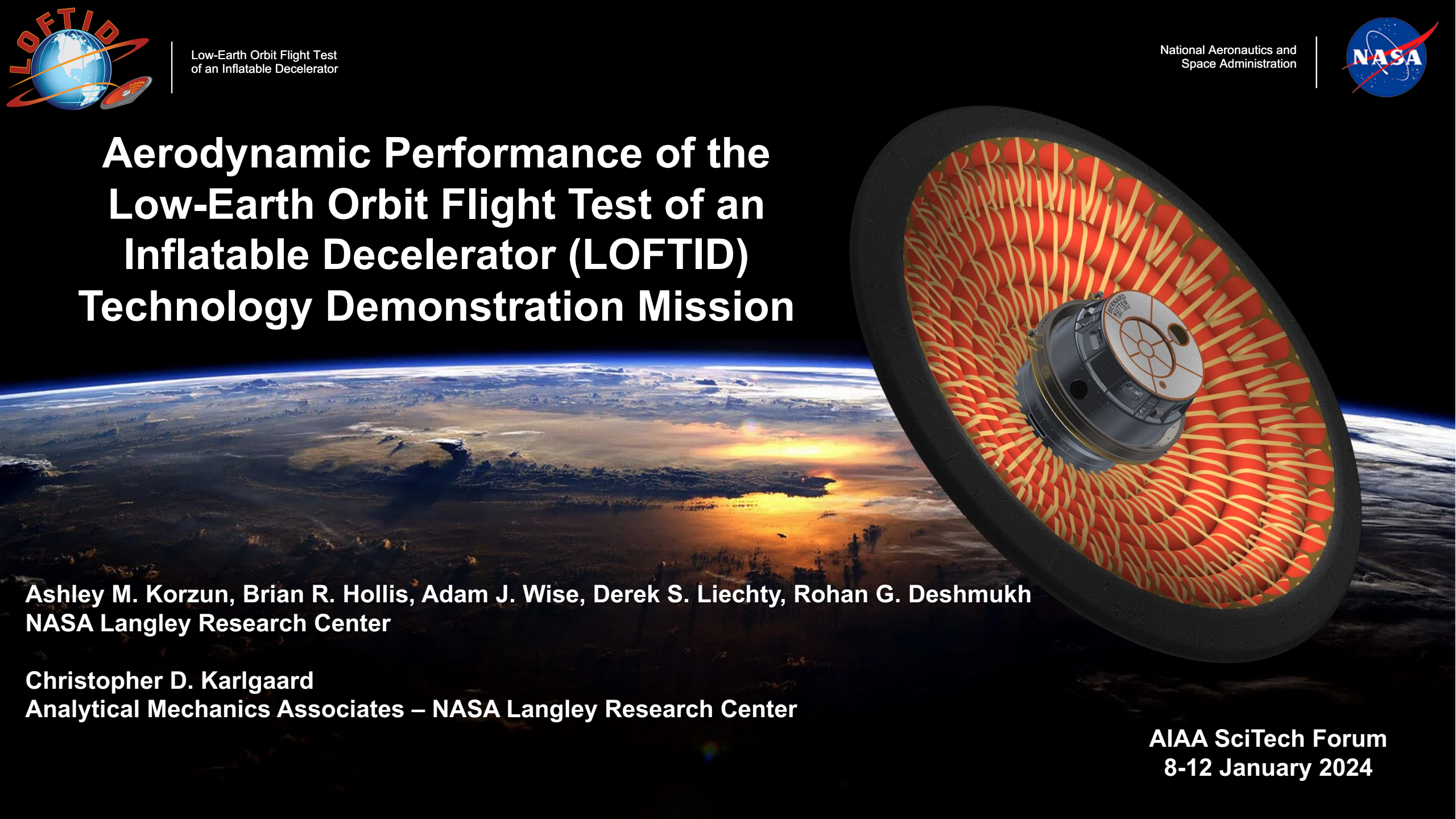

Aerodynamic Performance of the Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) Technology Demonstration Mission

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Introduction

LOFTID: Low-Earth Orbit Flight Test of an Inflatable Decelerator

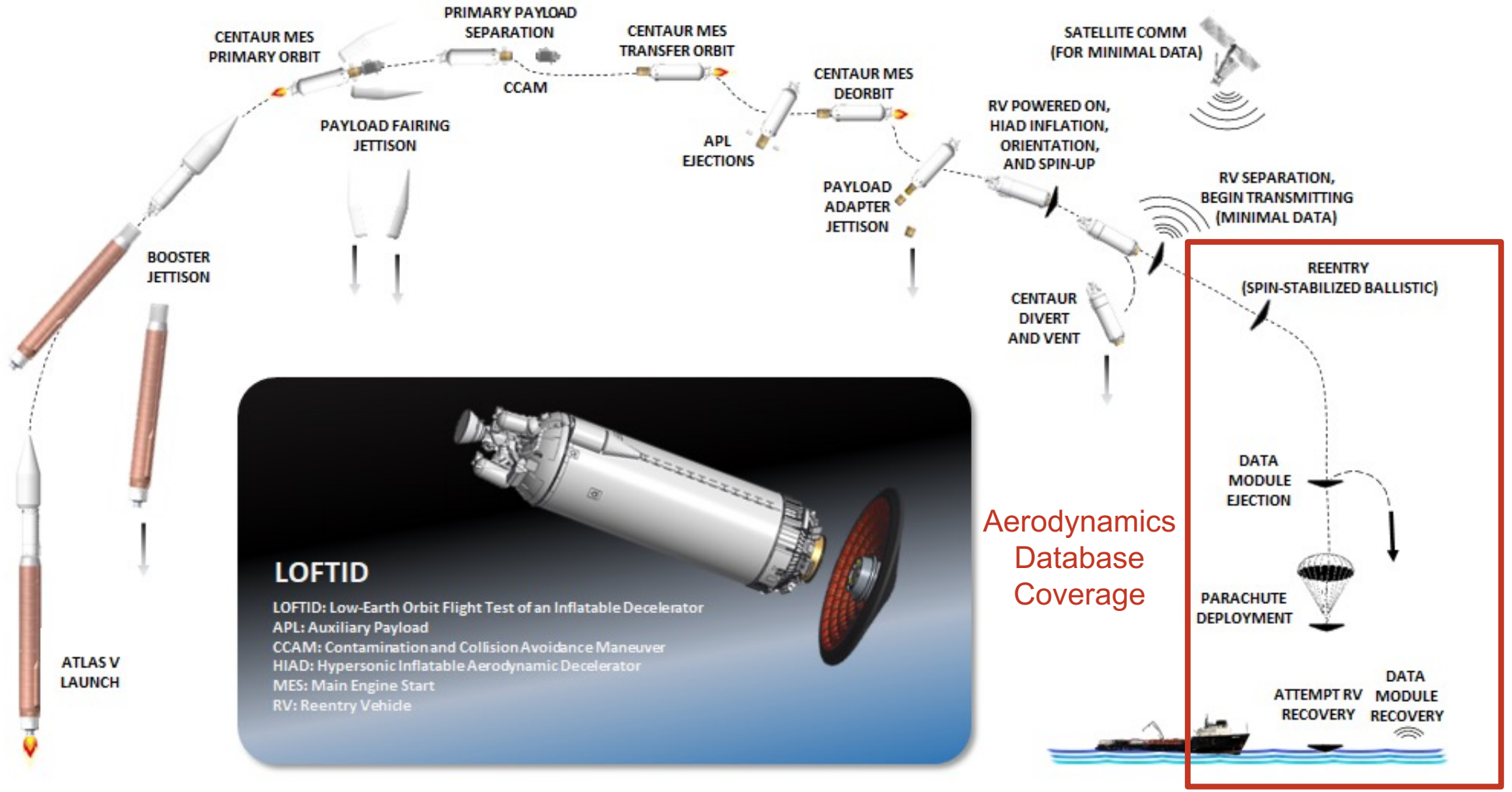
- November 10, 2022: launch from Vandenberg Space Force Base and splashdown in the Pacific Ocean off the coast of Hawaii
- Largest blunt-body flown to date
- Successful demonstration of inflatable aeroshell technology at scale and conditions relevant to Earth and Mars EDL

Image credit: NASA

Key requirements relevant to aerodynamics:

- Maintain total angle of attack less than 20º from hypersonic through subsonic regimes to Mach 0.7
- Demonstrate performance as a decelerator equivalent to a 70º sphere-cone rigid aeroshell

LOFTID Concept of Operations



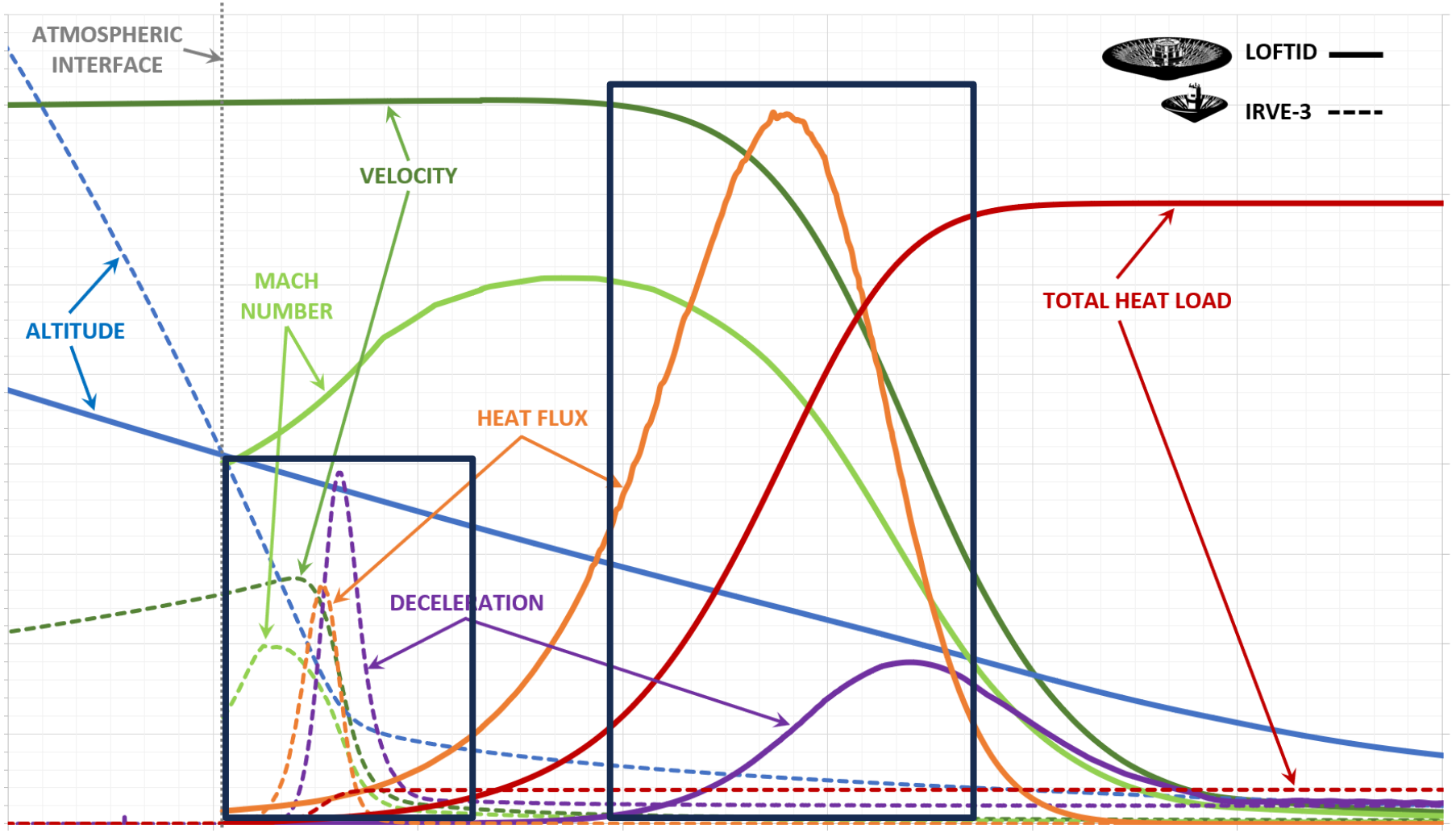
From IRVE-3 to LOFTID

IRVE-3: Inflatable Re-entry Vehicle Experiment-3

- HIAD flight demo (2012)
- Suborbital sounding rocket flight
- 3m diameter aeroshell
- 60º sphere-cone

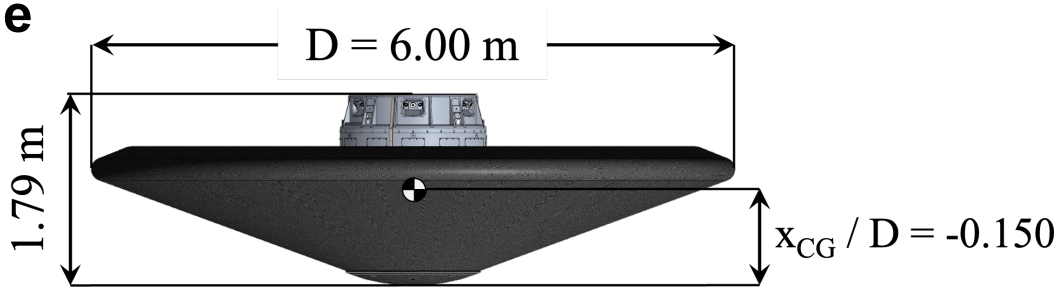
LOFTID

- Nearly 3x the entry velocity
- Orbital re-entry flight
- 6m diameter aeroshell
- 70º sphere-cone



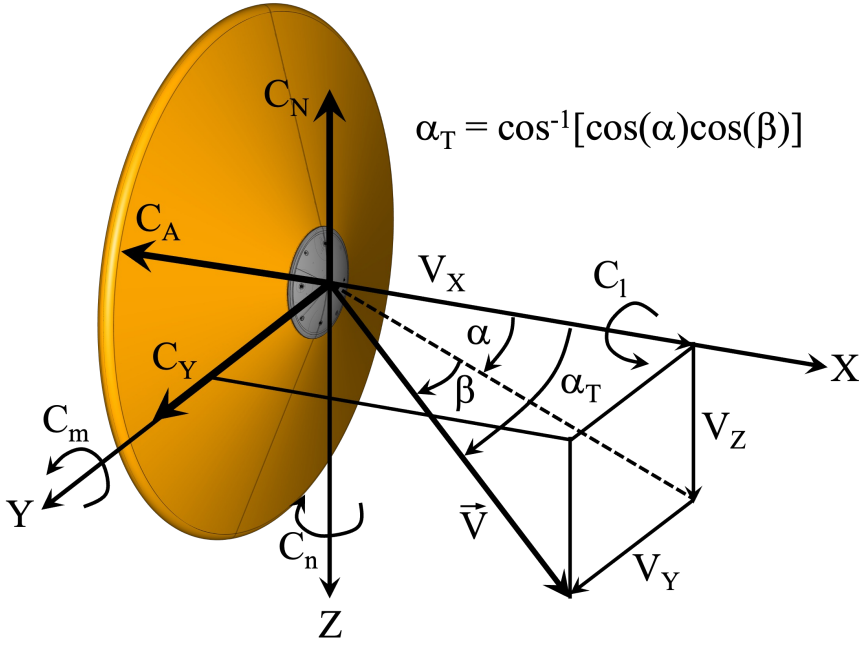
Aerodynamics Database Overview

- **Aerodynamics database provides 6-DOF coefficients as a function of flight conditions and vehicle attitude**
  - Non-continuum and continuum flight regimes
  - Static aerodynamics and dynamic damping
  - Uncertainties provided as function of flight regime and reflect underlying methods and data sources



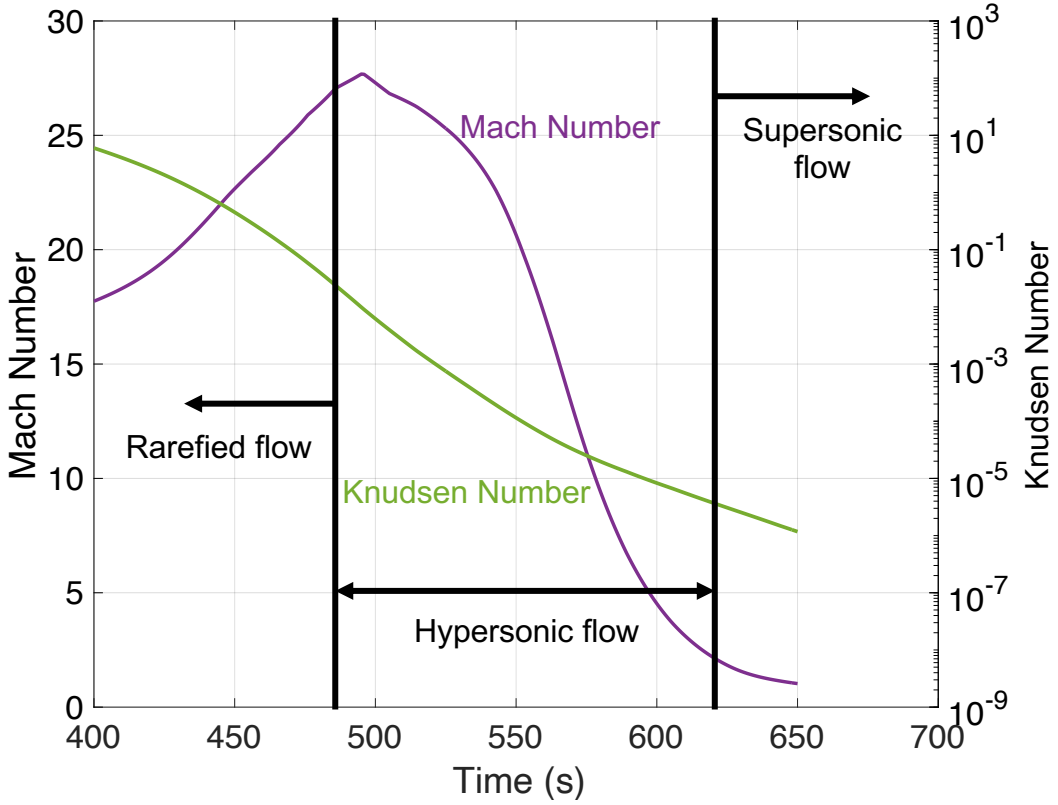
- **Aerodynamics datasets, methods, tools, and implementation draw on flight experience from IRVE-II and IRVE-3, as well as prior HIAD design studies and rigid aeroshell missions**

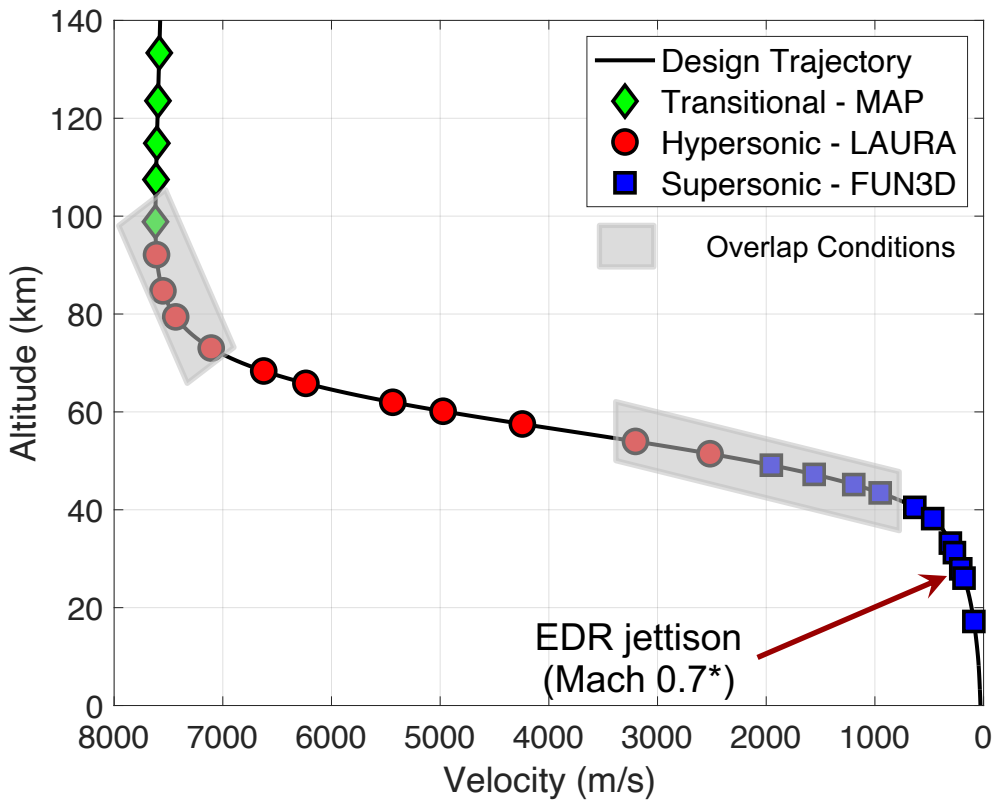
- **Vehicle modeled as axisymmetric, smooth, and rigid**



Design Reference Trajectory

- **Discrete points along a design reference trajectory used to define conditions for computational fluid dynamics (CFD) data generation**
- **Overlaps between flow regimes blend data from different sources**



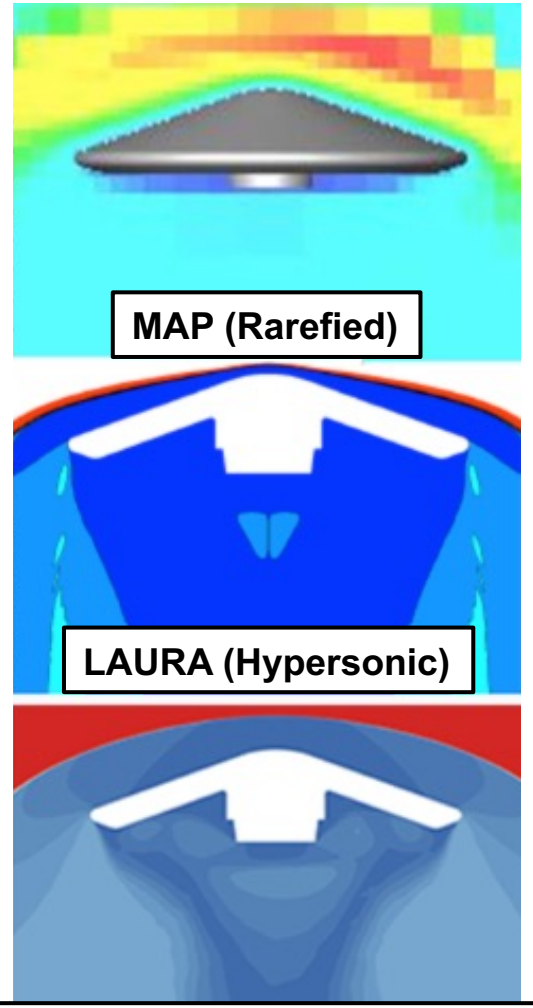


*Nominal target

*See paper by Deshmukh et al. in this session for more detail

Static Aerodynamics

	Flight Regime	Range	Input Parameters	Source
Non-Continuum	Free-Molecular	$Kn > 3.018, 0° \leq \alpha_T \leq 180°$	α_T	DAC [12]
	Transitional	$0.00572 \leq Kn \leq 3.018, 0° \leq \alpha_T \leq 8°$	α_T, Kn	MAP [13]
Continuum	Hypersonic	$M_\infty \geq 7.88$ and $Kn < 0.00572, 0° \leq \alpha_T \leq 8°$	α_T, M_∞	LAURA [14]
	Supersonic	$0.89 < M_\infty \leq 6.10, 0° \leq \alpha_T \leq 20°$	α_T, M_∞	FUN3D [15]
	Mid-Subsonic	$0.30 < M_\infty \leq 0.89, 0° \leq \alpha_T \leq 40°$	α_T, M_∞	FUN3D
	Low-Subsonic	$M_\infty \leq 0.30, 0° \leq \alpha_T \leq 40°$	α_T	FUN3D

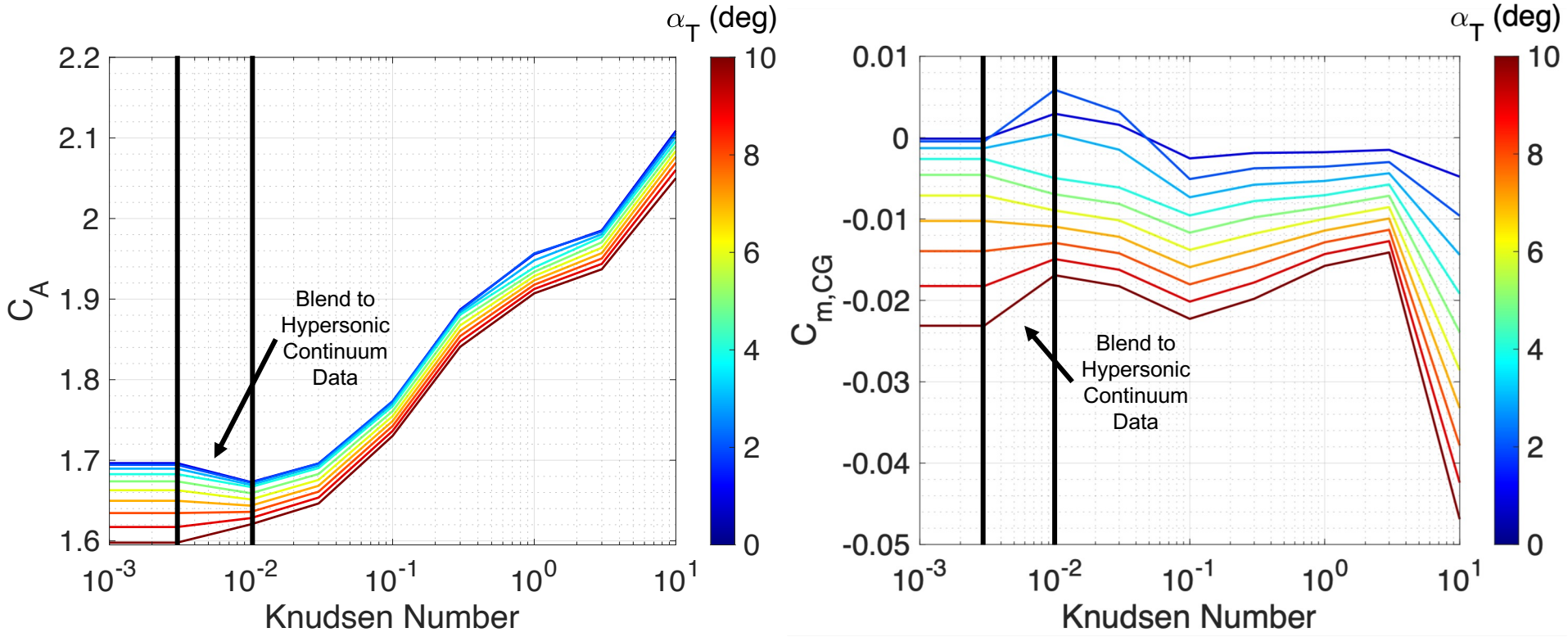


- **Relevant methods and tools dictated by flow regime**
- **Aerodynamics data tabulated as functions of α_T and Kn or M_∞**
- **Forebody-only solutions used for hypersonic conditions and above**
- **Full-geometry solutions used for supersonic conditions and below**
- **Continuum datasets linearly blended between breakpoints**

*See paper by Hollis et al. in this session for more detail

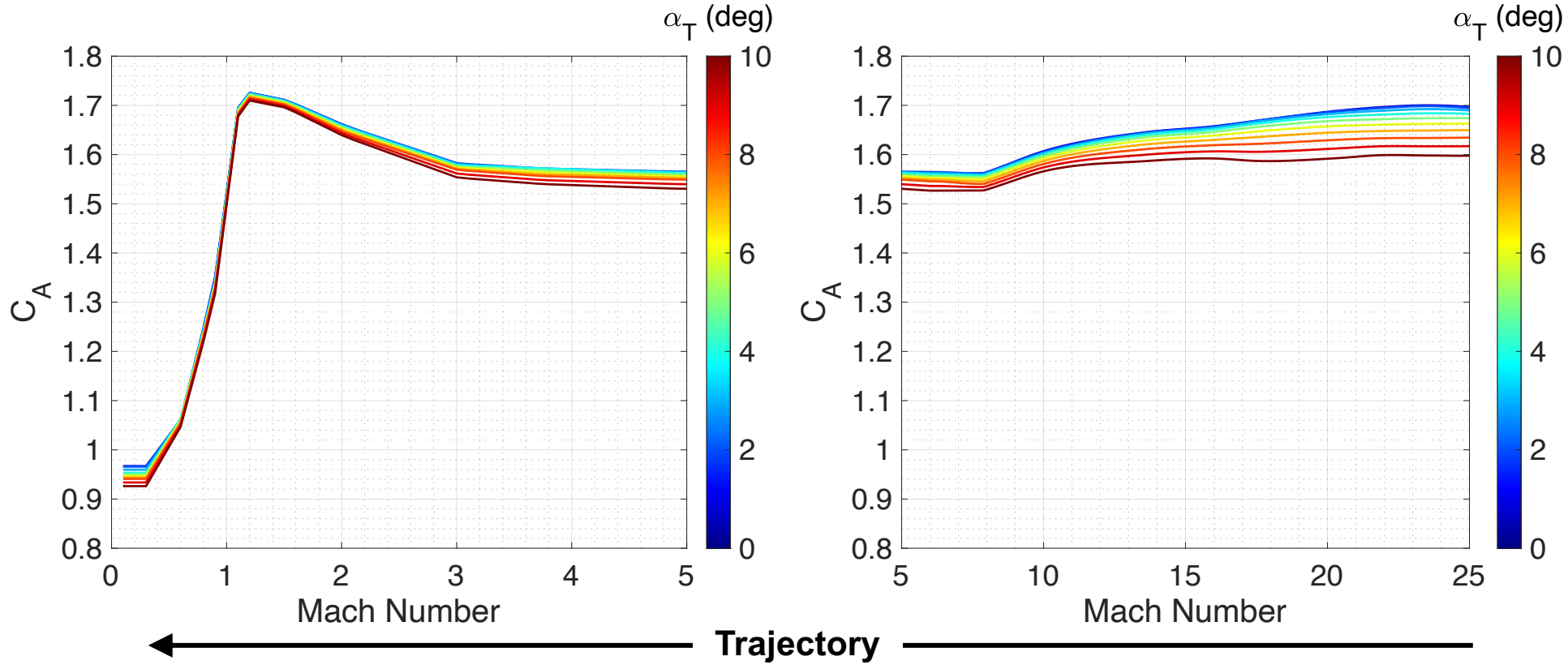
Static Aerodynamics Database – Non-Continuum

- Non-continuum aerodynamics generated using the MAP DSMC code
- Replaces traditional sine-squared bridging function through transitional flow regime
- Altitude range: above 98 km
- Minor static instability at low α_T (< 2º) for 0.003 < Kn < 0.1



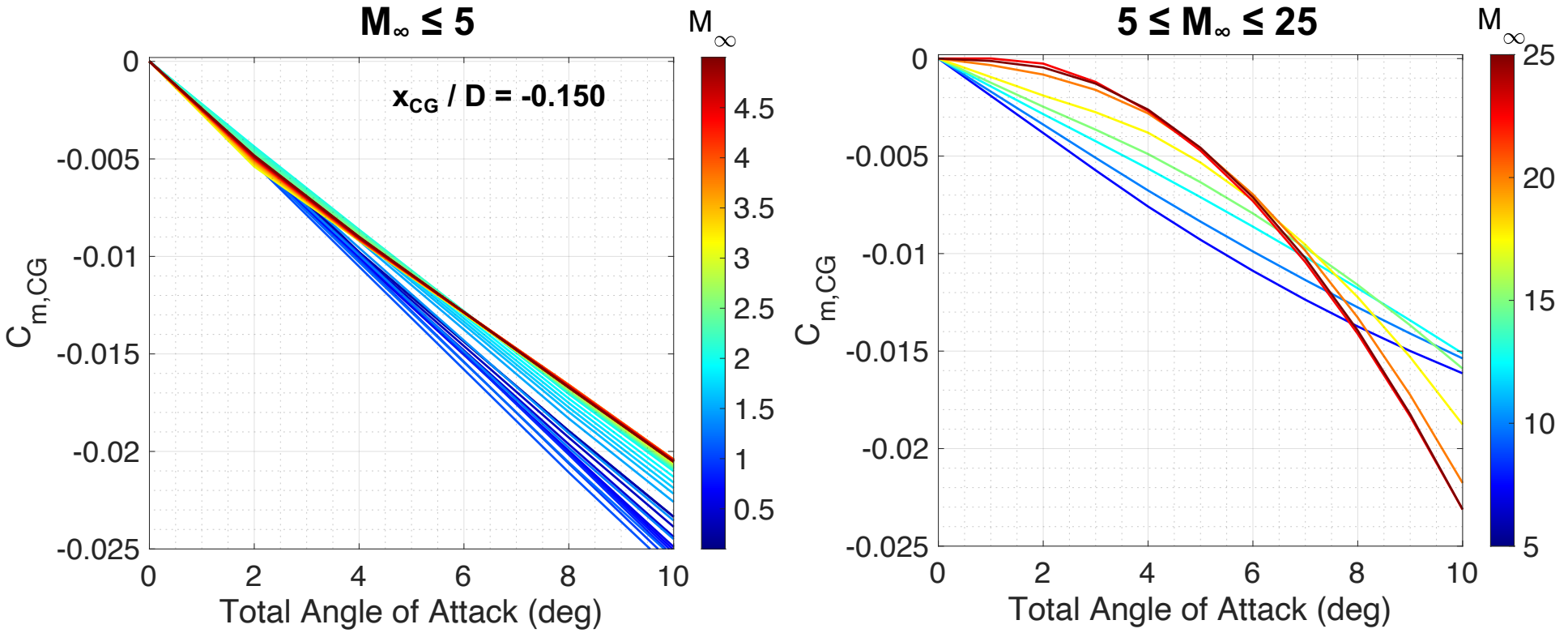
Static Aerodynamics Database – Continuum

- Entire dataset for continuum conditions generated using CFD
- C_A trend with both M_∞ and α_T are as-expected for a 70º sphere-cone at Earth
- Sensitivity of C_A to α_T decreases along the re-entry trajectory
- Full vehicle geometry used for all static coefficients below Mach 6.10



Static Aerodynamics Database – Continuum

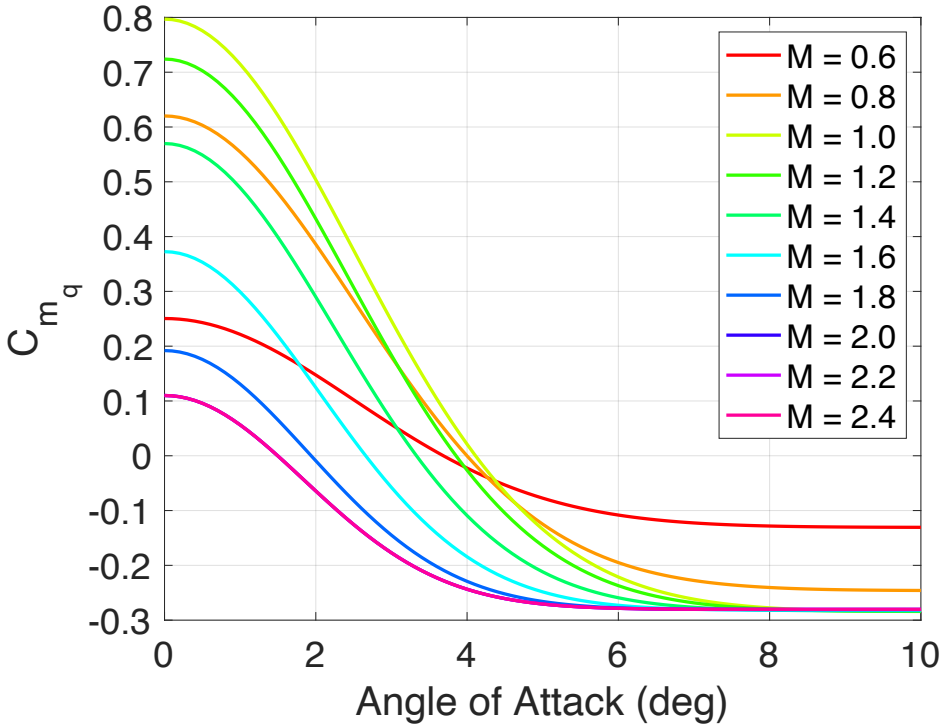
- Statically stable across the full continuum regime
- High hypersonic conditions show increasing static stability at very low α_T from non-continuum conditions



Pitch Damping Database

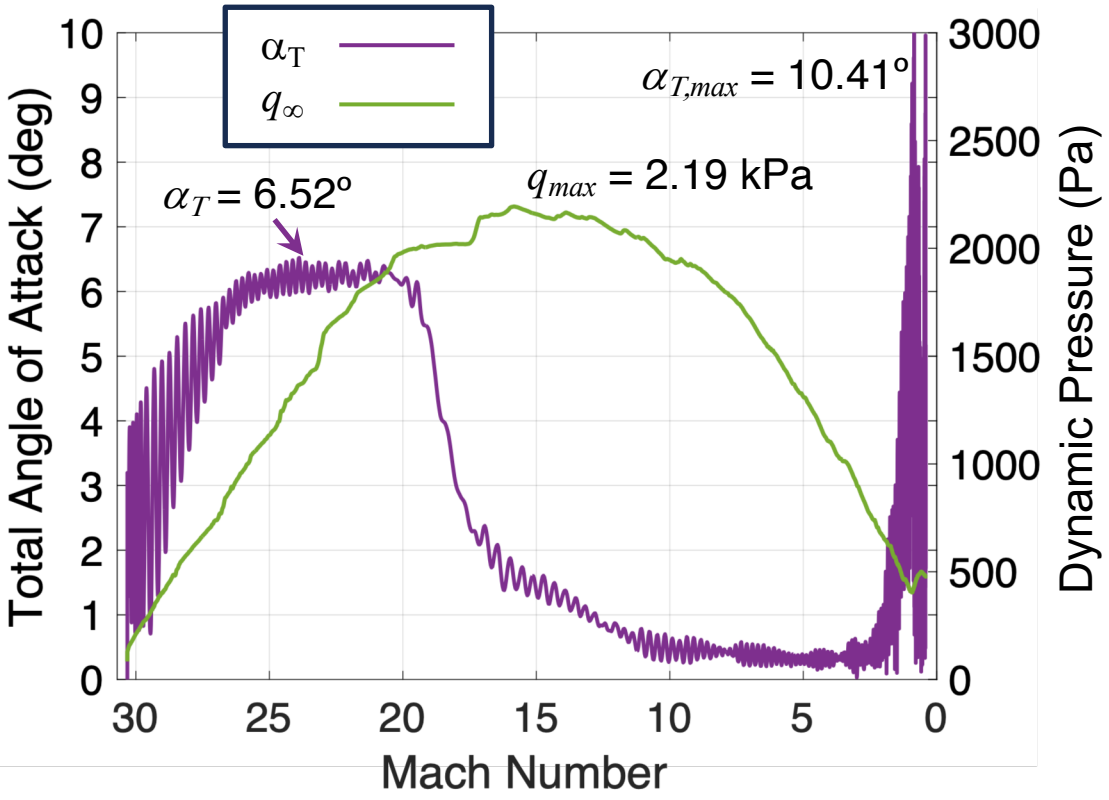
	Flight Regime	Range	Input Parameters	Source
Non-Continuum	Free-Molecular	$Kn \geq 10.0,\ 0° \leq \alpha_T \leq 180°$	none	–
	Transitional	$0.001 < Kn < 10.0,\ 0° < \alpha_T < 40°$	α_T, Kn	–
Continuum	Hypersonic	$M_\infty \geq 6.0$ and $Kn < 0.001,\ 0° \leq \alpha_T \leq 40°$	α_T, M_∞	IRVE-3
	Supersonic	$0.65 \leq M_\infty < 3.0,\ 0° \leq \alpha_T \leq 40°$	α_T, M_∞	IRVE-3
	Subsonic	$M_\infty < 0.65,\ 0° \leq \alpha_T \leq 40°$	α_T, M_∞	IRVE-3

- **Blunt bodies are characteristically dynamically unstable at low supersonic to transonic conditions**
- **Free-molecular: C_{mq} = -0.32 (constant)**
- **Transitional: sine-squared blend between free-molecular and hypersonic values as a function of Kn**
- **Hypersonic: C_{mq} = -0.20 (constant)**
- **IRVE-3 ballistic range functional forms for $0.65 \leq M_\infty \leq 3.0$**
- **C_{mq} constant for $M_\infty \leq 0.65$**



Reconstructed As-Flown Performance

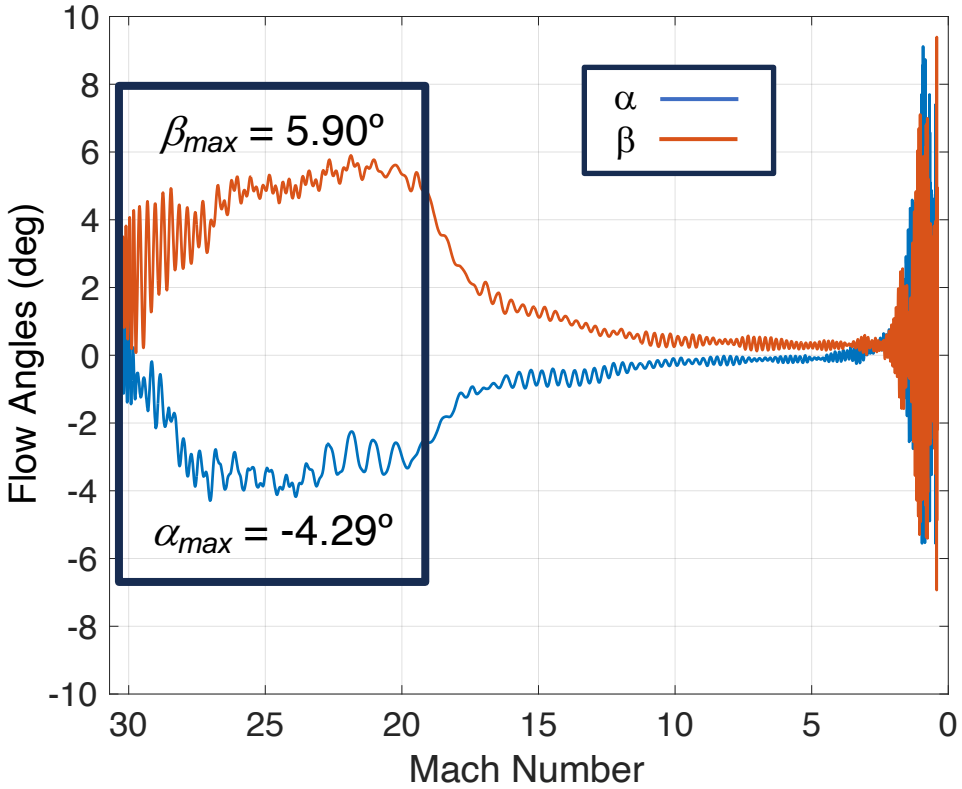
- **IMU data were not captured by the data recorder, preventing reconstruction of the as-flown aerodynamics**
- **Atmosphere-relative trajectory and attitude reconstructed using FADS and on-board video data***
- **Shift in α_T:**
  - Aeroshell settling into the nominal drag position from its zero-g inflation position
  - Aligns with a density change in the local atmosphere and resulting ”bump” in dynamic pressure



*See paper by Karlgaard et al. in this session for more detail

Reconstructed As-Flown Performance

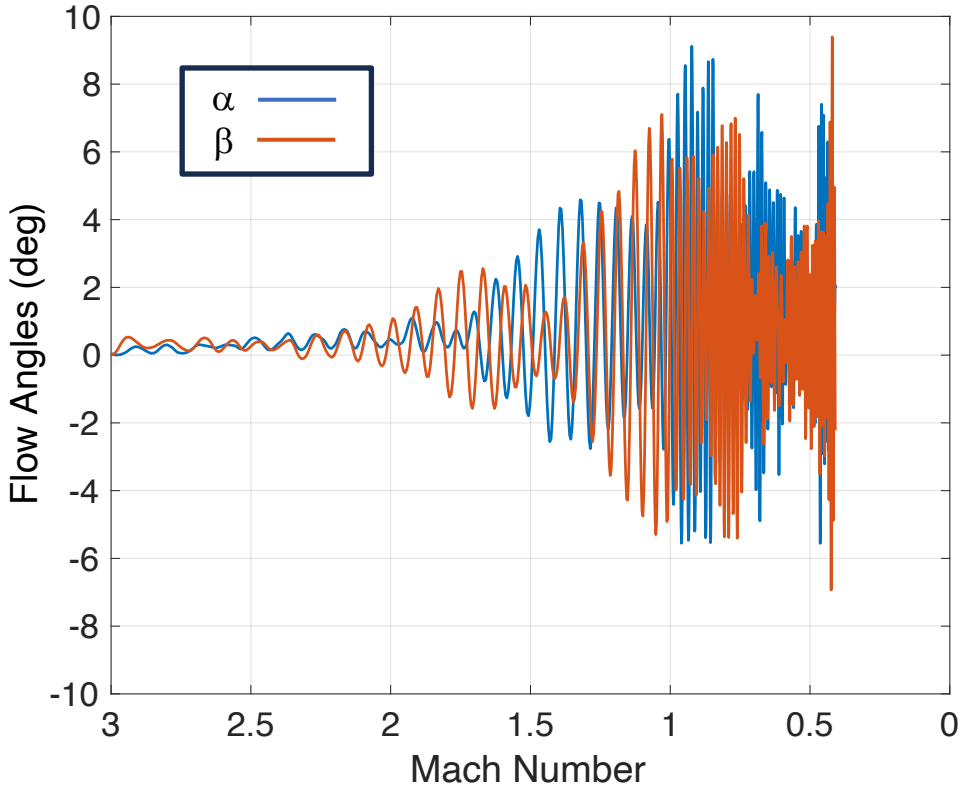
- Aeroshell orientation relative to the rigid nose was sufficient off-center to trim hypersonically before settling into the nominal drag position
- As expected, attitude begins to increase with deceleration through supersonic to subsonic conditions due to inherent dynamic instability of the blunt-body shape
- On-board video data confirmed no attitude or attitude rate excursions
- Nominal spin rate: 18 deg/s; Reconstructed estimated spin rate: 17.7 deg/s



*See papers by Deshmukh et al. and Karlgaard et al. in this session for more detail

Reconstructed As-Flown Performance

- Peak attitude well below the 20º mission requirement ($\alpha_{T,max}$ = 10.41º)
- Vehicle observed from the recovery vessel to be highly stable under parachute
- Both the data recorder and vehicle were successfully recovered from the ocean



α_{max} = 9.12º

β_{max} = 9.39º

Image credit: NASA

- Splashdown was 5.53 nmi from target, with the vehicle visible from the recovery vessel while descending under parachute

Summary

- LOFTID mission requirements were successfully met through orbital re-entry of a 6m diameter inflatable aeroshell
- Peak total angle of attack remained well below the 20º requirement
- Aerodynamics database for LOFTID leveraged and expanded on prior suborbital flight experience, with demonstration of decelerator performance and stability
- Lack of IMU data limited reconstruction of vehicle performance without reliance on nominal pre-flight aerodynamics

Image credit: Greg Swanson (NASA)

Back-up

Aerodynamics Uncertainties

- Dispersed aerodynamics applied through Monte Carlo flight mechanics analysis to establish vehicle performance and to verify requirements pre-flight
- Uncertainties based on flight experience from Genesis, IRVE, and IRVE-3
- Adders and multipliers used to independently disperse trim attitude (intercept) and static stability (slope), respectively

Static Aerodynamics (Uncorrelated)

Flight Regime	C_A	C_N, C_Y	C_m, C_n	C_l
Free-Molecular / Transitional $Kn > 0.1$	±5%	±0.01, ±20%	±0.005, ±20%	$\pm 1.24 \times 10^{-6}$
Hypersonic $M_\infty < 10$	±3%	±0.01, ±20%	±0.003, ±20%	$\pm 1.24 \times 10^{-6}$
Supersonic $1.5 < M_\infty < 5$	±10%	±0.01, ±20%	±0.005, ±20%	$\pm 1.24 \times 10^{-6}$
Transonic $0.4 < M_\infty < 1.5$	±10%	1.25 × Supersonic	1.25 × Supersonic	$\pm 1.24 \times 10^{-6}$

Dynamic Damping (Correlate

Flight Regime	C_{m_q}	C_{n_r}
Transitional / Free-Molecular $Kn > 0.1$	±0.15	±0.15
Hypersonic $M_\infty > 6$	±0.15	±0.15
Supersonic $1.5 < M_\infty < 3$	+0.4 × [1.5, 0.5] − 0.4 + [0.1, 0.0]	+0.4 × [1.5, 0.5] − 0.4 + [0.1, 0.0]
Transonic $1 < M_\infty < 1.5$	1.25 × Supersonic	1.25 × Supersonic

- All moments dispersed about the CG
- Fixed shift applied to dynamic damping forces more cases to be less stable

$$C_{disp} = [C_{nominal}(\alpha, \beta) + U_C^A](1 + U_C^M)$$

$$C_{m_q,disp} = (C_{m_q,nominal}(\alpha, \beta) - 0.4) * U_C^M + 0.4 + U_C^A$$