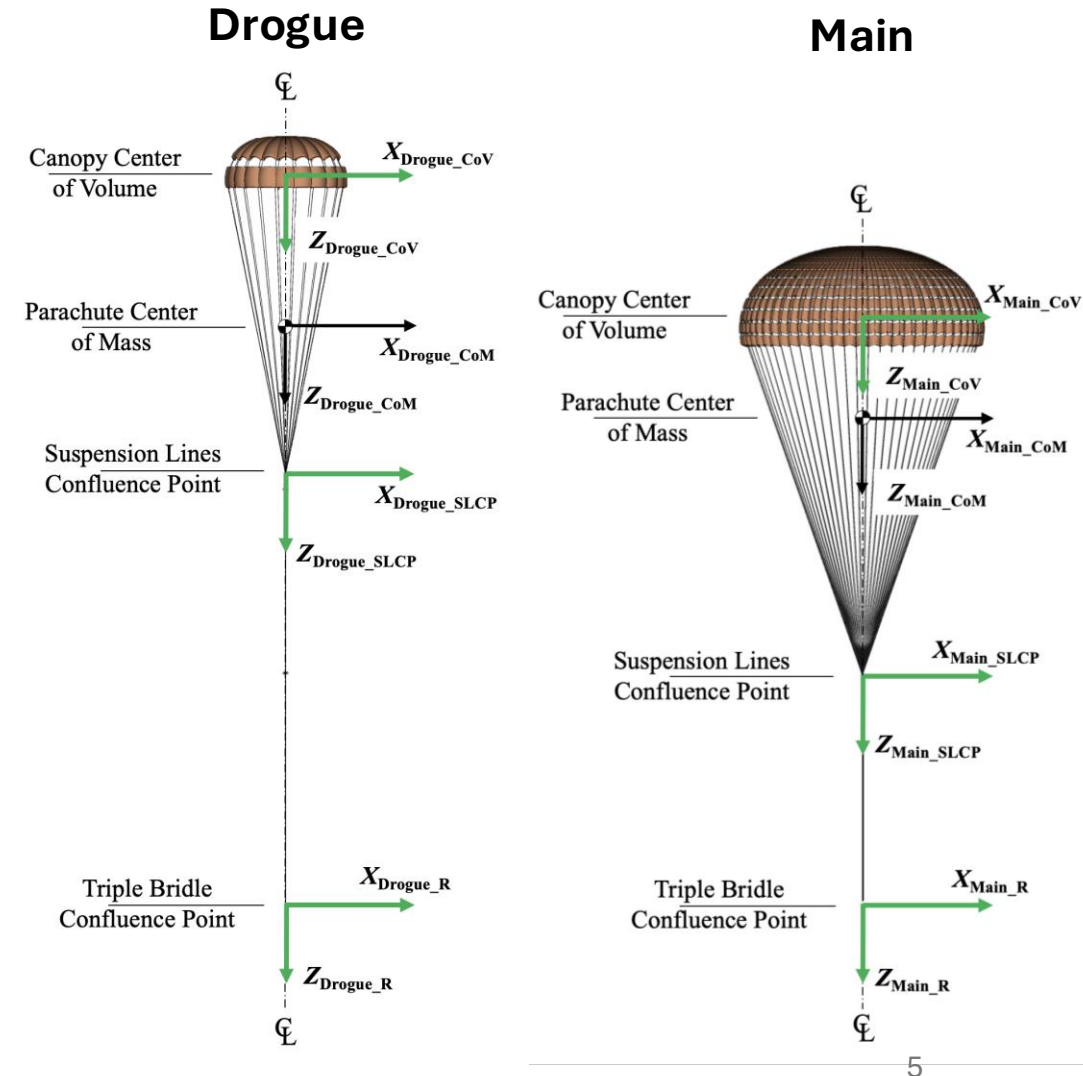


Drogue parachute

- Disk-Gap-Band (DGB) canopy scaled from the Viking configuration
- Stabilizes the aeroshell through low supersonic/transonic regime
- Deploys the main parachute at an altitude of approximately 4 km

Main parachute

- Conical-Ringslot canopy
- Enables heatshield release
- Designed to meet target terminal velocity (2.9 m/s) and dynamics for lander release



Multi-Body Simulation

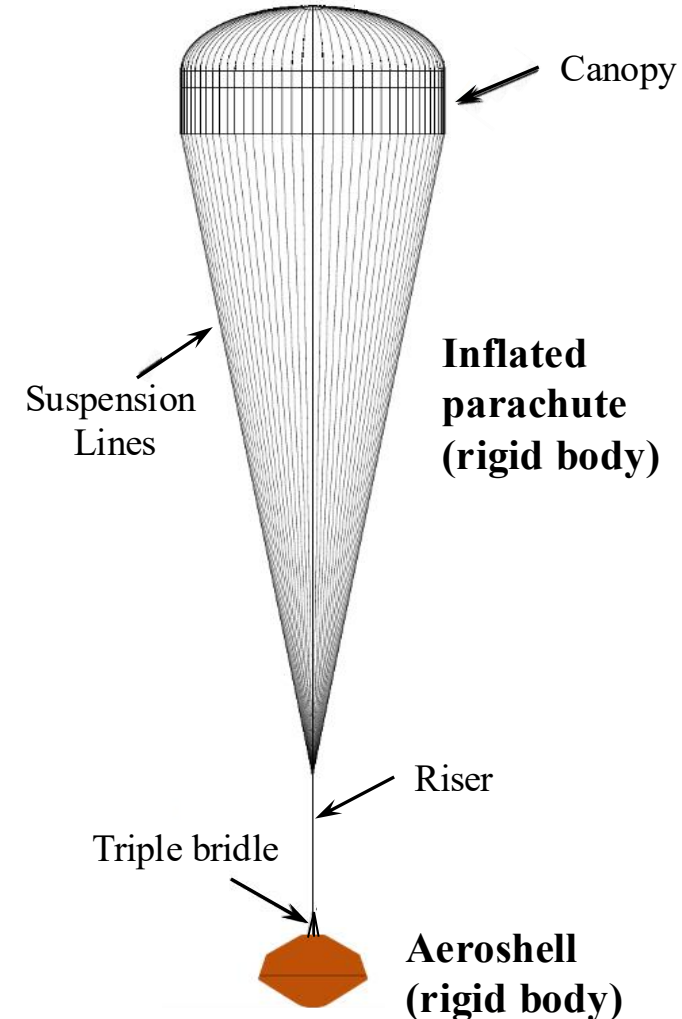
- The EDL sequence was modeled using Program to Optimize Simulated Trajectories II (POST2)
- Parachute and aeroshell are simulated as two rigid bodies (parachute and entry vehicle) connected by three flexible bridles

Entry Vehicle Model

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

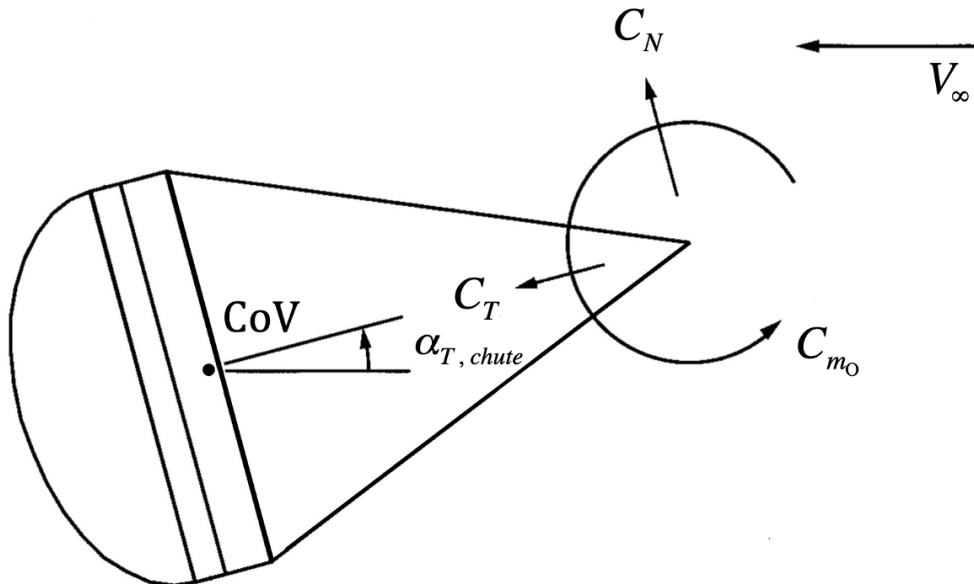
Parachute Model

- 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
- Aerodynamic wind angles (total angle of attack) are computed based on the airspeed at the parachute center of volume



Relevant Parachute Models

- Parachute Geometry
- Mass Properties
- Static Aerodynamic Coefficients
 - Pitching moment coefficient (C_{m_0})
 - Normal force coefficient (C_N)
 - Tangential force coefficient (C_T)



Feature	Drogue	Main
Canopy type	Disk-Gap-Band	Ringslot
Canopy fabric	Standard Porosity	Low Porosity
Geometric porosity (λ_g)	12.5 %	20 %
Nominal diameter (D_0)	8.25 m	16.7 m
Ratio of projected to nominal diameter (D_P/D_0)	0.734	0.704
Riser length (L_R)	26.6 m	17.3 m
Suspension lines length (L_S)	14.0 m	16.7 m
Length TBCP to CoM	29.1 m	32.9 m
Length TBCP to CoV	41.4 m	35.1 m
Deployed parachute mass	8.1 kg	13.3 kg
Total angle of attack (α_T) at trim	3.8°	10.7°

CoM

Center of Mass

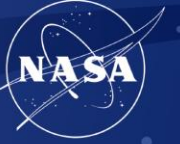
CoV

Center of Volume

TBCP

Triple Bridle Confluence Point

Apparent Mass Aerodynamics



- Apparent mass denotes the aerodynamic **forces and moments** due to **non-circulatory fluid flow** around a body. This phenomenon is relevant to lightweight bodies in flight (e.g., parachutes) or bodies moving through a high-density environment (e.g., submarines).
- The Dragonfly mission motivated a revision of the apparent mass theory published by Imlay in 1961. The general expressions for apparent mass aerodynamics were modified to maintain consistency with parachute literature notation (A_{ij} notation).
- General assumptions:
 1. The fluid is inviscid and incompressible (ideal fluid)
 2. Signals propagate through the fluid instantaneously
 3. The flow is attached (no flow separation)
 4. The body motion may be steady or accelerated
 5. The body moving through the fluid is rigid
- The general expressions (see appendix) are simplified for an axisymmetric body (valid for circular parachute canopy) with a coordinate system origin near the “center of apparent mass”. The simplified expressions are denoted the **tensor model**.

Parachute Apparent Mass Model

Tensor Model

- Non-circulatory forces and moments are defined from the parachute center of volume

$$F_{x,NC} = -A_{11}(\dot{u} - vr) - A_{33}wq$$

$$F_{y,NC} = -A_{11}(\dot{v} + ur) + A_{33}wp$$

$$F_{z,NC} = -A_{33}\dot{w} - A_{11}(vp - uq)$$

$$M_{x,NC} = -A_{44}(\dot{p} - rq)$$

$$M_{y,NC} = -A_{44}(\dot{q} + rp)$$

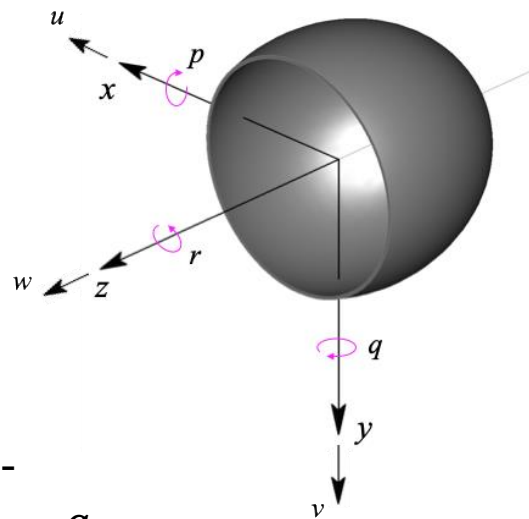
$$M_{z,NC} = 0$$

- A_{11} , A_{33} , and A_{44} depend on three non-dimensional model parameters: a_{11} , a_{33} , a_{44}

$$A_{11} = a_{11}\rho_{\infty}D_P^3 \quad A_{33} = a_{33}\rho_{\infty}D_P^3$$

$$A_{44} = a_{44}\rho_{\infty}D_P^5$$

- Expressed using implicit Ordinary Differential Equations (ODE)



Point Mass Model (Heritage)

- Adds a point mass (m_A) to the parachute center of mass
- Requires buoyancy force (proportional to m_A) to counteract gravity force

$$m_A = a_A\rho_{\infty}D_P^3$$

$$a_A = K_A\pi\left(\frac{D_P}{D_0}\right)^{-3}$$

Legend

a_A	nondimensional point mass model parameter
a_{ii}	nondimensional tensor model parameter
A_{ii}	dimensional tensor model parameter
D_P	projected parachute diameter
D_0	nominal parachute diameter
K_A	heritage nondimensional model coefficient
m_A	apparent mass for point mass model
p, q, r	body angular velocity components
u, v, w	wind relative velocity components
x, y, z	reference body coordinate system
ρ_{∞}	freestream density

Model Parameter Estimation

- Model parameters are estimated from the dynamic motions of a subscale ringsail parachute tested at the NASA Langley Transonic Dynamics Tunnel
 - Parachute underwent quasi-steady coning motion
 - Coning rate changed with tunnel wind speed and air density
- Derived an expression to estimate model parameters assuming a rigid parachute in steady coning motion

$$\frac{a_{11} - a_{22}}{a_{22} + \frac{I_{yy}}{\rho_{\infty} D_p^3 L_{CoV}^2}} = \left(\frac{L_{CoV} \dot{\phi}}{V_w} \right)^2$$

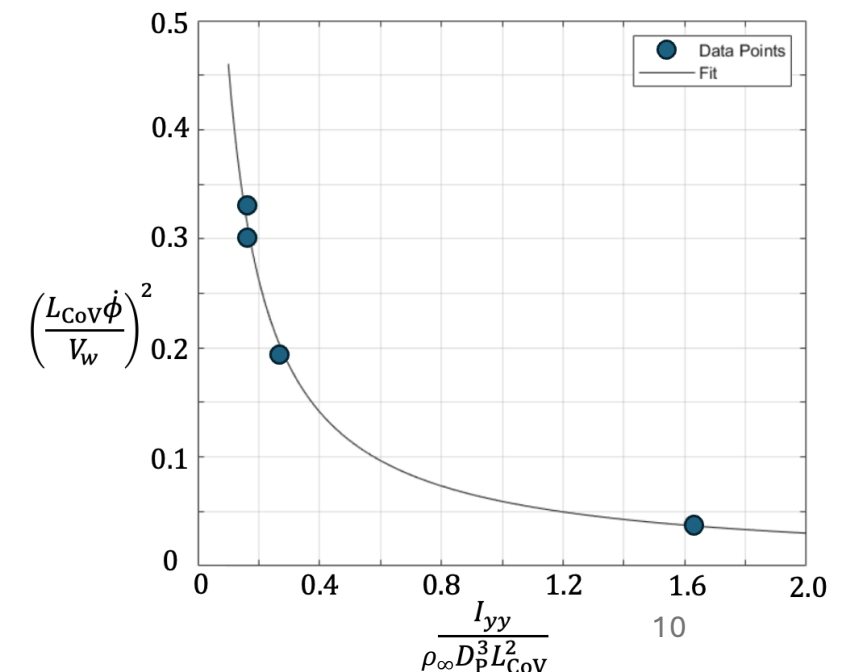
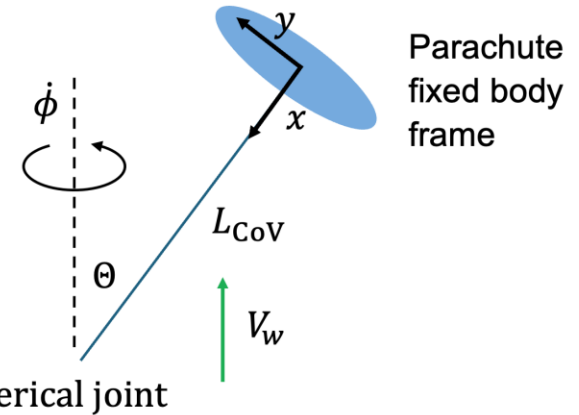
Legend

a_{ii}	nondimensional tensor model parameter
D_p	projected parachute diameter
I_{yy}	mass moment of inertia about y-axis
L_{CoV}	length from attachment point to CoV
V_w	tunnel wind speed
ρ_{∞}	freestream density
$\dot{\phi}$	parachute coning rate

Least-squares fit

$$a_{11} = 0.094, \quad a_{22} = 0.033$$

$$\frac{a_{11}}{a_{22}} = 2.85$$



Model Implementation

- Coordinate system definition

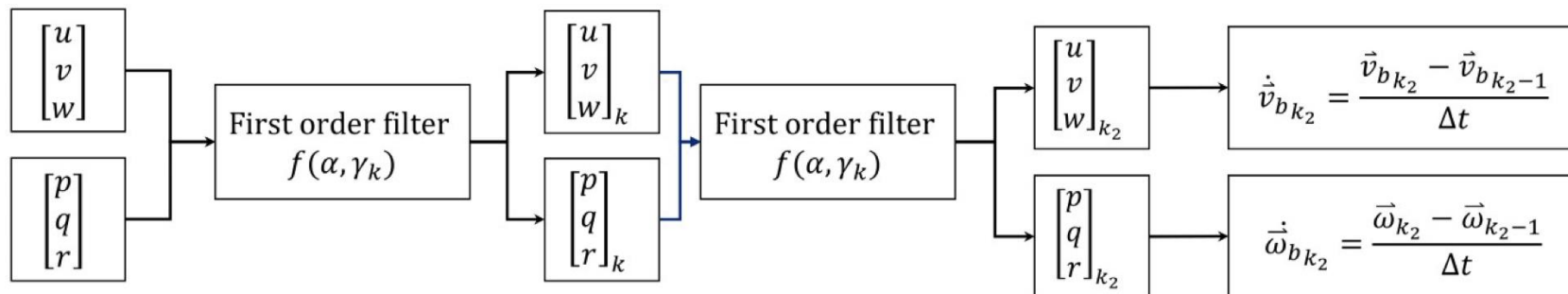
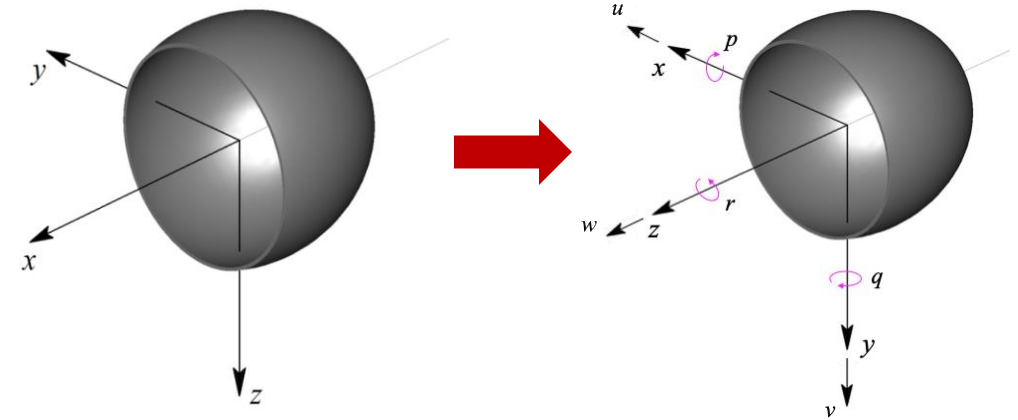
Axis of symmetry	X-axis	Z-axis
Axial motion	a_{11}	a_{33}
Lateral motion	a_{22}	a_{11}
Angular (pitch) motion	a_{55}	a_{44}

- Model parameters

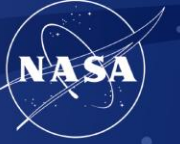
$$a_{33} = 0.094, \quad a_{11} = \left[\frac{a_{33}}{3}, a_{33} \right], \quad a_{44} = 0$$

- Numerical instability

- Using an explicit ODE solver (e.g., Runge-Kutta) to solve implicit ODEs can lead to numerical instability
- Applied two first-order filters to address numerical instability in computing the linear and angular acceleration terms

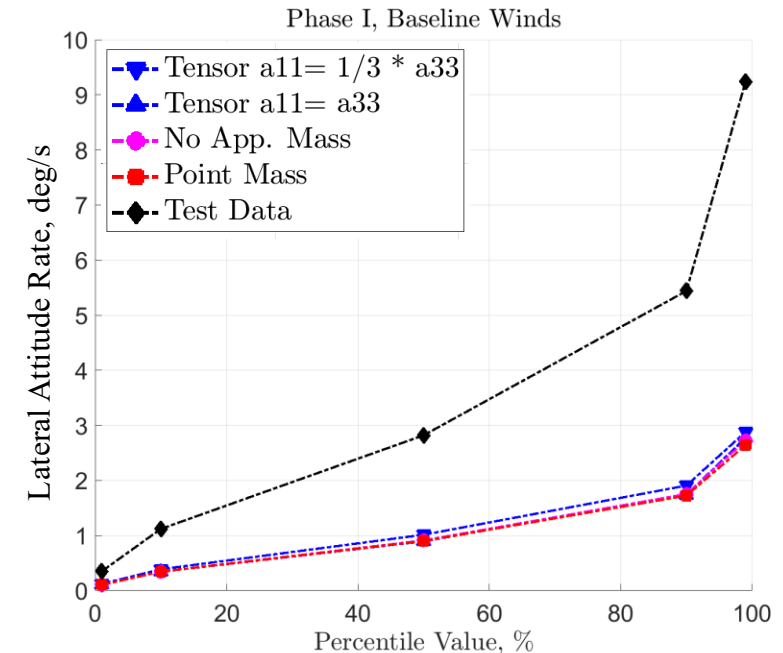
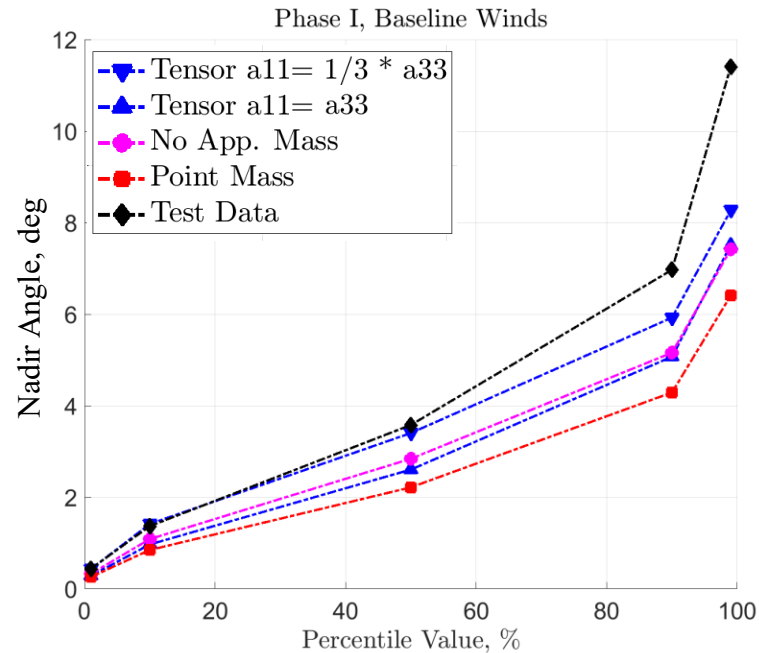


Model Validation (1)

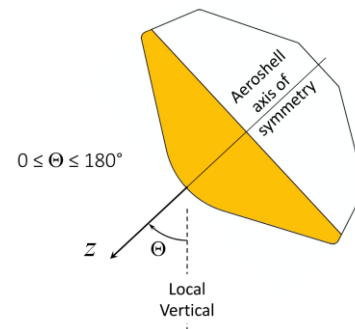


Drogue Parachute (Phase I)

- Test data:
 - Subscale (0.9 m) DGB parachute with entry vehicle
- Simulation variables
 - Apparent mass model
 - Wind model
- Observations:
 - System dynamics show low sensitivity to the the apparent mass model
 - Tensor model does not account for system dynamics measured from test



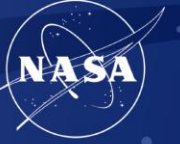
Nadir Angle Definition



Drone Drop Test Platform

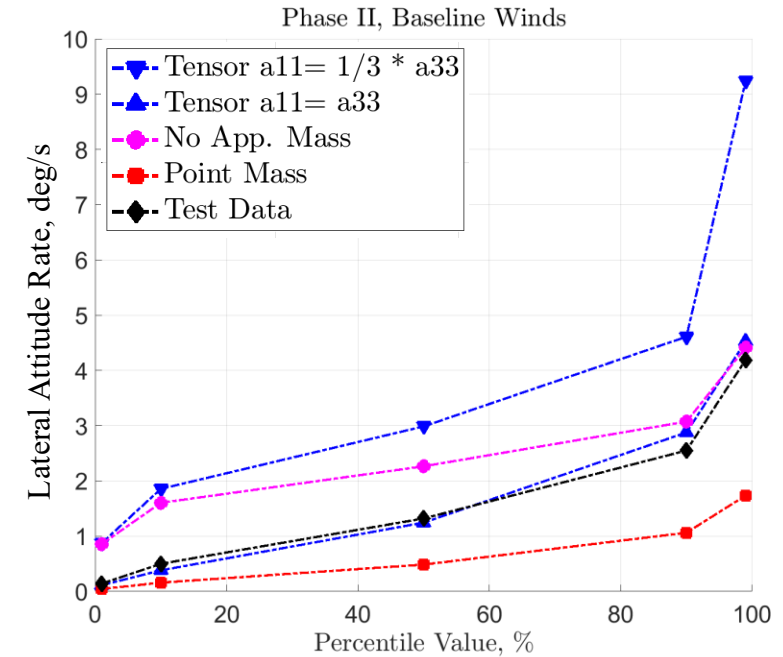
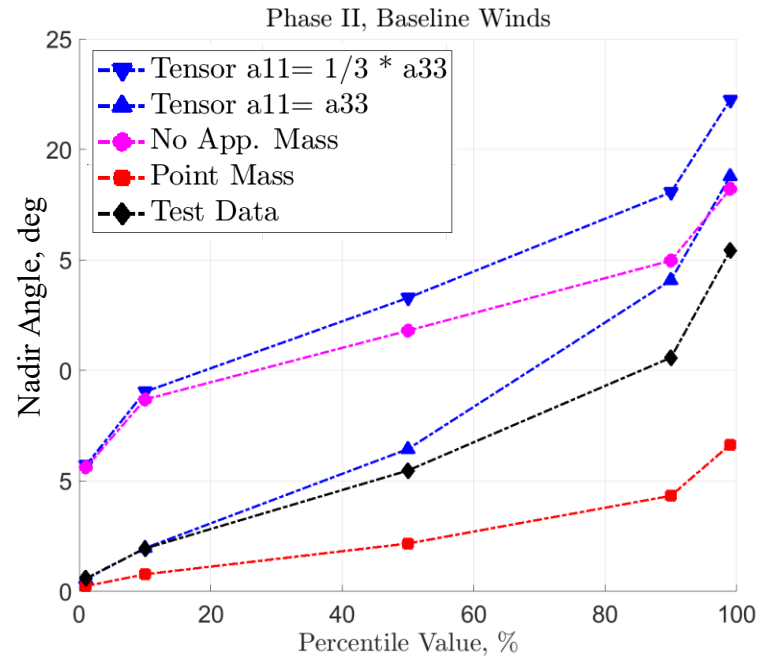


Model Validation (2)

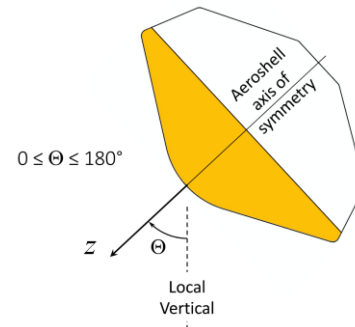


Main Parachute (Phase II)

- Test data:
 - Subscale (2.8 m) ringslot main parachute with entry vehicle
- Simulation variables
 - Apparent mass model
 - Wind model
- Observations:
 - The point mass model underpredicts system dynamics
 - Tensor model bounds system dynamics measured from test



Nadir Angle Definition



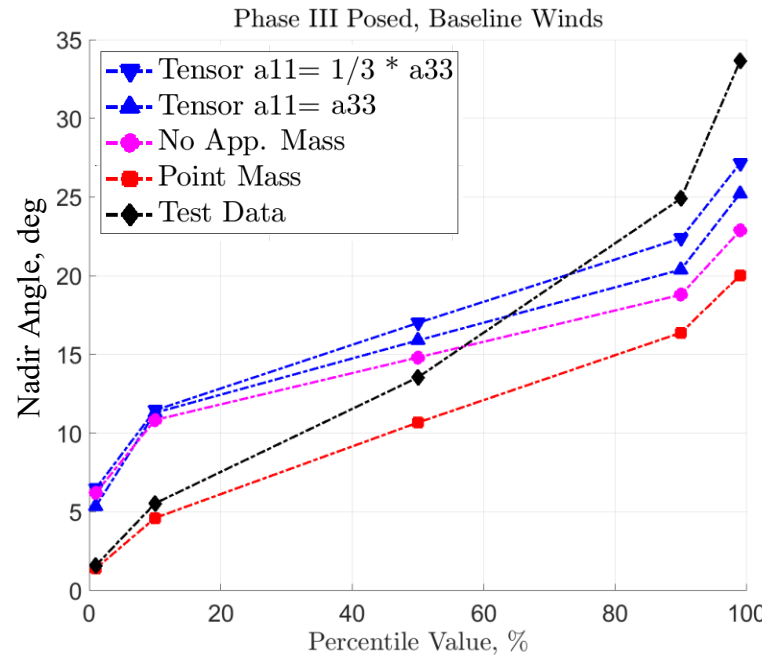
Drone Drop Test Platform



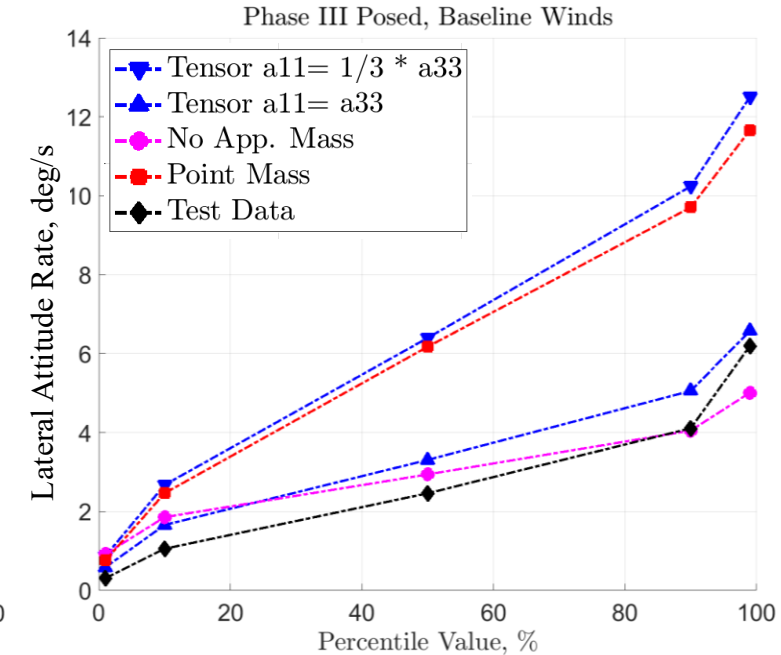
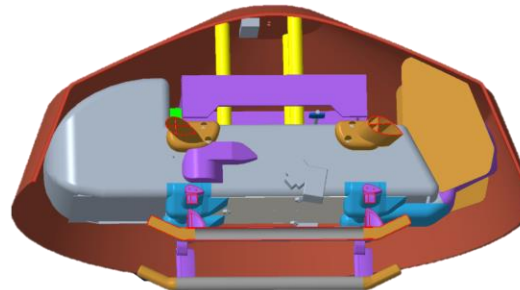
Model Validation (3)

Main Parachute (Phase III)

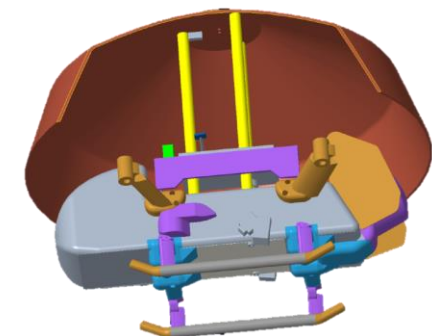
- Test data:
 - Subscale (2.8 m) ringslot main parachute and lander in stowed and **posed** configurations
- Simulation variables
 - Apparent mass model
 - Lander aerodynamics
- Observations:
 - Tensor model does not bound nadir angles from drop test
 - Tensor model provides closest match to experimental data



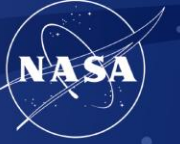
Stowed Lander



Posed Lander

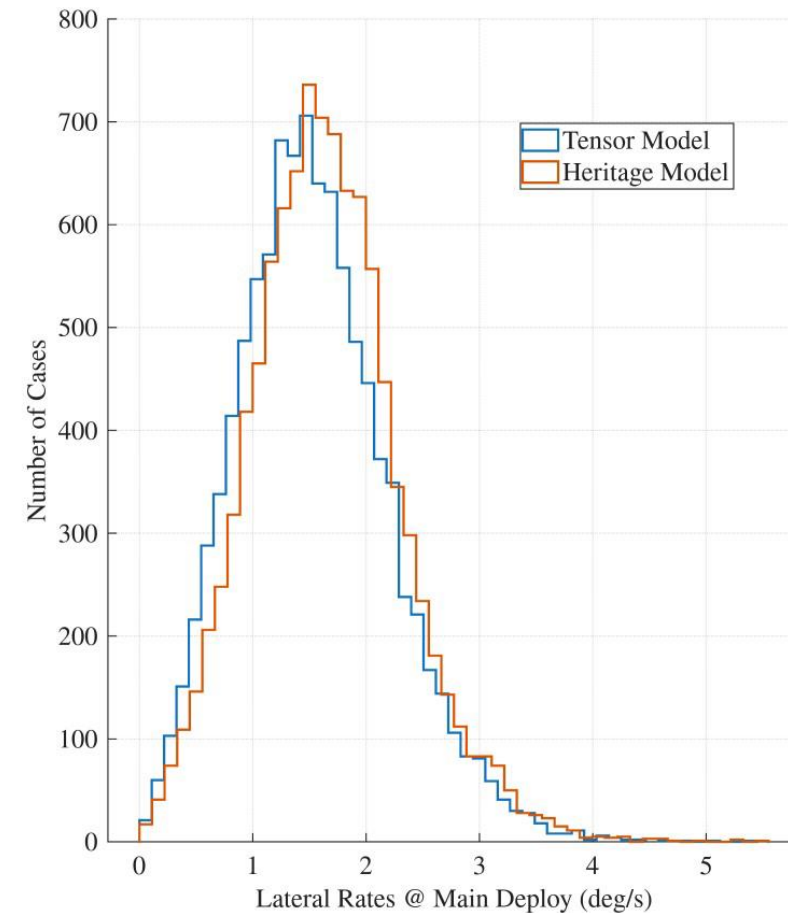
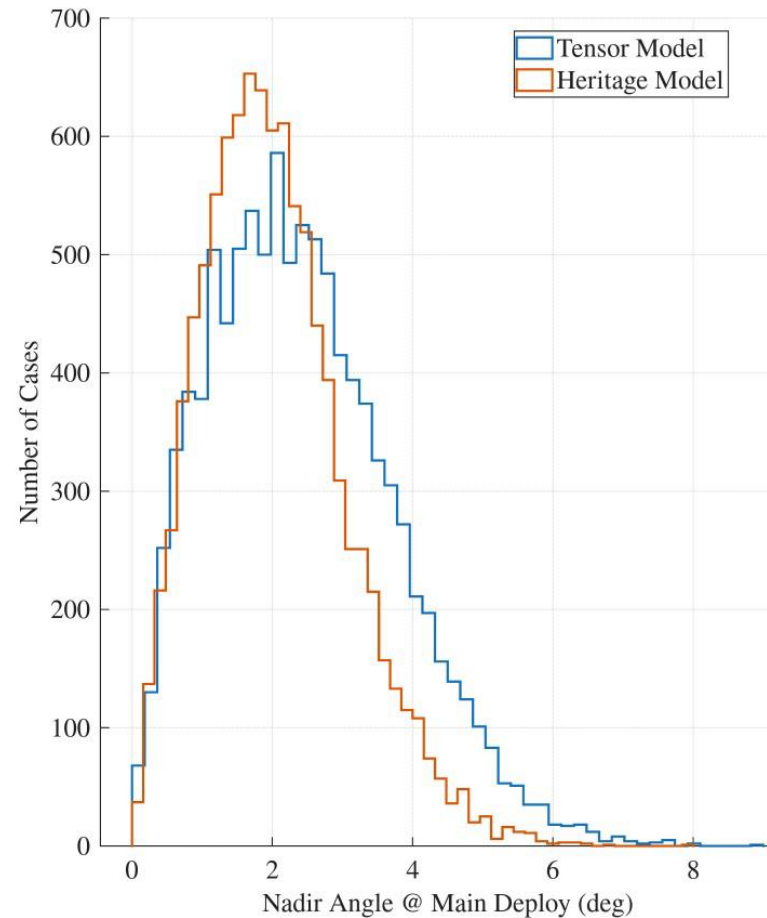


Titan Descent Simulation (1)

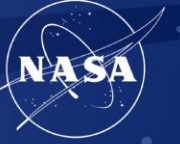


Drogue Parachute

- System dynamics at main parachute deployment
 - Monte Carlo simulation (10k cases)
- Apparent mass variations:
 - Tensor model
 - $a_{33} = a_{11} = 0.094$
 - $a_{44} = 0$
 - Heritage model
 - $a_A = [0, 0.56]$
- Observations:
 - System dynamics are not sensitive to the the apparent mass model

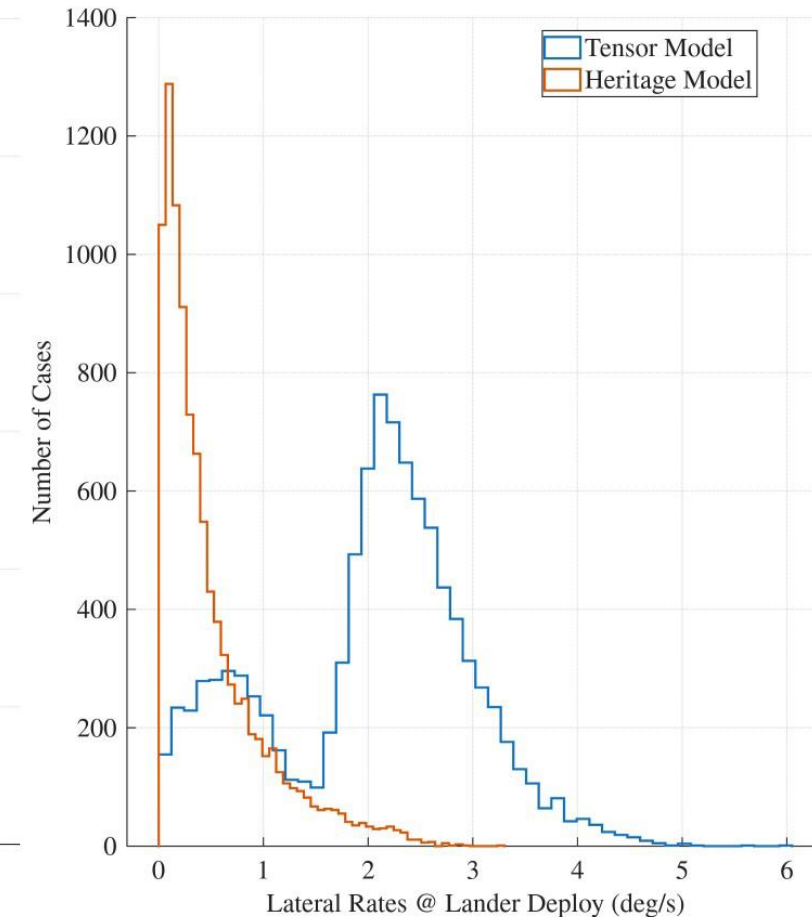
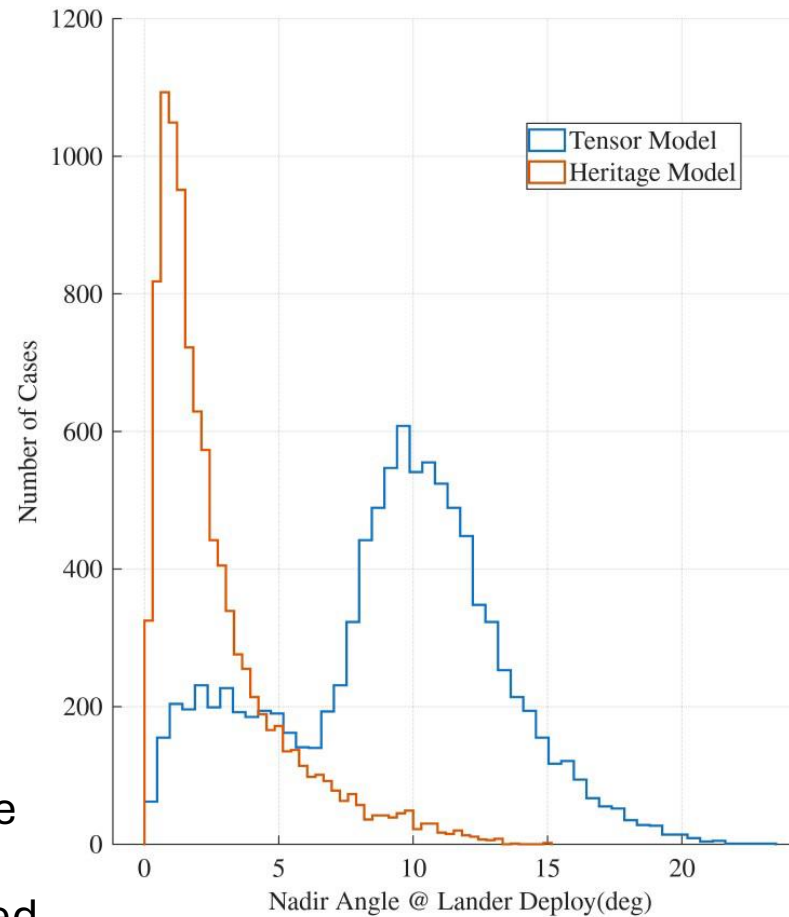


Titan Descent Simulation (2)

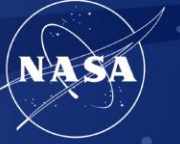


Main Parachute

- System dynamics at lander separation
 - Monte Carlo simulation (10k cases)
- Apparent mass variations:
 - Tensor model
 - $a_{33} = 0.094$, $a_{44} = 0$
 - $a_{11} = \left[\frac{a_{33}}{3}, a_{33} \right]$
 - Heritage model
 - $a_A = [0, 0.56]$
- Observations:
 - Tensor model introduces larger nadir angles and lateral rates due to coning motion.
 - Coning motion has been observed during drop tests.



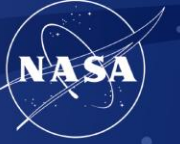
Conclusions



- System dynamics during drogue parachute descent are insensitive to the apparent mass model.
- The apparent mass model influences the system dynamics during main parachute descent in high-density atmospheric environments (Earth and Titan).
- The tensor apparent mass model does not bound nadir angles measured during subscale drop tests of the posed lander but provides closest match to test data.
- The tensor apparent mass model improves system dynamics predictions under main parachute (compared to heritage point mass model).
- Relevant papers presented at AIAA ADS 2026:
 - An Investigation of the Dragonfly Mission Lander, Backshell, Parachute Dynamics Through Subscale Drop Tests (J. Shafner et al.) AIAA-2026-3839
 - Implementation of an Explicit Formulation of Apparent Mass Dynamics for Planetary Parachutes (C. Leake et al.) AIAA-2026-3853
 - Experimental Investigation of the Effects of Lander Release Offloading for the Dragonfly Mission (J. Shafner et al.) AIAA-2026-3854

Acknowledgements

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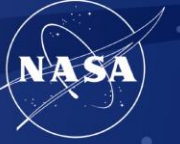


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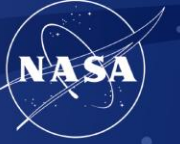
The Dragonfly mission is led by the Johns Hopkins University Applied Physics Laboratory (APL). NASA is leading the entry, descent and landing phase. Lockheed Martin Space (LMS) is developing the entry capsule and Airborne Systems North America (ASNA) is providing the Parachute Decelerator Subsystem (PDS).

Backup

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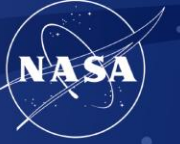
Apparent Mass Expressions (1)



Forces – General Expression

$$\begin{aligned}
 \begin{Bmatrix} F_{x,NC} \\ F_{y,NC} \\ F_{z,NC} \end{Bmatrix} &= \begin{bmatrix} -A_{11} & -A_{12} & -A_{13} \\ -A_{12} & -A_{22} & -A_{23} \\ -A_{13} & -A_{23} & -A_{33} \end{bmatrix} \begin{Bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{Bmatrix} + \begin{bmatrix} -A_{14} & -A_{15} & -A_{16} \\ -A_{24} & -A_{25} & -A_{26} \\ -A_{34} & -A_{35} & -A_{36} \end{bmatrix} \begin{Bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{Bmatrix} + \begin{bmatrix} 0 & -A_{34} & A_{24} & -A_{35} & (A_{25} - A_{36}) & A_{26} \\ A_{34} & A_{35} & (A_{36} - A_{14}) & 0 & -A_{15} & -A_{16} \\ -A_{24} & (A_{14} - A_{25}) & -A_{26} & A_{15} & A_{16} & 0 \end{bmatrix} \begin{Bmatrix} p^2 \\ pq \\ pr \\ q^2 \\ qr \\ r^2 \end{Bmatrix} \\
 &+ \begin{bmatrix} 0 & -A_{13} & A_{12} & 0 & -A_{23} & A_{22} & 0 & -A_{33} & A_{23} \\ A_{13} & 0 & -A_{11} & A_{23} & 0 & -A_{12} & A_{33} & 0 & -A_{13} \\ -A_{12} & A_{11} & 0 & -A_{22} & A_{12} & 0 & -A_{23} & A_{13} & 0 \end{bmatrix} \begin{Bmatrix} up \\ uq \\ ur \\ vp \\ vq \\ vr \\ wp \\ wq \\ wr \end{Bmatrix}
 \end{aligned}$$

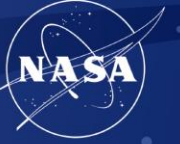
Apparent Mass Expressions (2)



Moments – General Expression

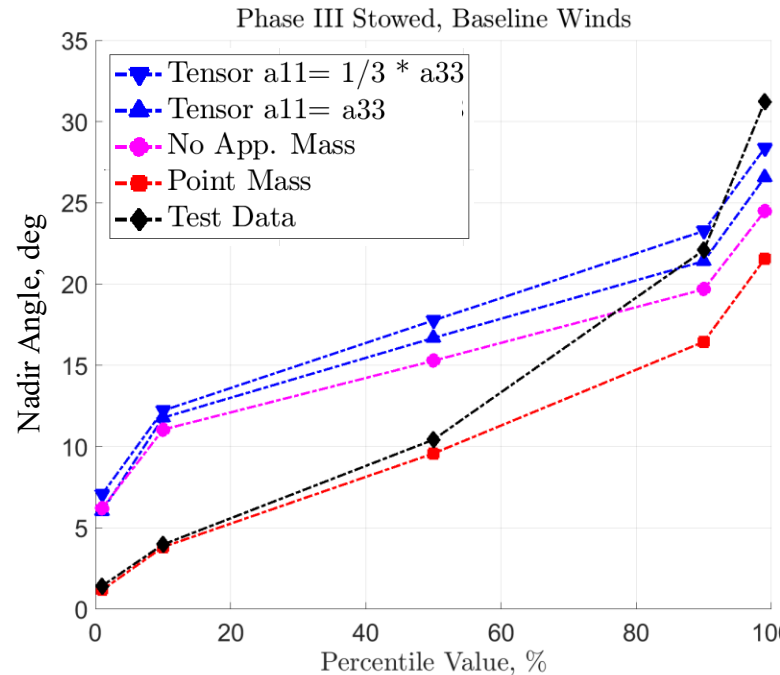
$$\begin{aligned}
 \begin{Bmatrix} M_{x,NC} \\ M_{y,NC} \\ M_{z,NC} \end{Bmatrix} &= \begin{bmatrix} -A_{14} & -A_{24} & -A_{34} \\ -A_{15} & -A_{25} & -A_{35} \\ -A_{16} & -A_{26} & -A_{36} \end{bmatrix} \begin{Bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{Bmatrix} + \begin{bmatrix} -A_{44} & -A_{45} & -A_{46} \\ -A_{45} & -A_{55} & -A_{56} \\ -A_{46} & -A_{56} & -A_{66} \end{bmatrix} \begin{Bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{Bmatrix} + \begin{bmatrix} 0 & -A_{46} & A_{45} & -A_{56} & (A_{55} - A_{66}) & A_{56} \\ A_{46} & A_{56} & (A_{66} - A_{44}) & 0 & -A_{45} & -A_{46} \\ -A_{45} & (A_{44} - A_{55}) & -A_{56} & A_{45} & A_{46} & 0 \end{bmatrix} \begin{Bmatrix} p^2 \\ pq \\ pr \\ q^2 \\ qr \\ r^2 \end{Bmatrix} \\
 &+ \begin{bmatrix} 0 & -A_{13} & A_{12} & -A_{23} & (A_{22} - A_{33}) & A_{23} \\ A_{13} & A_{23} & (A_{33} - A_{11}) & 0 & -A_{12} & -A_{13} \\ -A_{12} & (A_{11} - A_{22}) & -A_{23} & A_{12} & A_{13} & 0 \end{bmatrix} \begin{Bmatrix} u^2 \\ uv \\ uw \\ v^2 \\ vw \\ w^2 \end{Bmatrix} \\
 &+ \begin{bmatrix} 0 & -A_{16} & A_{15} & -A_{34} & -(A_{26} + A_{35}) & (A_{25} - A_{36}) & A_{24} & (A_{25} - A_{36}) & (A_{26} + A_{35}) \\ (A_{16} + A_{34}) & A_{35} & (A_{36} - A_{14}) & A_{26} & 0 & -A_{24} & (A_{36} - A_{14}) & -A_{15} & -(A_{16} + A_{34}) \\ -(A_{15} + A_{24}) & (A_{14} - A_{25}) & -A_{26} & (A_{14} - A_{25}) & (A_{15} + A_{24}) & A_{16} & -A_{35} & A_{34} & 0 \end{bmatrix} \begin{Bmatrix} up \\ uq \\ ur \\ vp \\ vq \\ vr \\ wp \\ wq \\ wr \end{Bmatrix}
 \end{aligned}$$

Model Validation (Backup)

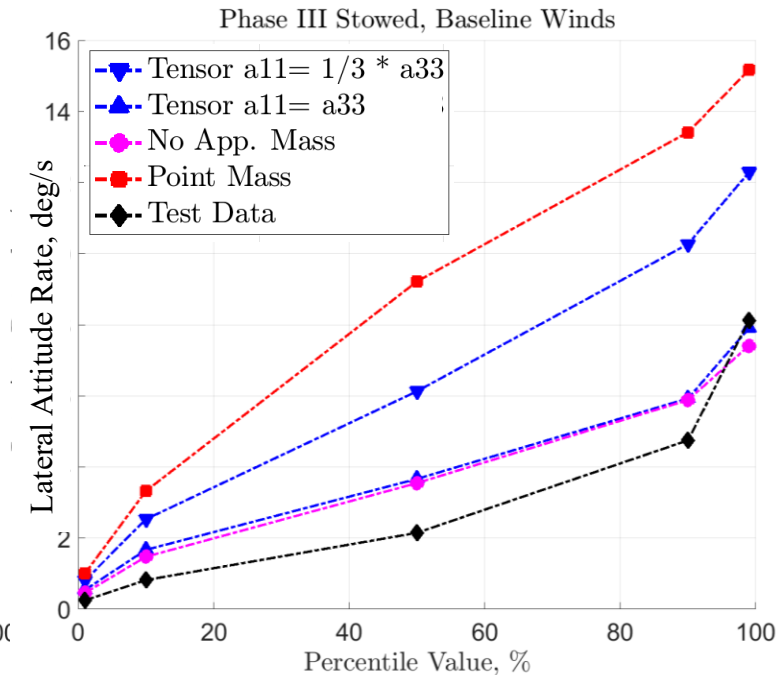
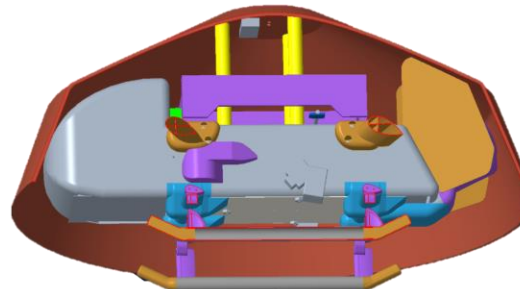


Main Parachute (Phase III)

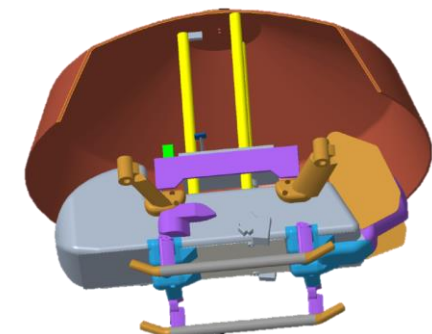
- Test data:
 - Subscale (2.8 m) ringslot main parachute and lander in **stowed** and posed configurations
- Simulation variables
 - Apparent mass model
 - Lander aerodynamics
- Observations:
 - Tensor model does not bound nadir angles from drop test
 - Tensor model provides closest match to experimental data



Stowed Lander

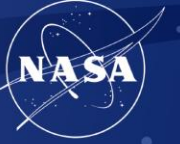


Posed Lander



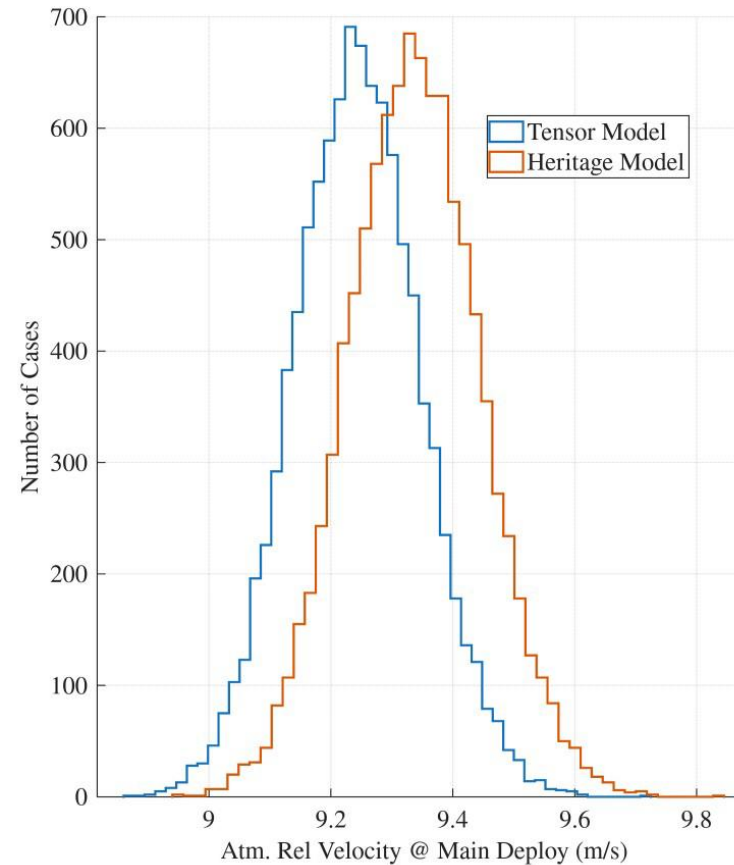
Titan Descent Simulation (Backup)

National Aeronautics
and Space Administration



- Dynamic pressure at key EDL events
 - Monte Carlo simulation (10k cases)
- Tensor model results in slightly lower dynamic pressure at main deploy
- Dynamic pressure has minimal variation at lander release (insensitive to apparent mass model)

Drogue Parachute



Main Parachute

