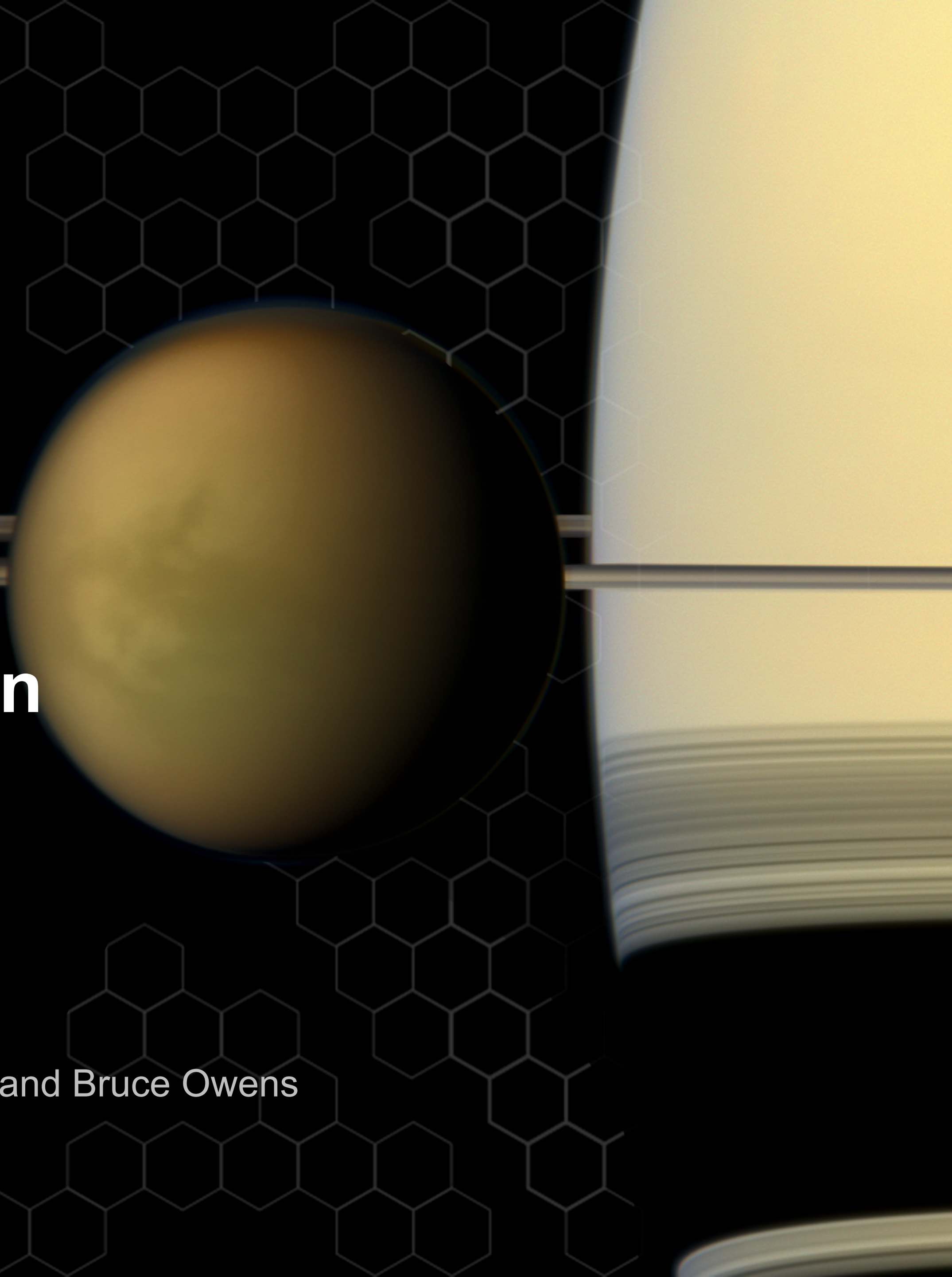
DRAGONFLY

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

Dragonfly: A Case Study in Dynamic Stability Characterization

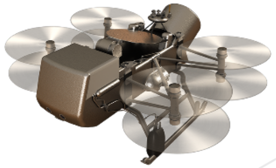


International Planetary Probe Workshop 2023

Presented by Eric Stern

With significant contributions from: Cole Kazemba, Quincy McKown, and Bruce Owens

“See-em-cue” is a four-letter word…



- **Typical blunt-body entry probes are *dynamically* unstable at low-supersonic to transonic Mach numbers**
  - Meaning: if left to their own devices, pitch and yaw oscillations will grow over time, eventually causing the capsule to tumble, likely leading to a catastrophic loss of mission

- To mitigate this harsh reality, many missions employ active control (i.e. RCS), and/or elect to deploy parachutes at high Mach number, providing a stabilizing effect

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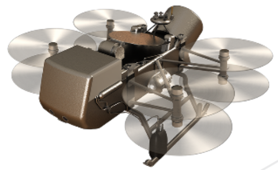

- **Whether due to the ConOps of a particular mission (e.g. Dragonfly or MSR-EES), or cost constraints, many missions must fly a fully passive entry and descent**
  - ➡ In these cases, accurate characterization of the dynamic performance of the probe is critical to closing the EDL phase design
- **Unfortunately, the importance of this vehicle attribute is matched only by its difficulty in characterization, both experimental and computationally**
  - Nascent computational capabilities (e.g. FF-CFD), while promising, do not yet have flight heritage and have yet to be demonstrated end-to-end for a flight mission
  - Experimental techniques remain the state-of-the-art, but suffer from poor flight similitude, and often sparse data (not to mention the cost!)
- **To make matters worse…**
  - The physical mechanisms of dynamic instability remain poorly understood, making forming of intuition about a particular vehicles performance difficult
  - Only a handful of subject matter experts have an intuitive grasp of the fundamentals, making it difficult for EDL phase managers to track risks

➡ **Ergo: Dynamic Stability is often referred to as a “Dark Art” within the EDL modeling community**

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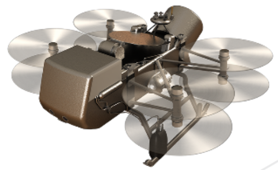
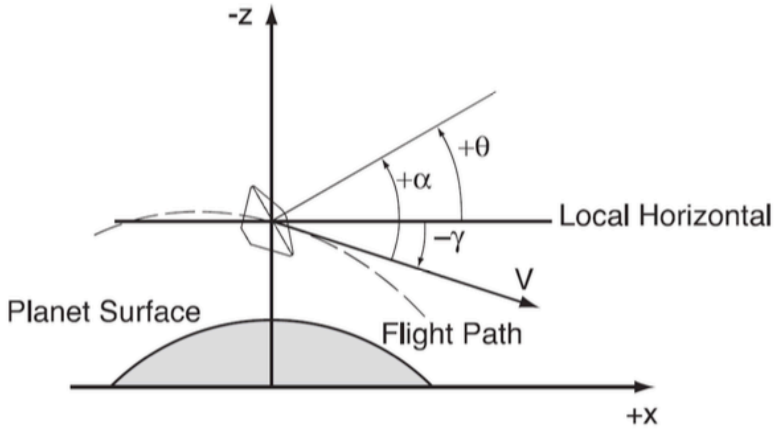


- **If one has had to engage with this dark art at any point, then they have doubtless encountered the notorious C_{mq} (“see-em-cue”) parameter, otherwise known as the pitch damping derivative**
- **A quick primer:**
  - The pitch damping derivative appears in the classical rigid body dynamics equations derived for a entry probe as a coefficient for the first derivative of the angle-of-attack (*simplified to planar motion here for clarity*)



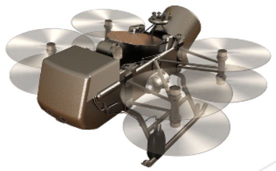
$$\ddot{\alpha} - \frac{\rho V_\infty S d^2}{4I}\left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)\dot{\alpha} - \frac{\rho V_\infty^2 S d}{2I} C_{m_\alpha}\alpha = 0$$

Damping

Spring constant

  - In the harmonic oscillator analogy, C_{mq} acts as the damping term, and the pitching moment slope acts as the spring constant

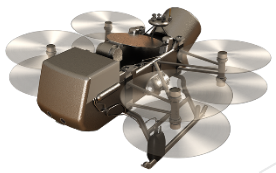
“See-em-cue” is a four-letter word…



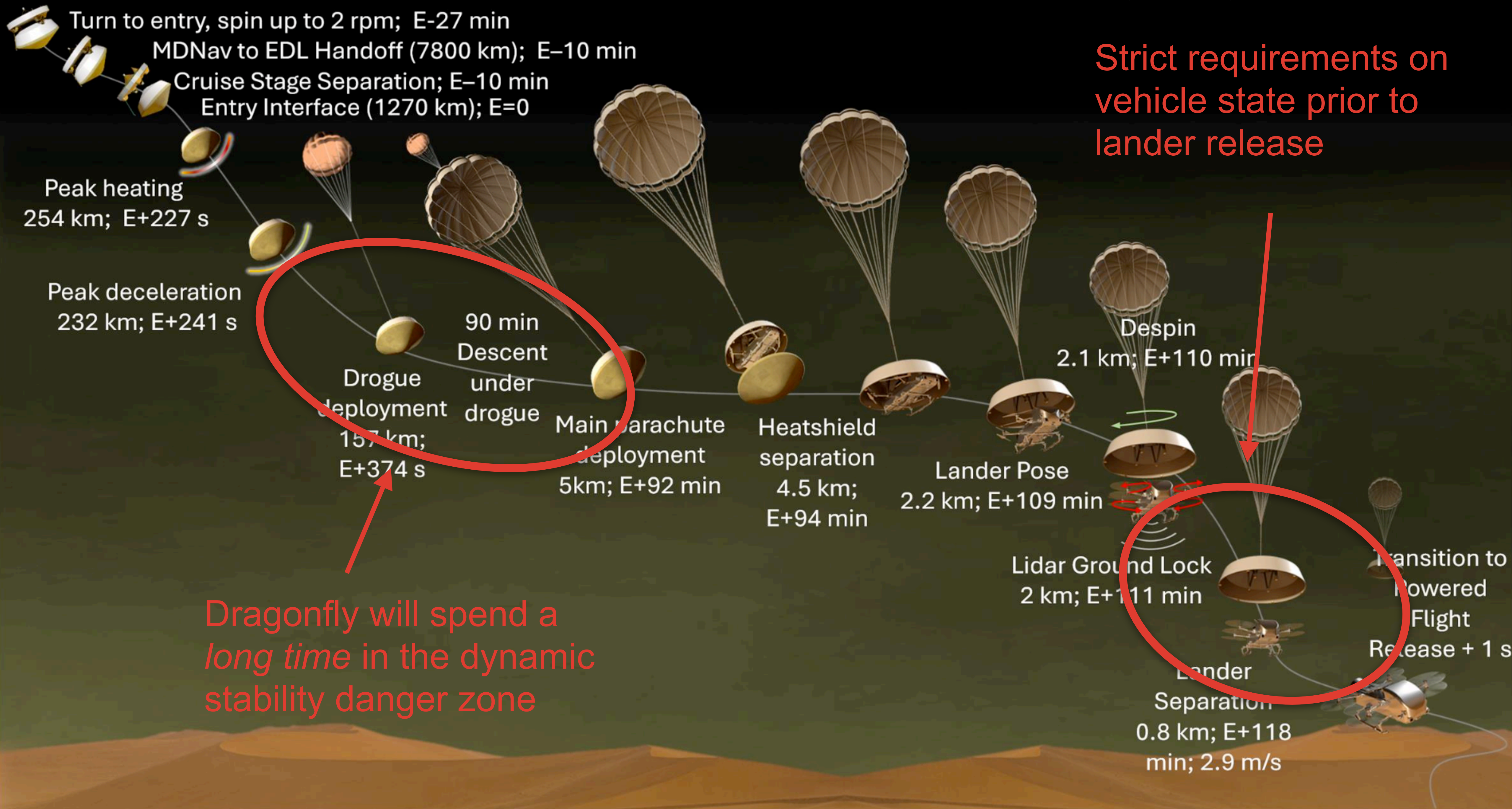
- ***HOWEVER*, though it may appear like another aerodynamic coefficient, it is fundamentally different than the well-known parameters like lift and drag**
  - C_{mq} is simply a byproduct of the Taylor series expansion used to derive the equations of motion, and should be thought of as a useful heuristic, rather than as a fundamental property of the vehicle
- **A couple postulates/correctives:**

➡ **Currently, there is no method or theory to accurately compute Cmq from a static experiment or computation, rather it must be derived from a posteriori analysis of dynamically oscillating data**

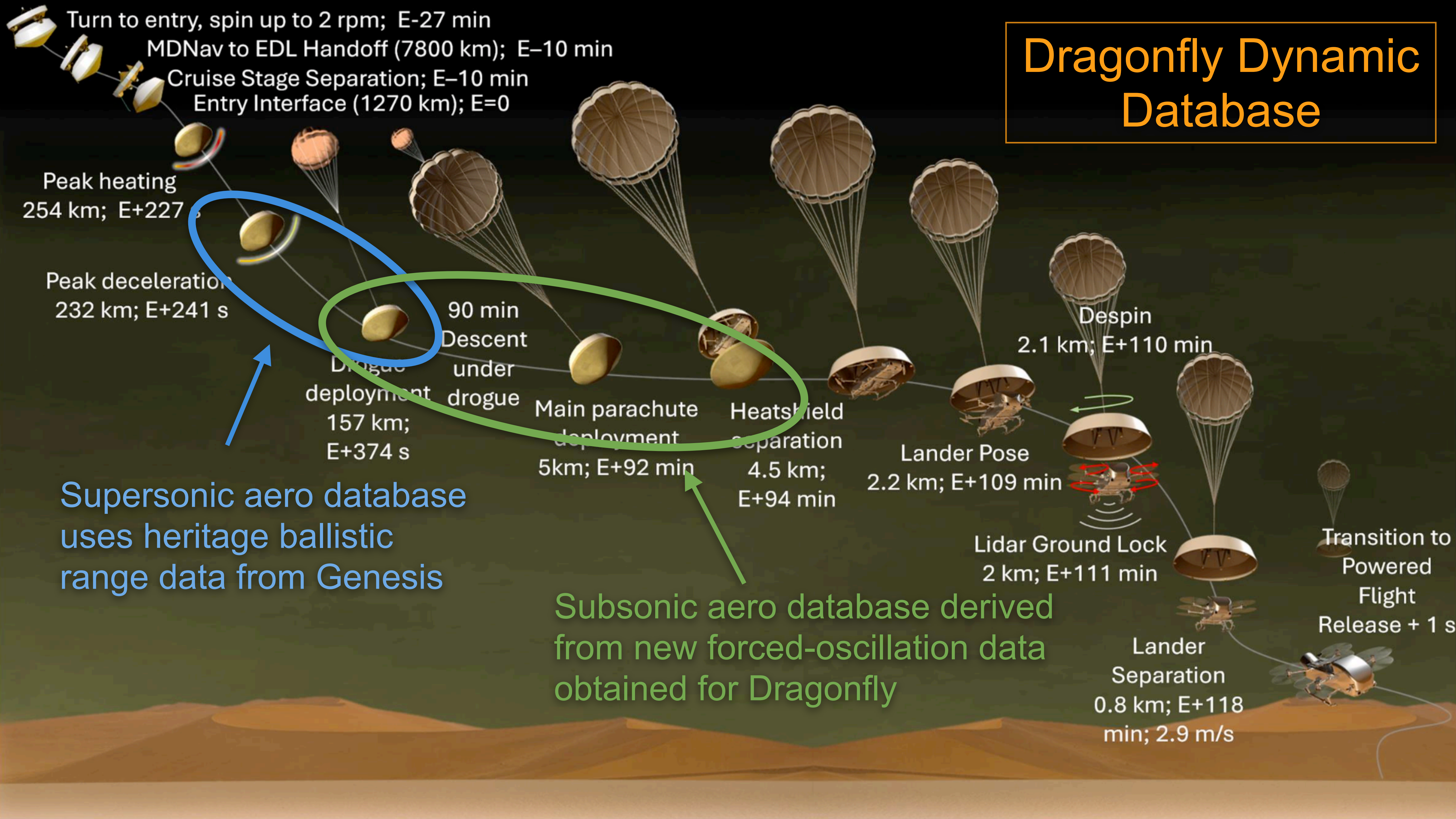
➡ **Cmq is an inherently *stochastic* quantity, due its dependence on unsteady and random pressure fluctuations on the aftbody of the aeroshell, thus deriving a quality pitch damping model requires statically significant amounts of data spanning the relevant independent variable ranges**



Dragonfly: A Challenging Mission Profile for Dynamic Stability

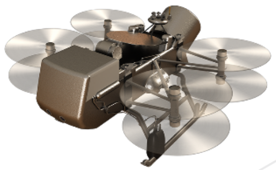


** *for more on the ConOps, see poster by A. Pensado*



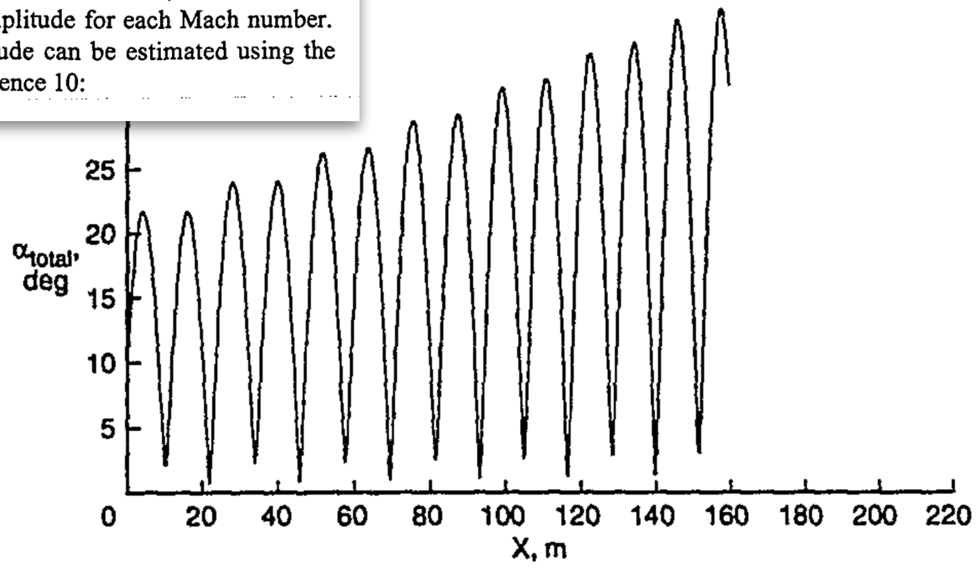
Dragonfly Dynamic Database
Turn to entry, spin up to 2 rpm; E-27 min
MDNav to EDL Handoff (7800 km); E–10 min
Cruise Stage Separation; E–10 min
Entry Interface (1270 km); E=0
Peak heating 254 km; E+227 s
Peak deceleration 232 km; E+241 s
Drogue deployment 157 km; E+374 s
90 min Descent under drogue
Main parachute deployment 5km; E+92 min
Heatshield separation 4.5 km; E+94 min
Lander Pose 2.2 km; E+109 min
Despin 2.1 km; E+110 min
Lidar Ground Lock 2 km; E+111 min
Lander Separation 0.8 km; E+118 min; 2.9 m/s
Transition to Powered Flight Release + 1 s
Supersonic aero database uses heritage ballistic range data from Genesis
Subsonic aero database derived from new forced-oscillation data obtained for Dragonfly

Genesis SRC Heritage



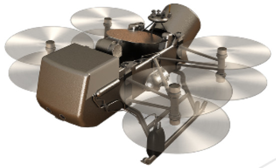
- The Dragonfly aeroshell is based on the heritage OML of the Genesis Sample Return Capsule (SRC)
- The Genesis shape is known to be dynamically unstable at low supersonic to transonic speeds

Although no limit cycles were found experimentally, the aerodynamics for this configuration suggest that potential limit cycles exists. Because the pitch damping is a function of Mach number, there will be a different limit cycle amplitude for each Mach number. The limit cycle amplitude can be estimated using the approach given in Reference 10:



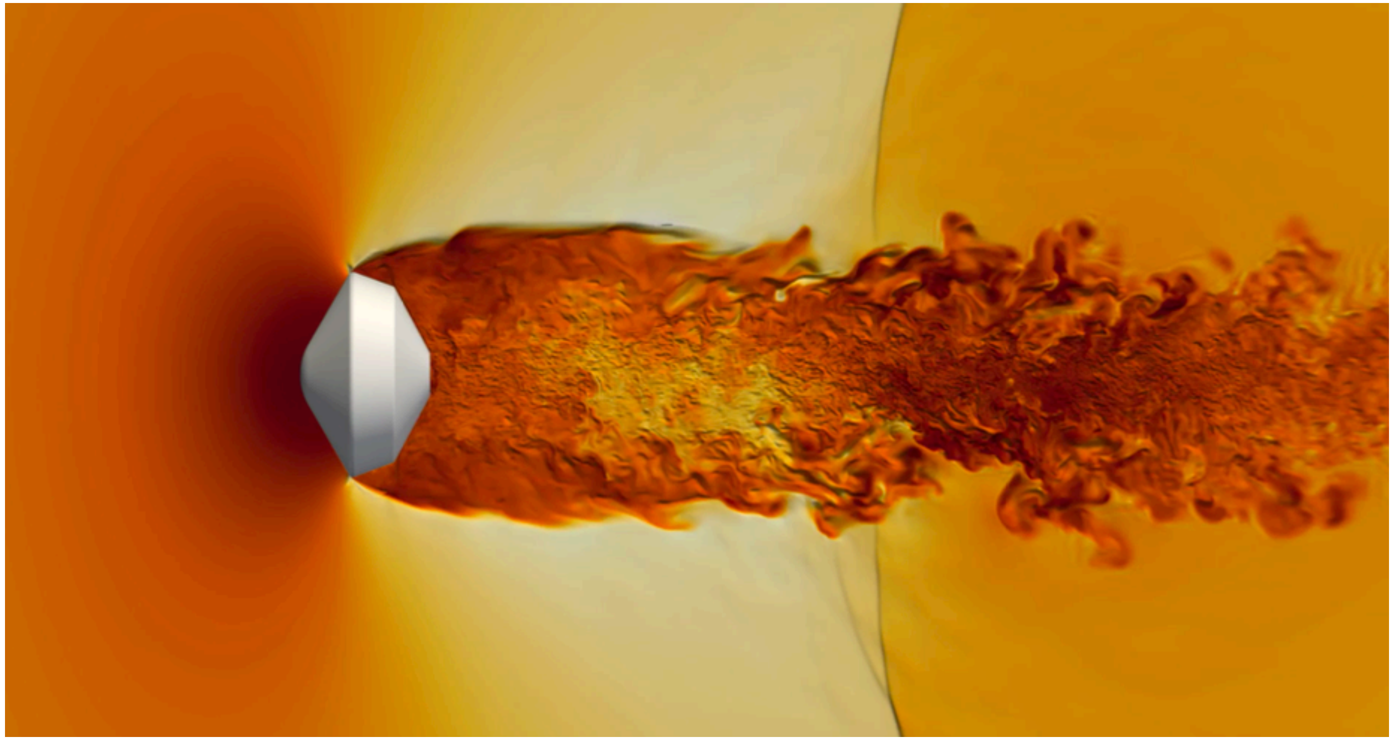
a. Mach 1.4 Average (M = 1.88 to 0.99).

“Sharpening the Pencil…”

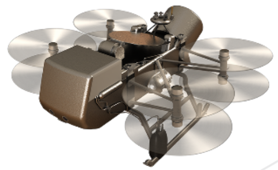


- Given the known characteristics of the Dragonfly aeroshell, and the stringent requirement levied on its performance, the EDL team has had refine the dynamic stability analysis in order to close the design

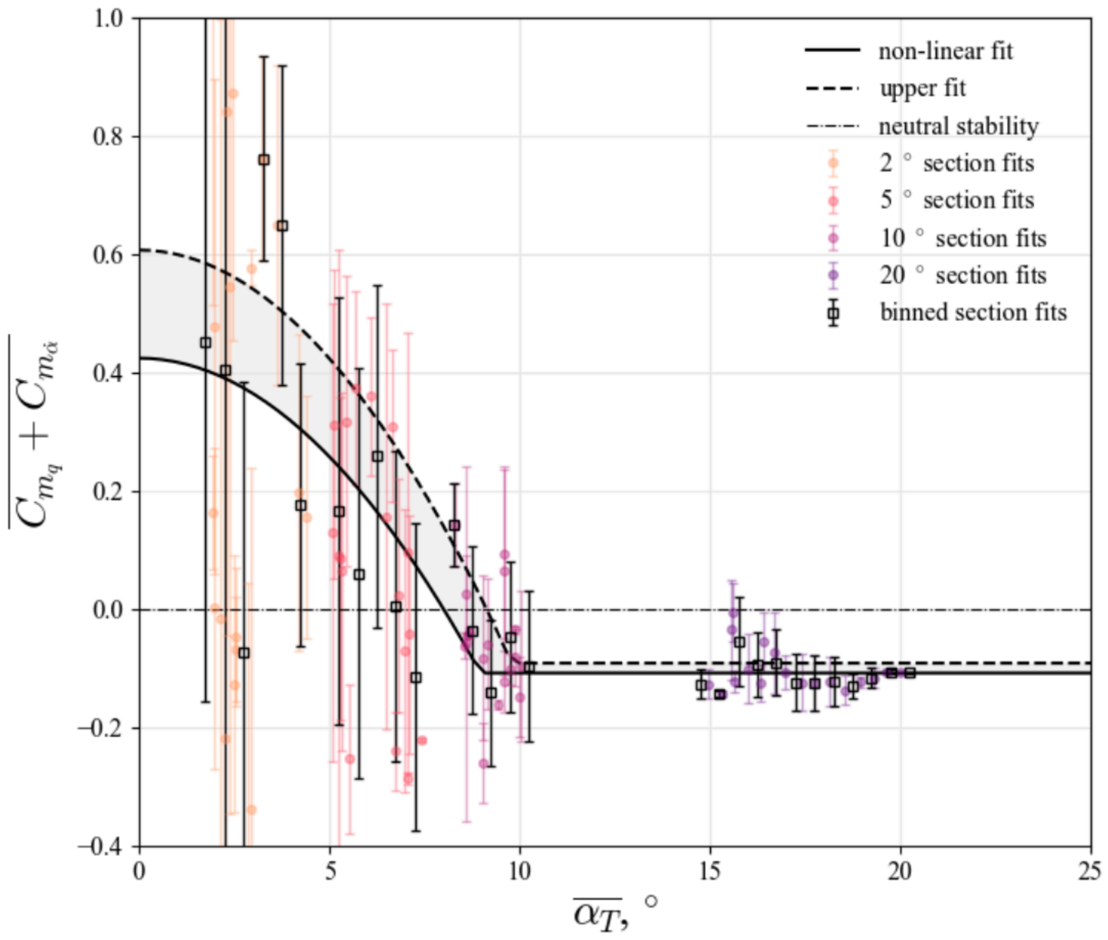
- Here we highlight two such refinements:
  - Reduction in pitch damping uncertainties using FF-CFD
  - Knock-down factor for pitch damping when at non-zero sideslip angle



Alpha-dependent Uncertainty

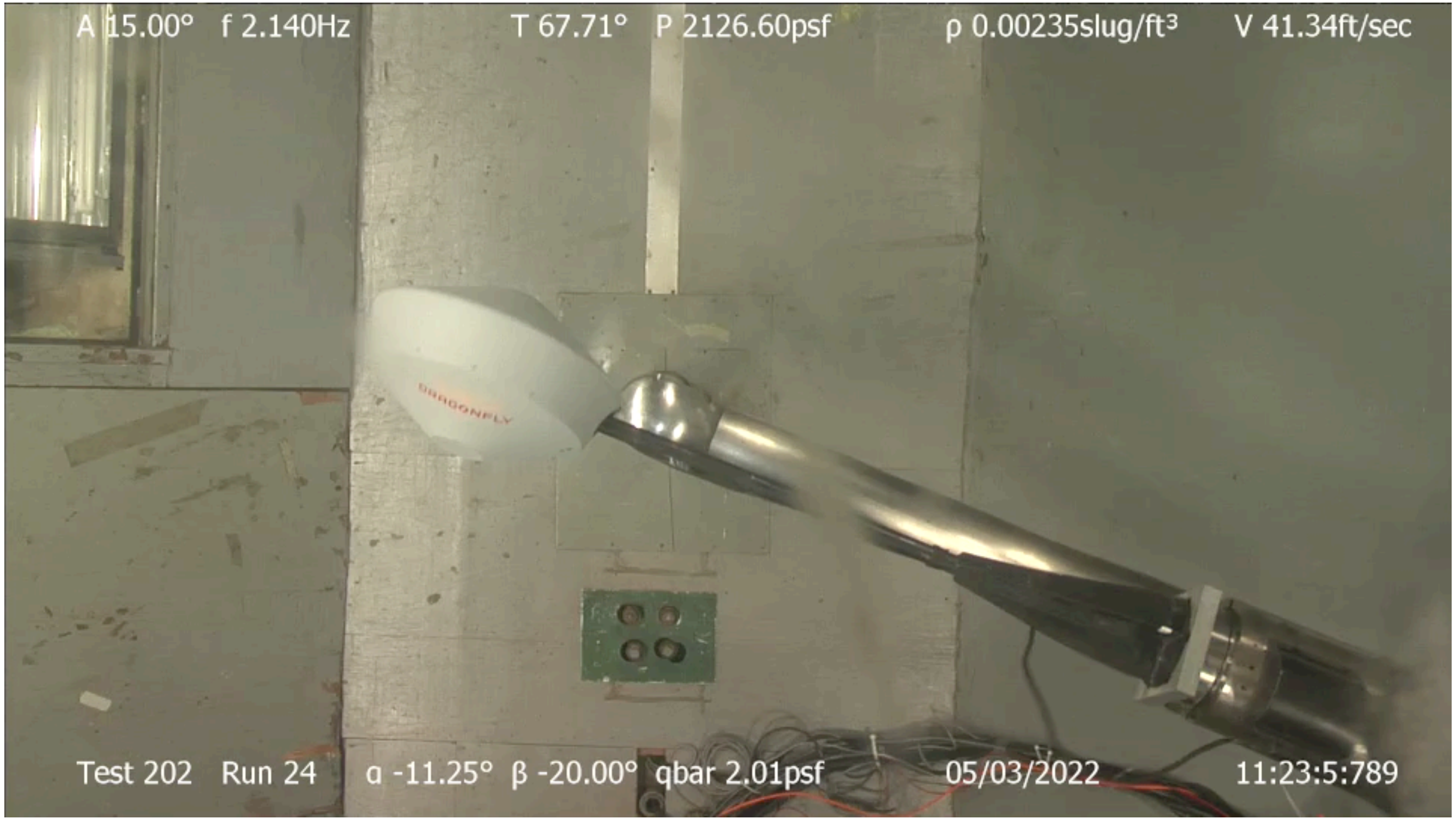


- **Typically, in design dispersions, the uncertainty in Cmq is assumed to be invariant with angle of attack**
- **However, using the large amounts data available through Free-flight CFD simulations, we can show that dispersions in effective damping are much lower at high angle-of-attack**
  - ➡ The reason for this is that unsteady fluctuations in pressure have less influence on the overall moment at large alpha
- **Based on this analysis, the project has deployed variable Cmq uncertainty, which in turn has improved predicted vehicle states at drogue mortar fire**

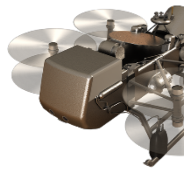


"Beta-decay Model"

- **Pitch damping is typically assumed to be a function of the angle of attack alone**
- **However, we know from experimental data that the pitch damping characteristics of a given vehicle can be strongly influenced by the sideslip angle ("beta"), particularly when that angle is large**
  - ➡ The project is currently working to develop a modified Cmq formulation which takes sideslip angle as an additional variable
  - ➡ Model uses new data gathered for Dragonfly in the Langley 12' wind tunnel



Poster Plugs!



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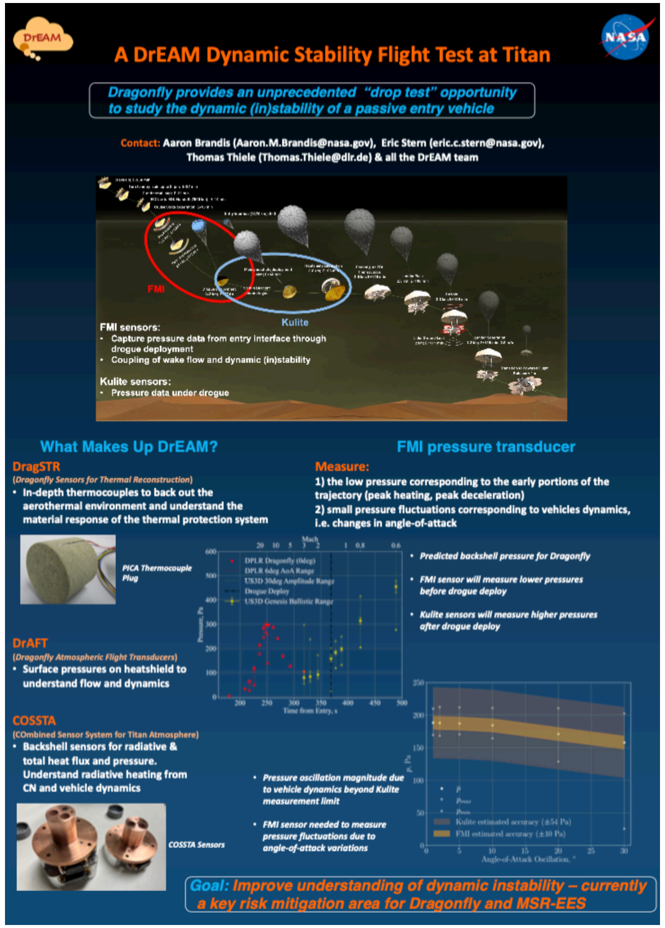

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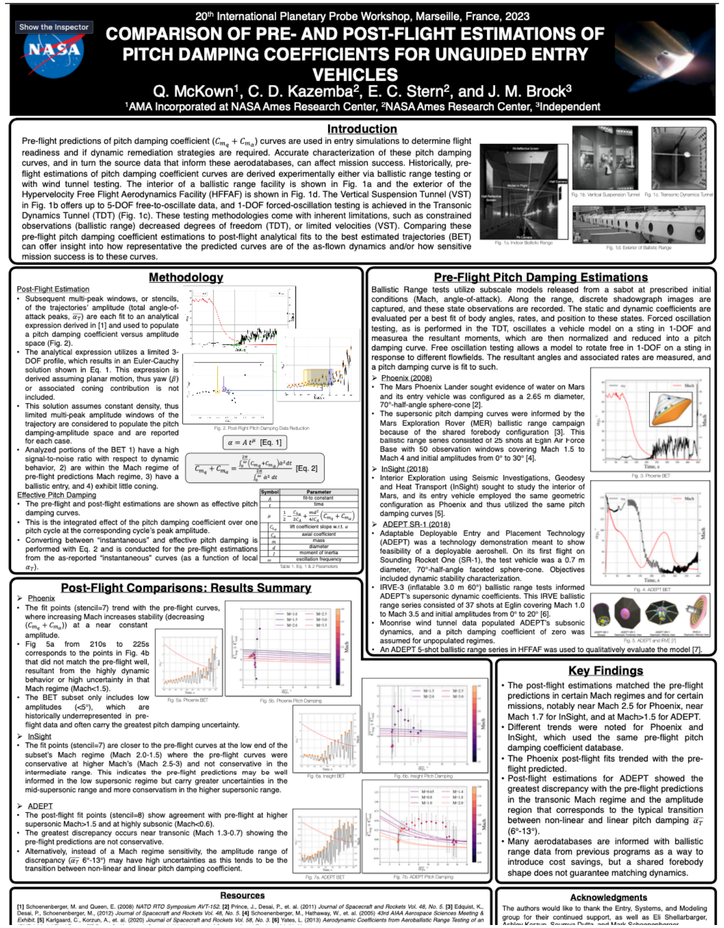

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