



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

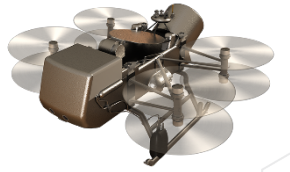
Dragonfly: A Case Study in Dynamic Stability Characterization

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...

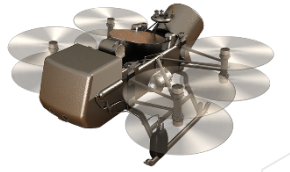


- Typical blunt-body entry probes are *dynamically* unstable at low-supersonic to transonic Mach numbers
 - Meaning: if left to their own devices, pitch and yaw oscillations will grow over time, eventually causing the capsule to tumble, likely leading to a catastrophic loss of mission



- 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

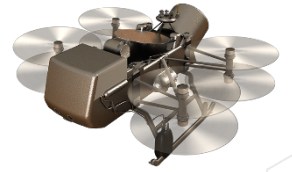
“See-em-cue” is a four-letter word...



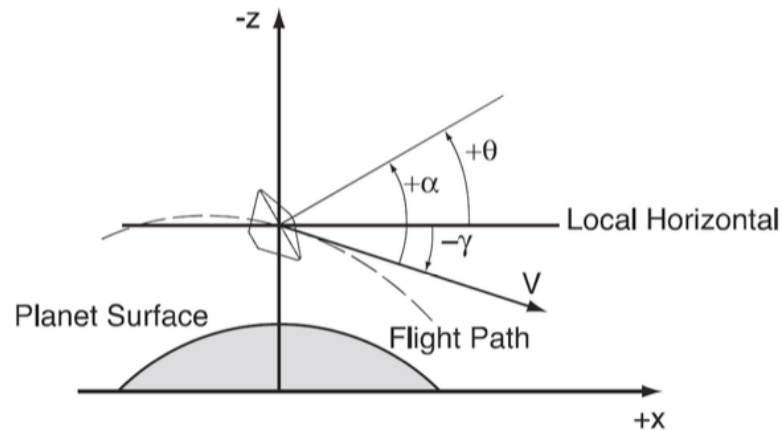
- **Whether due to the ConOps of a particular mission (e.g. Dragonfly or MSR-EES), or cost constraints, many missions must fly a fully passive entry and descent**
 - ➔ In these cases, accurate characterization of the dynamic performance of the probe is critical to closing the EDL phase design
- **Unfortunately, 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**

“See-em-cue” is a four-letter word...



- 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*)



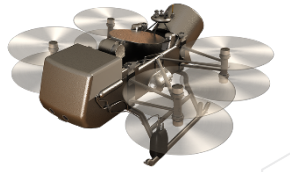
$$\ddot{\alpha} - \frac{\rho V_{\infty} S d^2}{4I} (C_{mq} + C_{m_{\dot{\alpha}}}) \dot{\alpha} - \frac{\rho V_{\infty}^2 S d}{2I} C_{m_{\alpha}} \alpha = 0$$

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

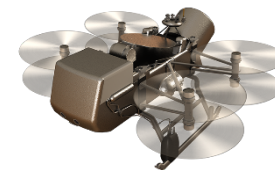
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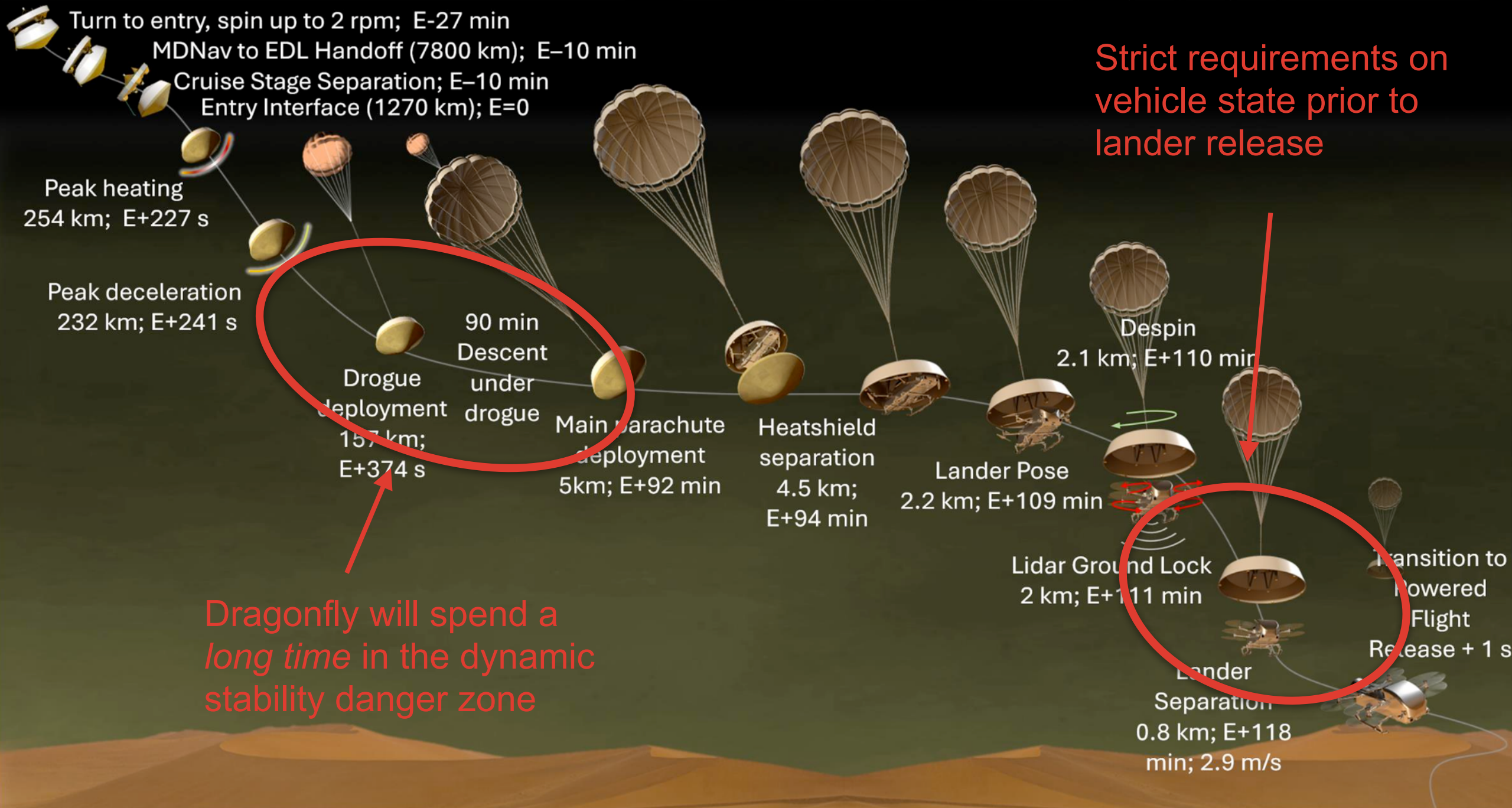
- **HOWEVER**, though it may appear like another aerodynamic coefficient, it is fundamentally different than the well-known parameters like lift and drag
 - C_{mq} is simply a byproduct of the Taylor series expansion used to derive the equations of motion, and should be thought of as a useful heuristic,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

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

➔ **C_{mq} 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**

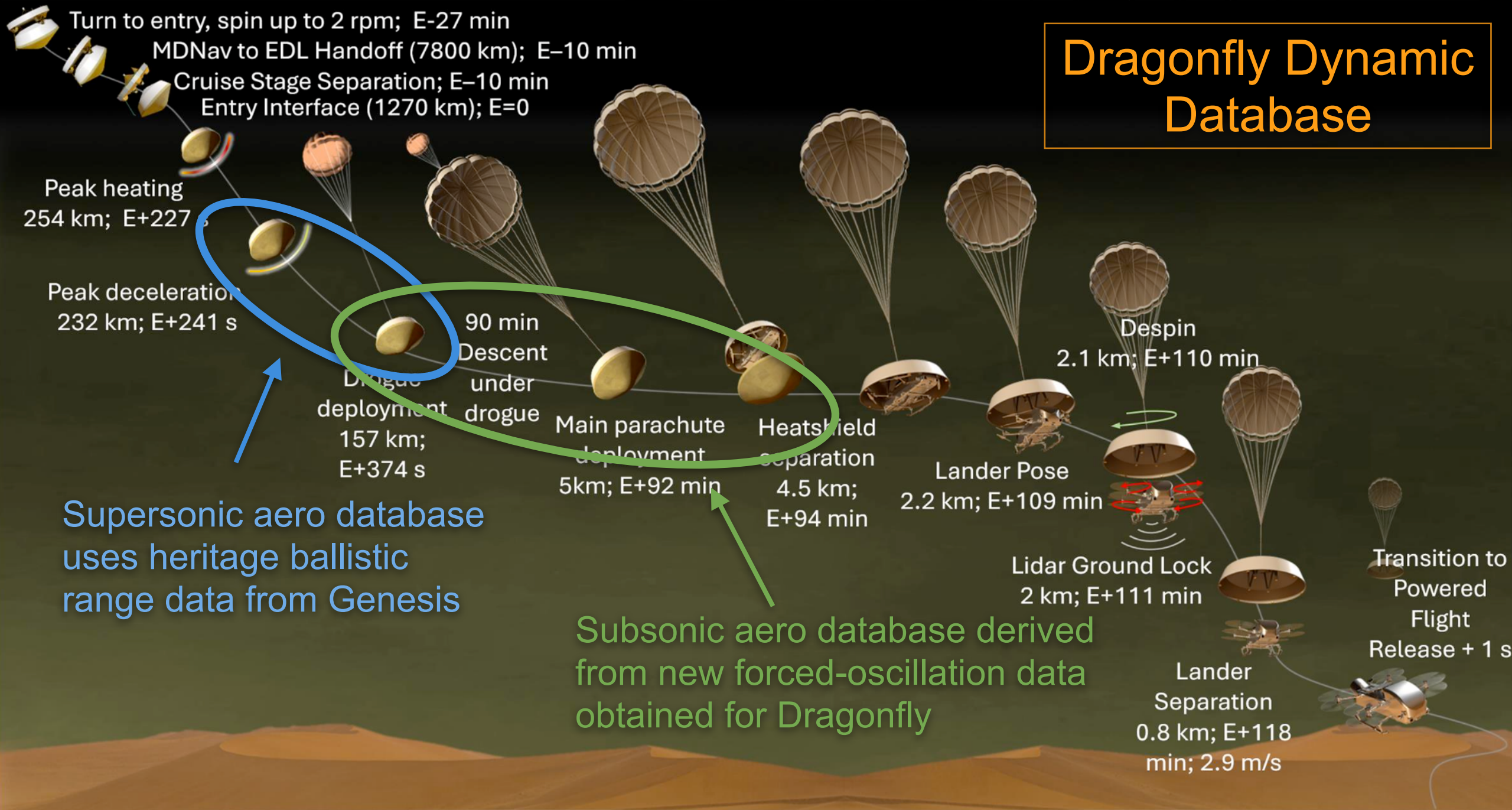


Dragonfly: A Challenging Mission Profile for Dynamic Stability

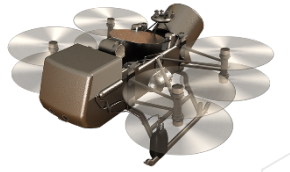


** for more on the ConOps, see poster by A. Pensado

Dragonfly Dynamic Database

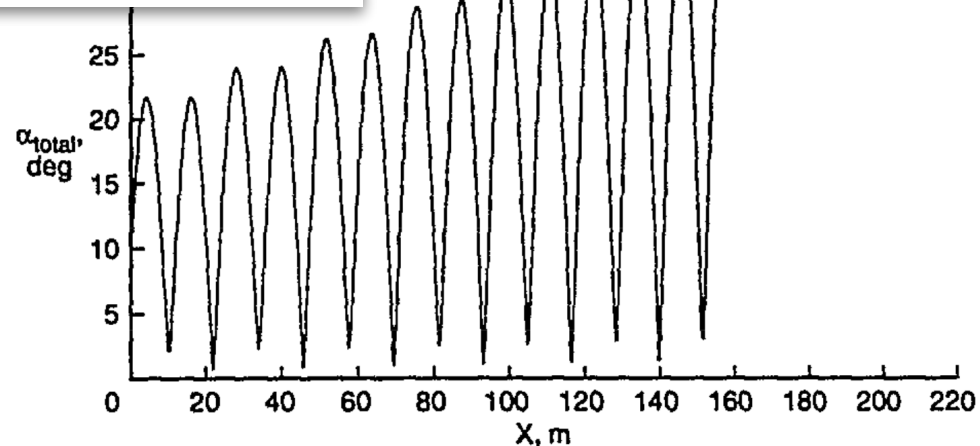


Genesis SRC Heritage



- 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

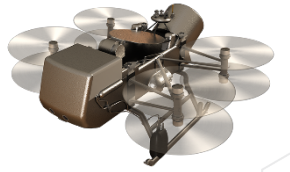
Although no limit cycles were found experimentally, the aerodynamics for this configuration suggest that potential limit cycles exist. Because the pitch damping is a function of Mach number, there will be a different limit cycle amplitude for each Mach number. The limit cycle amplitude can be estimated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



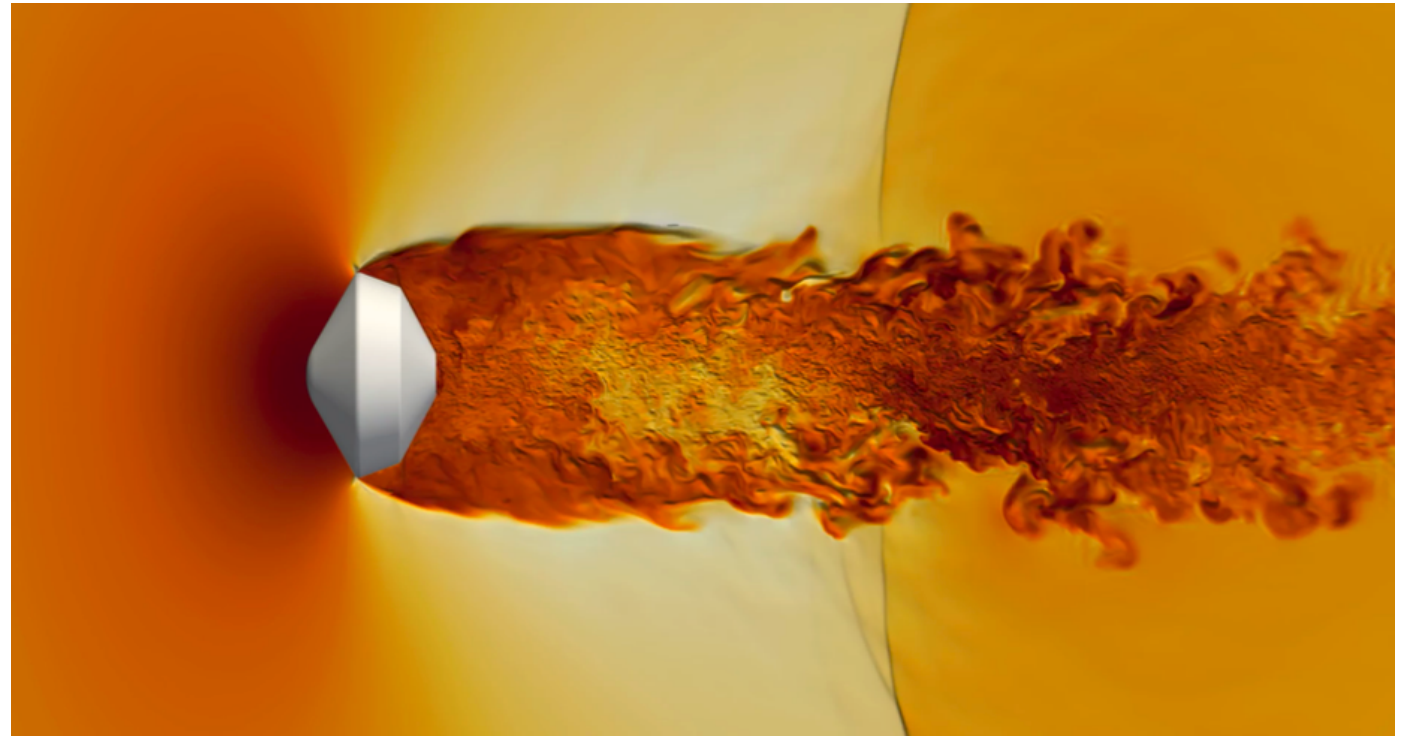
a. Mach 1.4 Average ($M = 1.88$ to 0.99).



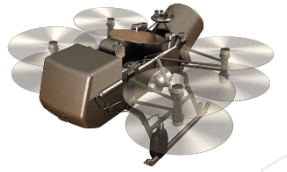
“Sharpening the Pencil...”



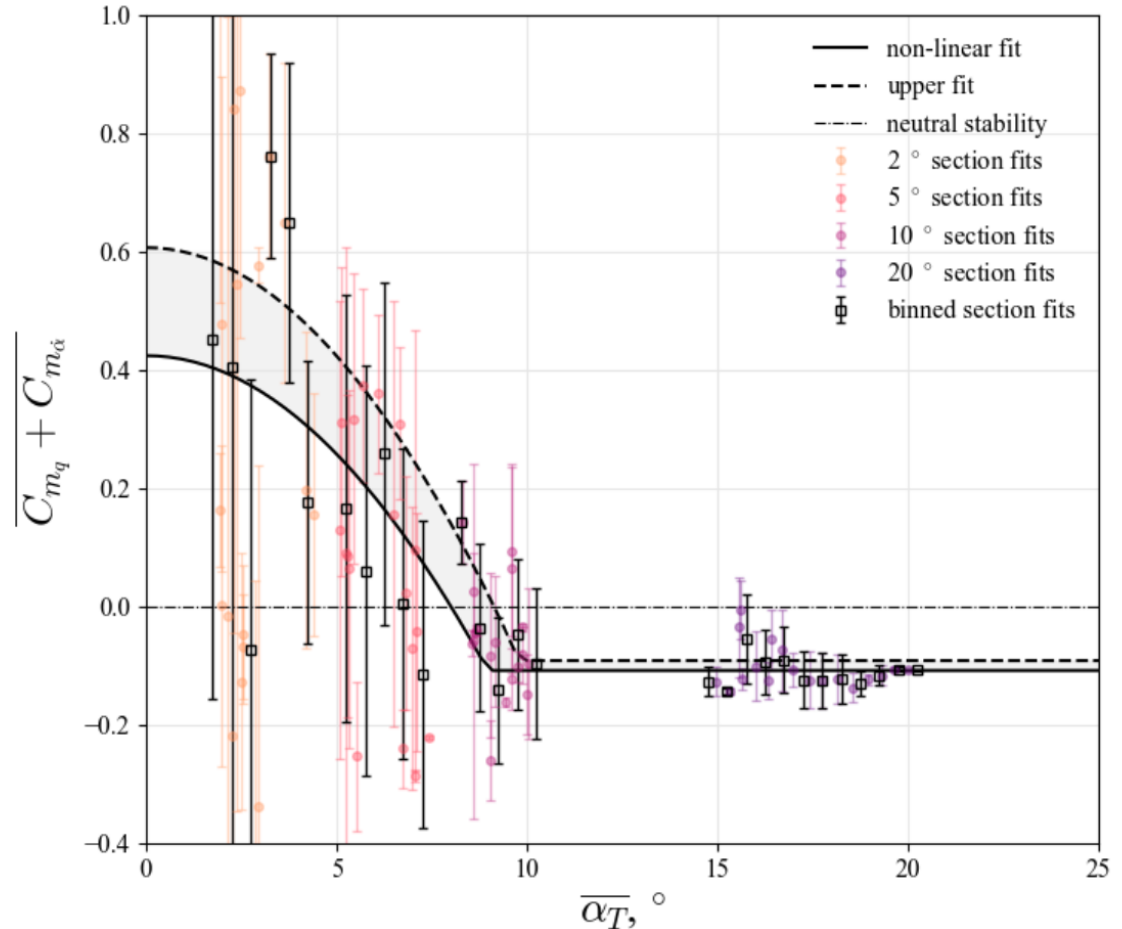
- Given the known characteristics of the Dragonfly aeroshell, and the stringent requirement levied on its performance, the EDL team has had refine the dynamic stability analysis in order to close the design
- Here we highlight two such refinements:
 - Reduction in pitch damping uncertainties using FF-CFD
 - Knock-down factor for pitch damping when at non-zero sideslip angle



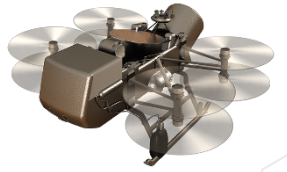
Alpha-dependent Uncertainty



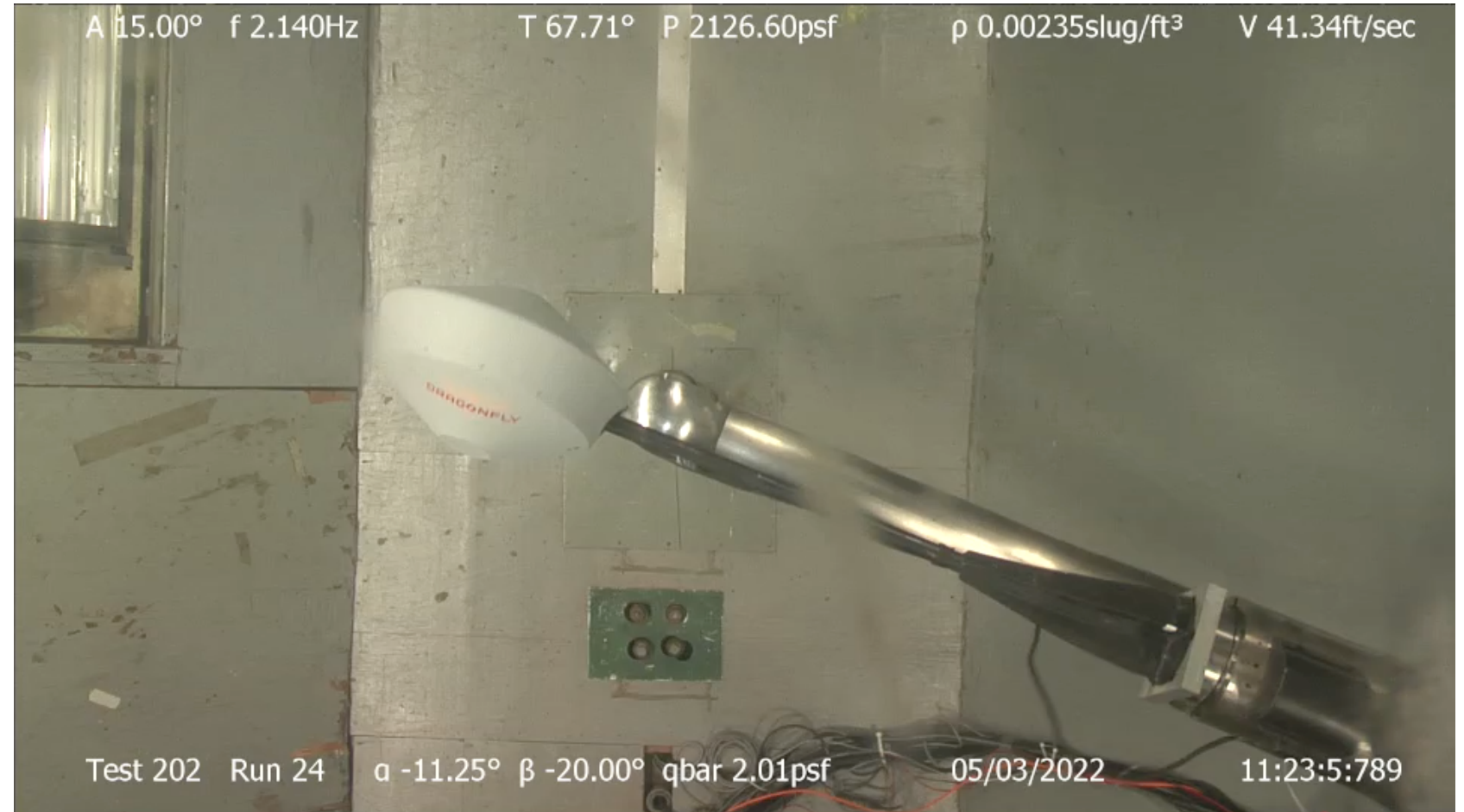
- Typically, in design dispersions, the uncertainty in C_{mq} is assumed to be invariant with angle of attack
- However, using the large amounts data available through Free-flight CFD simulations, we can show that dispersions in effective damping are much lower at high angle-of-attack
 - ➔ The reason for this is that unsteady fluctuations in pressure have less influence on the overall moment at large α
- Based on this analysis, the project has deployed variable C_{mq} 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



Alejandro Pensado et al.

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COMPARISON OF PRE- AND POST-FLIGHT ESTIMATES OF PITCH DAMPING COEFFICIENTS FOR UNGUIDED ENTRY VEHICLES

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Introduction

Pre-flight predictions of pitch damping coefficient ($C_{m\dot{\alpha}}$ & $C_{m\ddot{\alpha}}$) values are used in entry simulations to determine flight readiness and if dynamic remediation strategies are required. Accurate characterization of these parameters is difficult, and in turn the source data that inform these aerobalistics, can affect mission success. Historically, pre-flight estimates of pitch damping and pitch damping coefficients are derived experimentally using ballistic range testing or with wind tunnel testing. The interior of a ballistic range facility is shown in Fig. 1a and the exterior of the Hypervelocity Free Flight Aerodynamics Facility (HFAF) is shown in Fig. 1d. The Vertical Suspension Tunnel (VST) in Fig. 1b is used to 3-DOF free-to-oscillate data, and 1+DOF forced-oscillation testing is achieved in the Transonic Dynamics Tunnel (TDT) in Fig. 1c. These testing methodologies come with inherent limitations, such as constrained observables (ballistic range) decreased degrees of freedom (TDT), or limited velocities (VST). Comparing these pre-flight estimates with post-flight estimates and pitch damping analysis fits to the best estimated trajectories (BET) can offer insight into how representative the predicted curves are of the as-flown dynamics and/or how sensitive mission success is to these curves.

Methodology

Post-Flight Estimation

- Subsequent to mission success, or stencils, of the trajectories' amplitude (total angle-of-attack) (α) are each built to fit an analytical expression derived in [1] and used to populate a pitch damping coefficient versus amplitude curve (Fig. 2).

- The analytical expression utilizes a limited 3-DOF pre-flight results in an Euler-Cone (EC) shown in Fig. 1. This expression is derived assuming stator motion, but yaw (ψ) or associated coning contribution is not included.
- This solution assumes constant density, thus limited multi-amplitude windows of the trajectory are considered to populate the pitch damping-amplitude space and are reported as such in each conical region.

- Analysis portions of the BET (1) have a high pre-to-rise ratio and are due to dynamic behavior, 2) are within the Mach regime of pre-flight predictions, 3) have a ballistic entry and 4) exhibit little coning.

Effective Pitch Damping

The pre-flight and post-flight estimates are shown as effective pitch damping curves.

- The BET integrated effect of the pitch damping coefficient over one pitch cycle at the corresponding cyclic peak amplitude.

- Correlating between the pre-flight and effective pitch damping curves (Fig. 2) and is conducted for the pre-flight estimates from the as-reported "instantaneous" curves (as a function of local

Pre-Flight Pitch Estimation Results

Ballistic Range tests utilize subscale models released from a sabot at prescribed initial conditions (Mach, angle-of-attack). Along the range, accurate shadowgraph images are captured, and these state observables are recorded. The static and dynamic coefficients evaluated per a best fit of body angles, rates, and position to these states. Force coefficient testing, as is performed in the TDT, oscillates a vehicle model on a spring in 1+DOF measures the resultant moments, which are then normalized and reduced to a single damping curve. Free oscillation testing allows a model to rotate free in 1+DOF on a single response to different flowfields. The resultant angles and associated rates are measured, a pitch damping curve is fit to such.

Phoenix (2008)

- The Mars Phoenix Lander sought evidence of water on Mars and the Mars Reconnaissance Orbiter (MRO) was used to study the interior of Mars.

- The supersonic pitch damping curves were informed by the Mars Exploration Rover (MER) ballistic range campaign because of the shared torbody configuration [3].

- This ballistic range series consisted of 20 shots at 8-gn at Egn nose base with 50 mm diameter windows covering Mach 1.5 to Mach 4 and 1-inch ballistics sphere-cone. Objectives included dynamic stability characterization.

Insight (2018)

- Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) sought to study the interior of Mars, and its entry vehicle utilized the same geometric configuration as Phoenix and thus utilized the same pitch damping curves [5].

ADAPT (RS) (2018)

- Adaptive-Optimizable Entry and Placement Technology (ADAPT) was a technology demonstration meant to show how to design an entry vehicle.

- On sounding Rocket One (SR-1), the test vehicle was a 0.7 m diameter, 70-half-angle tapered sphere-cone. Objectives included dynamic stability characterization.

- IRVE-3 inflatable 3.0 m diameter large target tests informed ADAPT's supersonic dynamic coefficients. This IRVE ballistic range series consisted of 37 shots at Egn covering Mach 1.0 to Mach 3.5 and 1-inch ballistics sphere-cone [6].

- Moonrise wind tunnel data populated ADAPT's subsonic dynamic coefficients. The wind tunnel was a 1.5 m diameter, 70-half-angle tapered sphere-cone. Objectives included dynamic stability characterization.

- An ADAPT 5-inch ballistics range series in HFAF was used to qualify the pre-flight estimates [7].

Post-Flight Comparisons: Results Summary

Phoenix

- The IRVE (stencil-7) trend with the pre-flight curves, where increasing Mach increases stability decreasing ($C_{m\dot{\alpha}}$ & $C_{m\ddot{\alpha}}$) at a near constant

- Fig. 5a from 210s to 225s did not match the pre-flight test resultant from the high dynamic behavior of coning at Mach regime (Mach=5).

- The BET below only indicates low amplitudes (<5°), which are historically underrepresented in pre-flight data and often carry the greatest pitch damping uncertainty.

Insight

- The IRVE (stencil-7) coners closer to the pre-flight curves at the low end of the subsonic Mach regime (Mach 2-5) where the pre-flight curves were conservative at higher Mach (Mach 2-5) and not conservative in the intermediate-range. This indicates the pre-flight predictions may be well informed in the low supersonic regime but carry greater uncertainty in the mid-supersonic range and more conservative in the higher supersonic range.

ADAPT

- The post-flight pitch curves (stencil-8) show agreement with pre-flight at higher supersonic Mach 3 and 4, and agree with pre-flight at lower supersonic Mach 2 and 3.

- The greatest discrepancy occurs near transonic (Mach 1.3-1.7) showing the pre-flight estimates are not conservative.

- Alternatively, instead of a Mach regime sensitivity, the amplitude range of discrepancy (< 6°-13°) may have high uncertainties as this tends to be the transition between near-linear and linear pitch damping coefficient.

Key Findings

- The post-flight estimates matched the pre-flight predictions in certain Mach regimes and for certain scenarios, notably near Mach 2-5 for Phoenix, near Mach 1-7 for InSight, and near Mach 1-5 for ADAPT.

- Different trends were noted for Phoenix and InSight, which used the same pre-flight pitch damping coefficient database.

- The Phoenix post-flight fits tended with the pre-flight predicted.

- Post-flight estimations for ADAPT showed the greatest discrepancy with the pre-flight predictions in the transonic Mach regime and the amplitude region that corresponds to the typical transition between non-linear and linear pitch damping (< 6°-13°).

- Many aerobalistics are informed as ballistics range data from previous programs as a way to reduce cost savings, but a shared forced response does not guarantee matching dynamics.

Dragonfly Entry and Descent Flight Mechanics Modeling and Analysis for Mission PDR



Abstract ID: 19

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Introduction

Dragonfly is a New Frontiers Program mission led by John Hopkins Applied Physics Laboratory (APL) which will deliver a nominal lander on Saturn's moon, Titan (1). Relative to other missions, Dragonfly represents a significant increase in mission Preliminary Design Review (PDR) (2). This study presents the updated design and analysis performed for the Dragonfly mission PDR. The entry vehicle analysis includes the phases of entry and descent prior to cruise stage separation until lander separation. These results reflects the robustness of the overall entry sequence as assessed through a Monte Carlo uncertainty analysis as well as sensitivity analysis of the

Concept of Operations

The POST2 simulation begins 10 prior to cruise stage separation. The entry vehicle is separated from the cruise stage using a spring mechanism and is designed to eliminate the drag field moment risk. After entry vehicle separation, the vehicle is subjected to a 10 second coast period. The drag parachute deploys during a 5 s window after reaching a second acceleration, using a smart trigger to minimize the main parachute deployment risk. The vehicle is designed to ensure the vehicle does not become unstable and that the drag parachute opening loads are within requirements. The vehicle continues until the dragline loss on the main parachute is depleted. The parachutes are inflated 10 s after the main parachute deploys. The lander is lowered into its "pneup" position after main parachute deployment. By 800 m the vertical descent is completed and the lander is released. The simulation continues to track all pertinent bodies to their respective conclusions.

Modeling and Simulation

The integrated trajectory is simulated and analyzed using Program to Optimize Simulated Trajectories II (POST2) (3). Models are provided by interdisciplinary teams from APL, the Air Population Laboratory (JPL), NASA Ames Research Center (ARC), NASA Langley Research Center (APL), Lockheed Martin (LM), and University of Central Florida (UCF). Figure 1 shows an overview of the models and the corresponding model owners.

During the design analysis cycle, models are incorporated and combined in POST2, which enables overall trajectory performance assessment. The integrated trajectory is provided to the development team to support the subsystem design process. This model will be refined as the design matures during Phase C and hardware is built.

Fig. 2 The concept of operations of the entry vehicle from pre-entry interface to touchdown.

Preparation for Power Flight

One of the novel challenges for the Dragonfly mission is the lander release sequence. This section presents the preparation for power flight modeling efforts for mission PDR. The lander is lowered into the "pneup" position while situated to the backshell to control clearance issues while the rotors are turned on. As the vehicle is descending, the rotors are turned on to control the lander's y-axis rate (6). The lander release trigger is initiated at 1000 m to meet optimal flight conditions for the lander to separate. Further logic is included in the release mechanism to ensure the lander is released no lower than 500 m (Fig. 3).

Due to the complexity of the dynamics, this problem is being modeled concurrently by the POST2 EDL simulation, the APL Mobility simulation, and the LM ADAMS simulation. Fig. 4 shows the model integration against an aerodynamic (APL) for the entry vehicle and the aerodynamic (APL) and a Dragline Controller provided by APL to ensure consistency.

Vehicle and Parachute Design

The entry vehicle design, a 4.5 m 60° half-angle sphere cone, is based on the Gemini Sample Return Capsule (GSRC) and was modified to meet the Dragonfly mission's unique requirements.

This work applied the aerodynamic from GSRC. The GSRC flow molecular and hypersonic data was adjusted using computational fluid dynamics (CFD) analysis. Relative to the previous design, the data collected from the Langley Transonic Dynamics Tunnel (TDT) has been incorporated to assess the aerodynamic in the geometry of the capsule, there are dynamic stability changes during the transonic regime that require further investigation.

APL PDR, the EDL vehicle used a 5.4 m Disk Drag Parachute (DDP) design. The DDP parachute and 16.5 m DDPB main parachute were used model as separate, six-degrees-of freedom rigid bodies. The drag parachute is nose deployed. The deployment, inflation, and opening loads are defined by the model provided by the parachute design team. The models are expected to update with upcoming drag data.

The main chute canopy is expanded to be updated to a Kingdon canopy.

Fig. 4 Geometry of the dragline and main parachute (not to scale)

Fig. 3 Dragonfly lander coordinate system (see: APL)

Fig. 4 Spin control for a dispend of trajectories

Fig. 5 Overview of the lander dynamics integration prior to separation

Fig. 6 Overview of the lander dynamics integration prior to separation

Fig. 7 Dragonfly lander coordinate system (see: APL)

Fig. 8 Spin control for a dispend of trajectories

Fig. 9 Overview of the lander dynamics integration prior to separation

Fig. 10 Overview of the lander dynamics integration prior to separation

Fig. 11 Overview of the lander dynamics integration prior to separation

Fig. 12 Overview of the lander dynamics integration prior to separation

Fig. 13 Overview of the lander dynamics integration prior to separation

Fig. 14 Overview of the lander dynamics integration prior to separation

