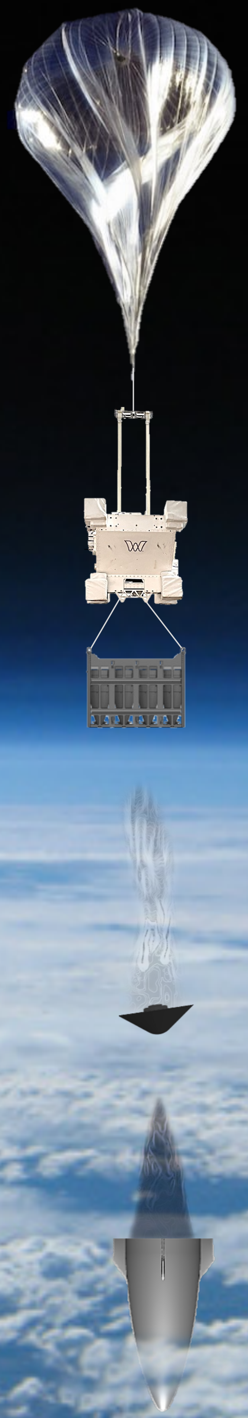
NASA

SPEED

Design and Technology Maturation of the Stratospheric Projectile Experiment of Entry Dynamics



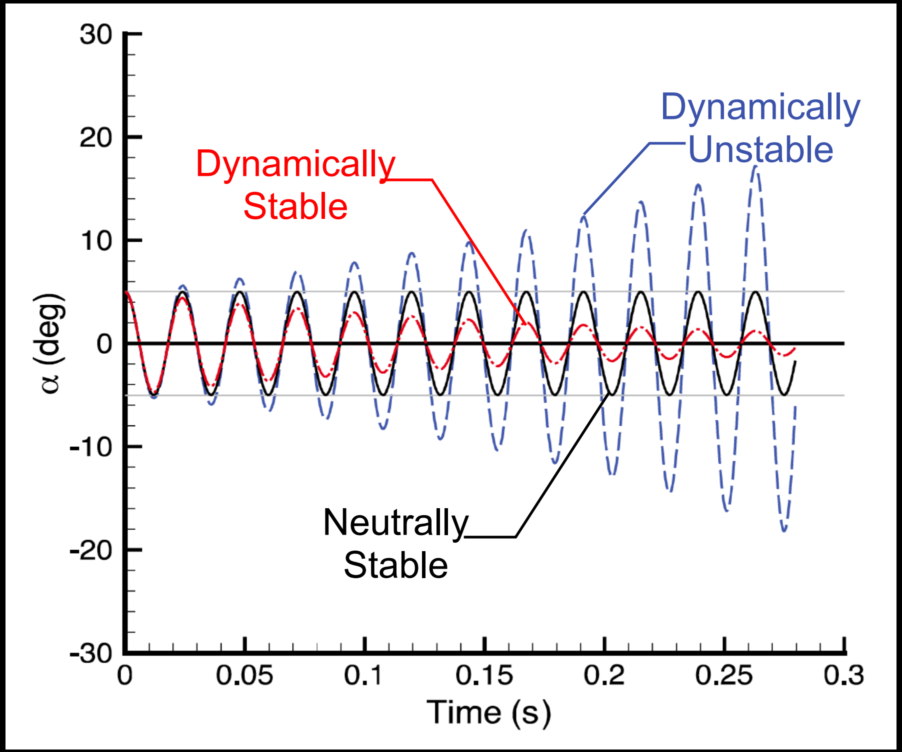
EDL Summer Seminar Series

August 5th, 2024

Cole Kazemba
Ben Libben
Hannah Alpert
Quincy McKown
Mike Wilder
Greg Swanson

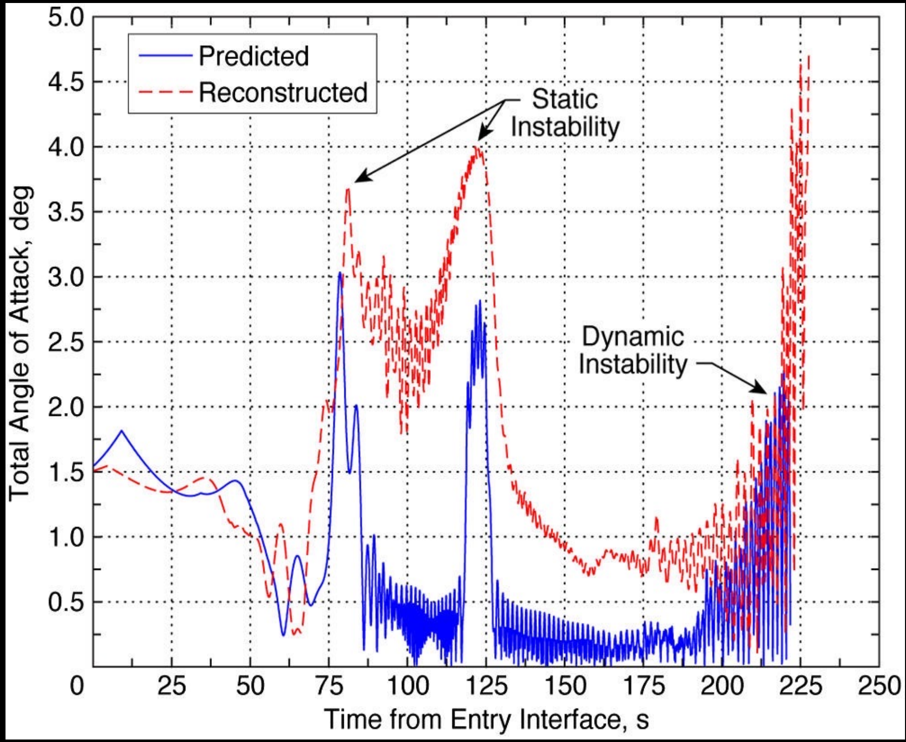
Dynamic Stability

Schoenenberger RTO-MP-AVT-152B



Genesis Capsule

Mars Phoenix Lander (Desai, 2011)



Not Pictured: Tumbling OSIRIS-REx

What We Know

- Fundamental understanding of dynamic stability is lacking
    - Problem is both highly nonlinear and stochastic

- To date, have gotten by with:
    - Linearized in the Equations of Motion of a *very* non-linear phenomenon
    - Basic design heuristics
    - Reaction Control Systems (RCS)

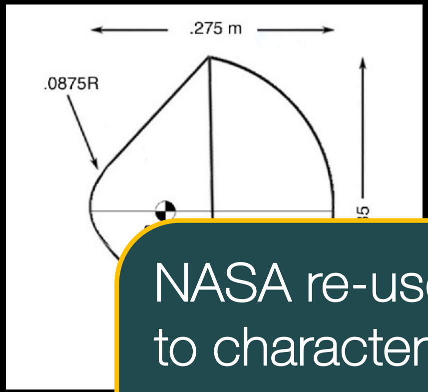
- All of the nonlinearity and complex physics that contribute to a capsule's tendency to be dynamically (un)stable is smashed into a single parameter: The "pitch damping sum"

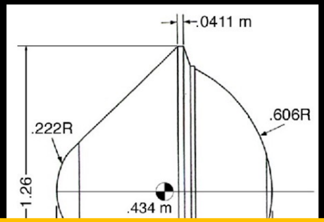
$$\ddot{\alpha} - \frac{\rho V S}{2m}\left(-C_{L_\alpha} + \frac{md^2}{2I}\boxed{\left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)}\right)\dot{\alpha} - \frac{\rho V^2 S d}{2I} C_{m_\alpha}\alpha = 0$$

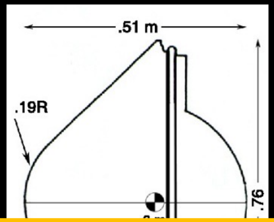
- Dynamic stability of a capsule is driven primarily by interactions between the wake and vehicle shape:
    - Forebody shape driven by need to manage entry heating with a blunt shape
    - Backshell shape is typically governed by packaging considerations for the payload within

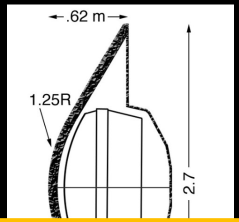
Ugly Ducklings

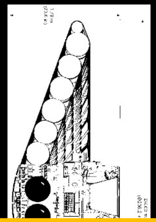
Generally *More* Dynamically Stable

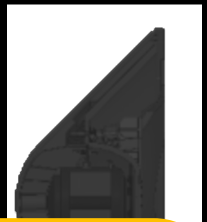








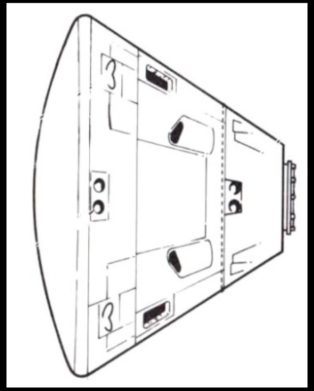




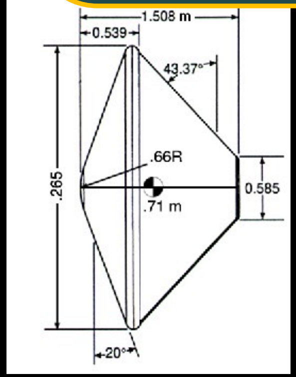
M

NASA re-uses capsules shapes so frequently because it is resource intensive to characterize the static and dynamic aerodynamics of new shapes.

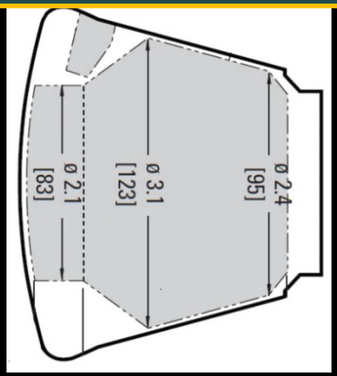
AND because we cannot pre-determine the dynamic stability of a backshell prior to an extensive test campaign



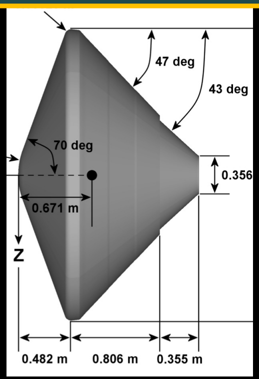
Apollo / Orion



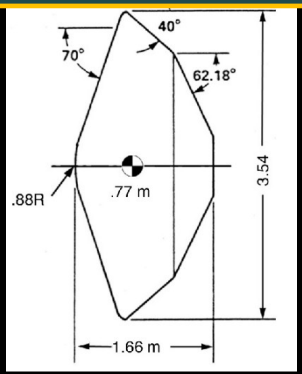
MER



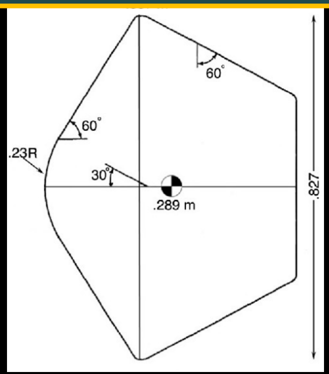
SpaceX Dragon



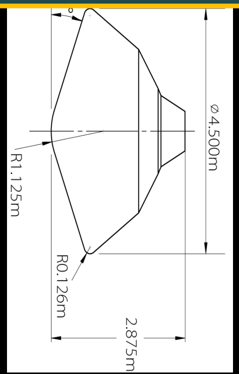
Phoenix / Insight



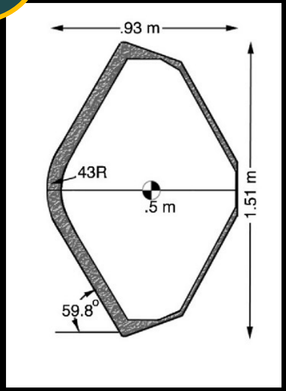
Viking



Stardust / OSIRIS-REx



MSL / M2020



Genesis / Dragonfly

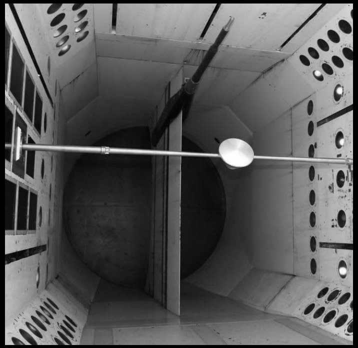
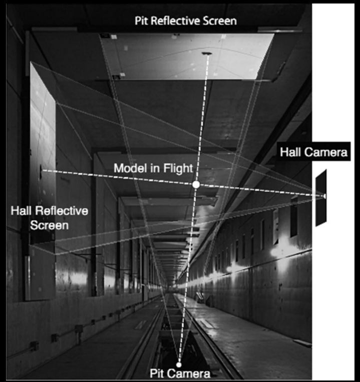
State of the Art

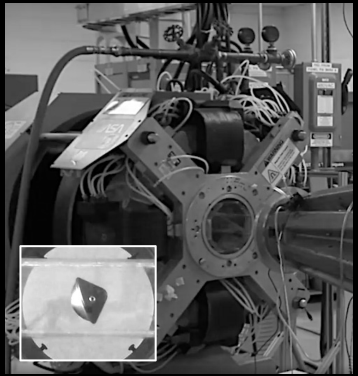
- Characterized exclusively via experiment: forced oscillation & ballistic range
    - These methods have a long pedigree of producing dynamic aero for missions
    - Each relies on a different data reduction approach, all of which differ from flight reconstruction methods
    - Little overlap between the attainable Mach numbers for the different methodologies.

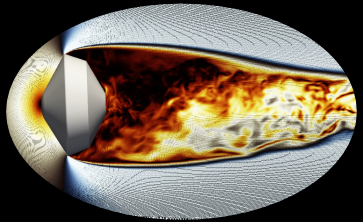
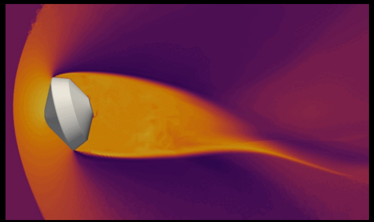
- Each test approach has one or more key weaknesses
    - Facility induced effects (e.g. stings)
    - Ability to match dynamic similitude and/or Reynolds Number
    - Sparse data for reconstruction and ADB development

- Number of available test facilities is limited:
    - NASA Ames HFFAF and Aberdeen are the only available ballistic range facilities
    - NASA LaRC TDT facility is for forced oscillation, but is booked out 1+ years
    - Subsonic MWST being developed NASA LaRC

- Validated computational methods are emerging
    - Suffer from not having great data to validate against



Desire for Flight Test

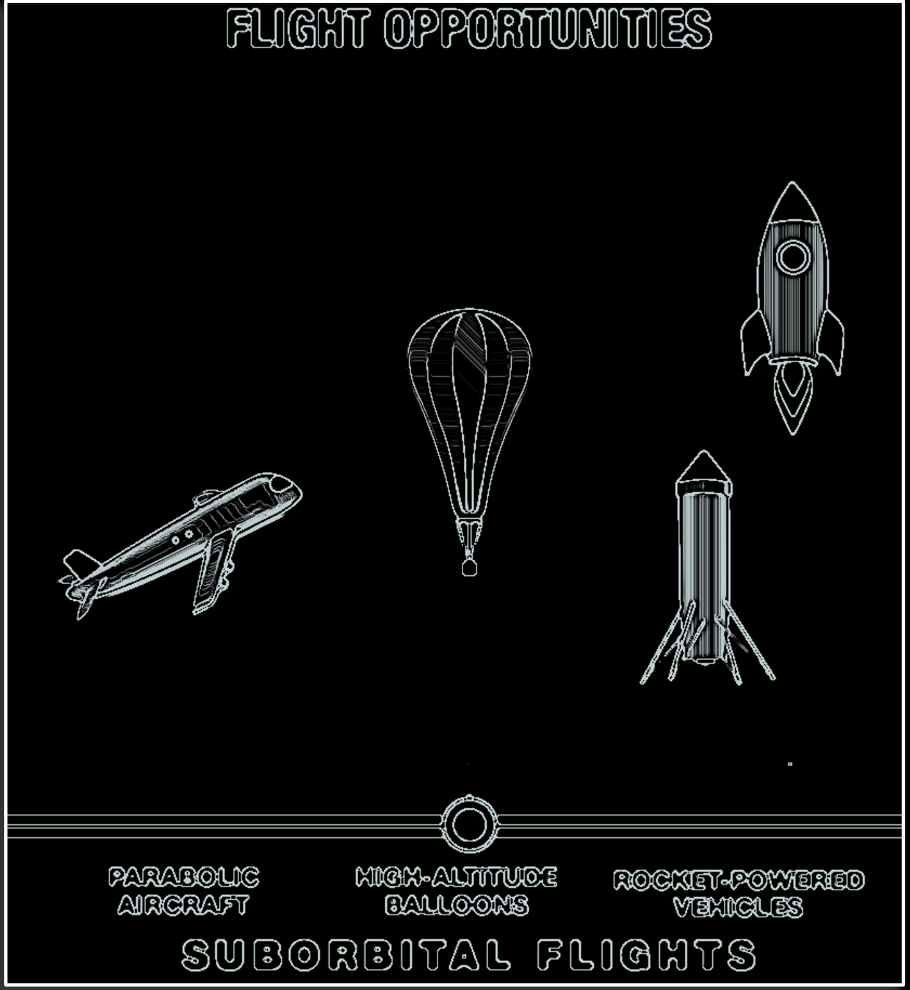
- Could ”another Spiderman” help bridge the gap between ground testing, CFD, & Flight?

- “Is there a *flight test* that can help this dynamic stability mess?”
  - Could provide an independent and flight-like data source for cross-comparison of results deduced from different test facilities and CFD to identify systematic test and data reduction effects
  - Could provide a data source with more quiescent initial conditions and more instrumentation (relative to BR) for use in validation of computational methods and their associated data reduction approach
  - Could serve as a standalone test platform tailorable to mission specific needs

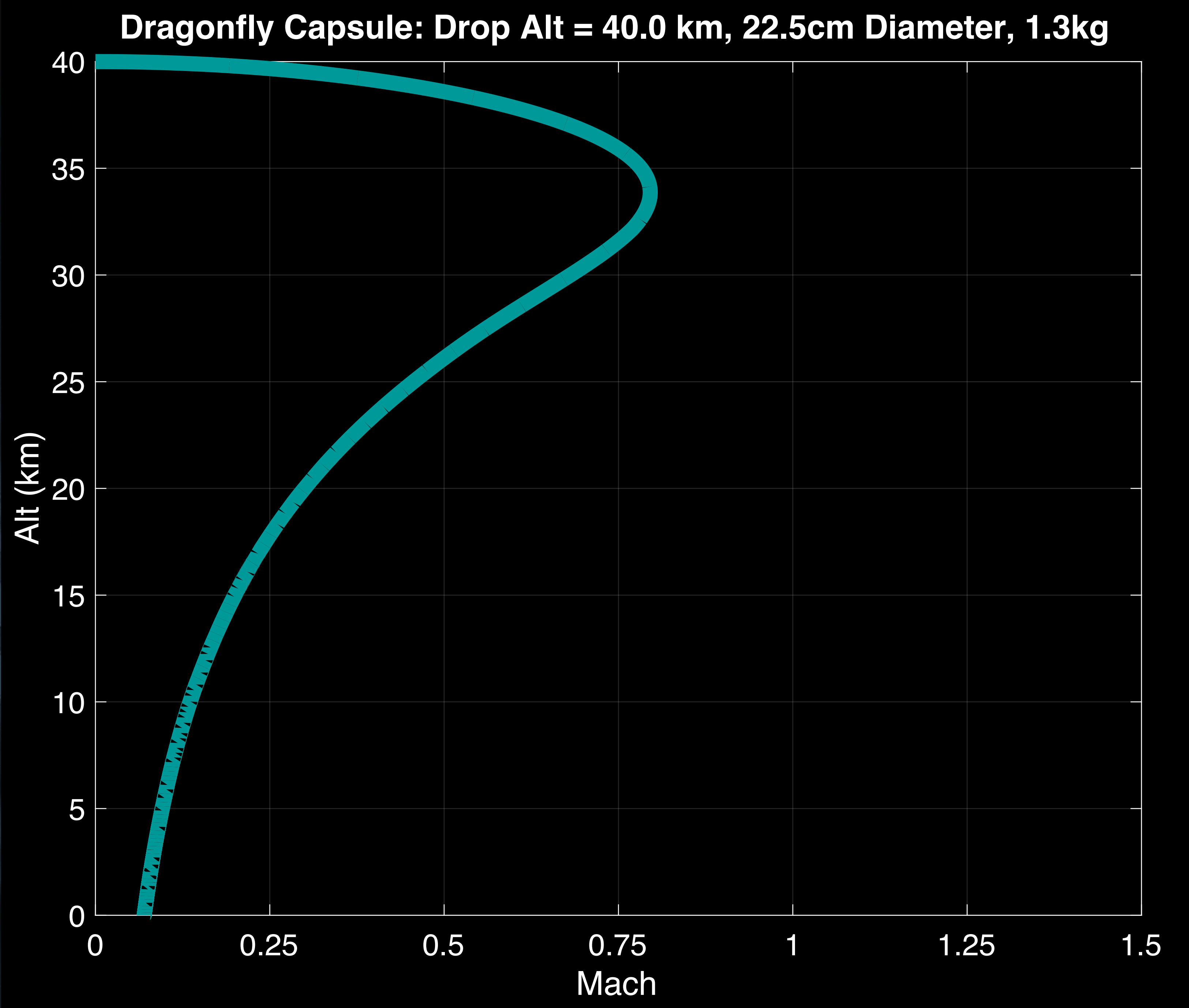
Flight Test Options Considered

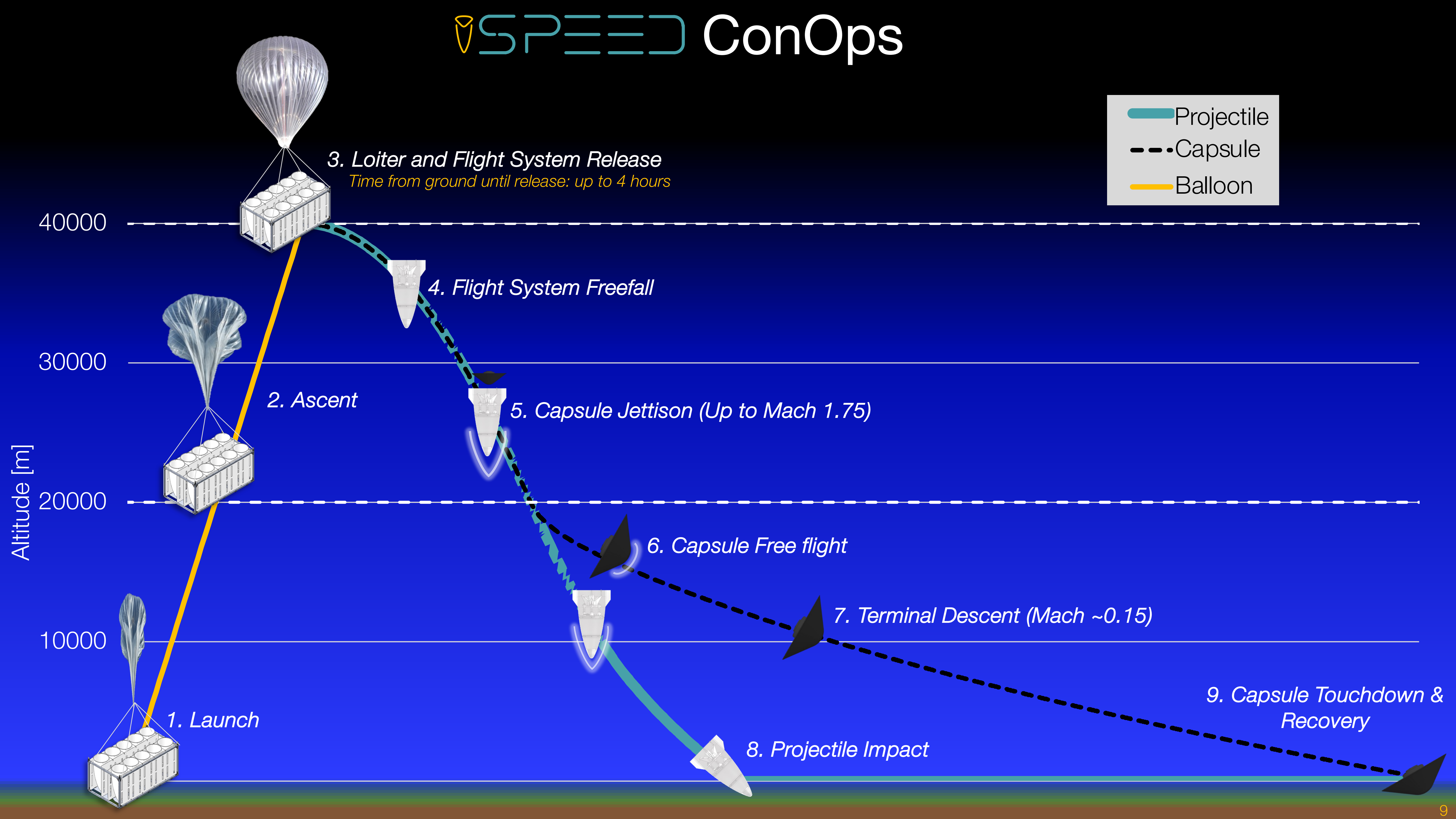
- High Altitude Drop test via Blue Origin New Shepard
  - Free flight capsules are unable to reach the Mach number **and** match dynamic similitude based on achievable initial conditions
- Sounding Rocket
  - Cost, Complexity, and singular data point do not provide a justifiable use case for mission validation or science purposes
- High Altitude Drop test via Balloon

Stratospheric balloon drop tests can provide the most compelling technical solution for the problem while also being cost competitive to existing ground test facilities…Requires ***one small innovation***

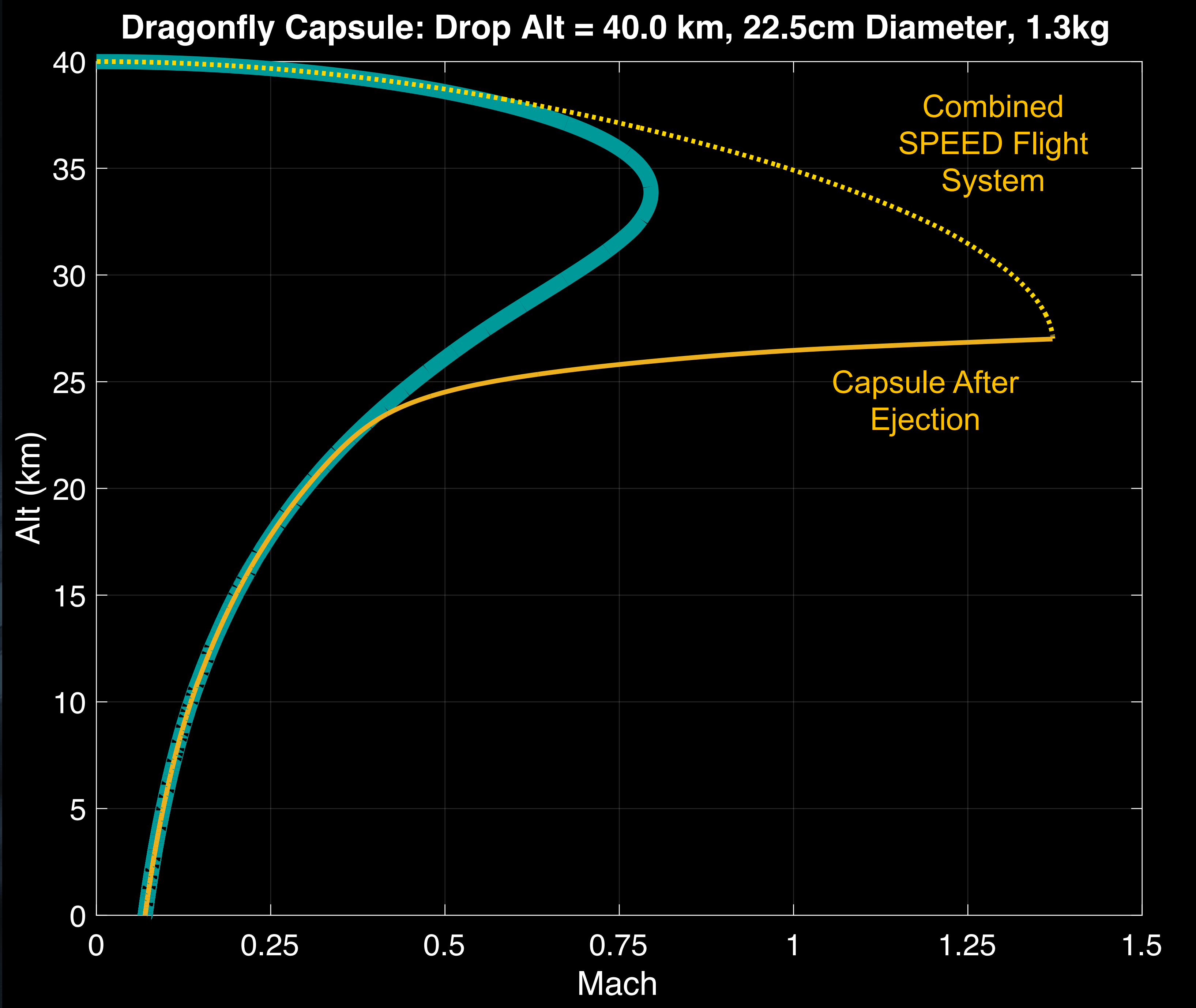



One small
Innovation

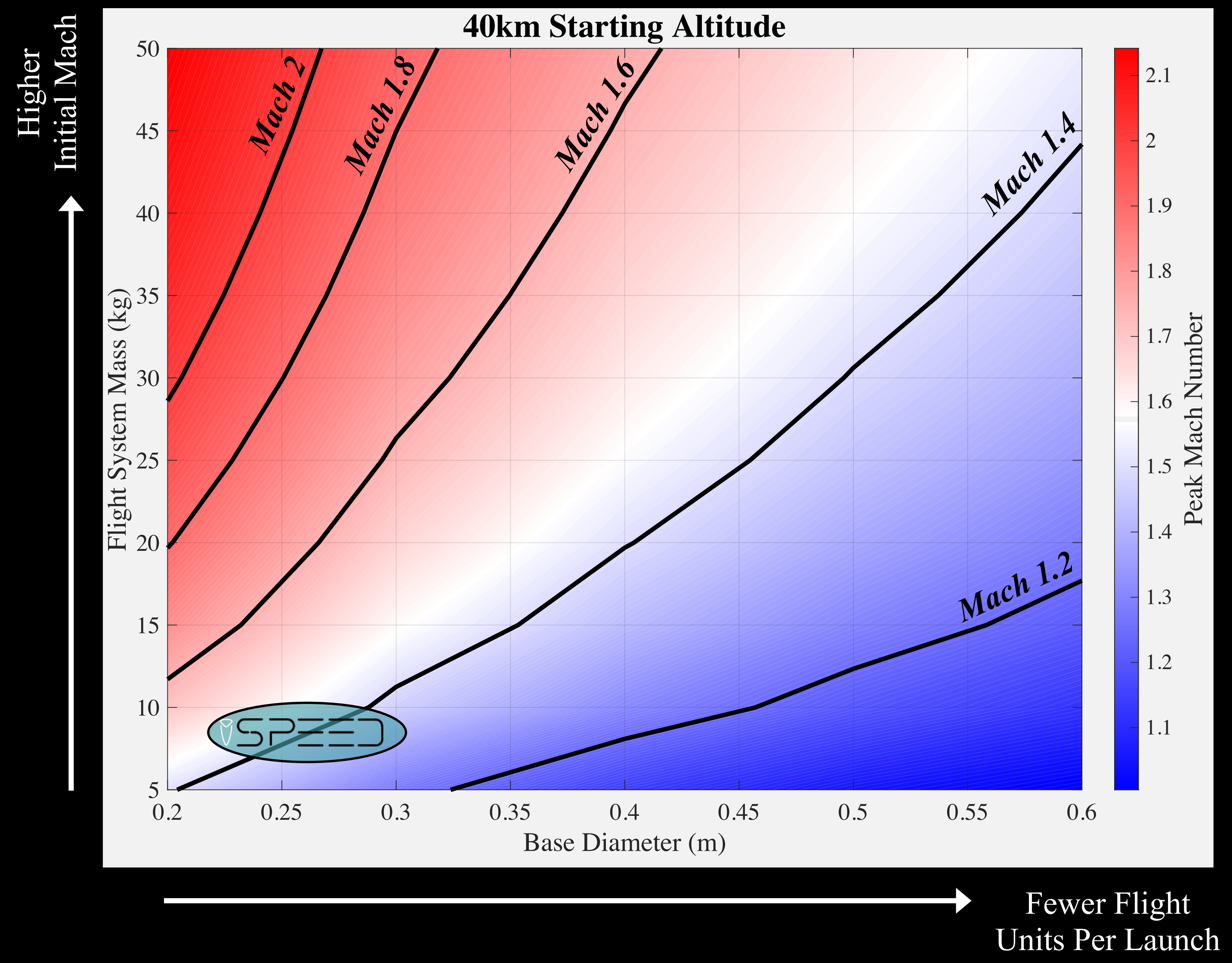

Dragonfly Capsule: Drop Alt = 40.0 km, 22.5cm Diameter, 1.3kg
40
35
30
25
20
15
10
5
0
Alt (km)
0
0.25
0.5
0.75
1
1.25
1.5
Mach

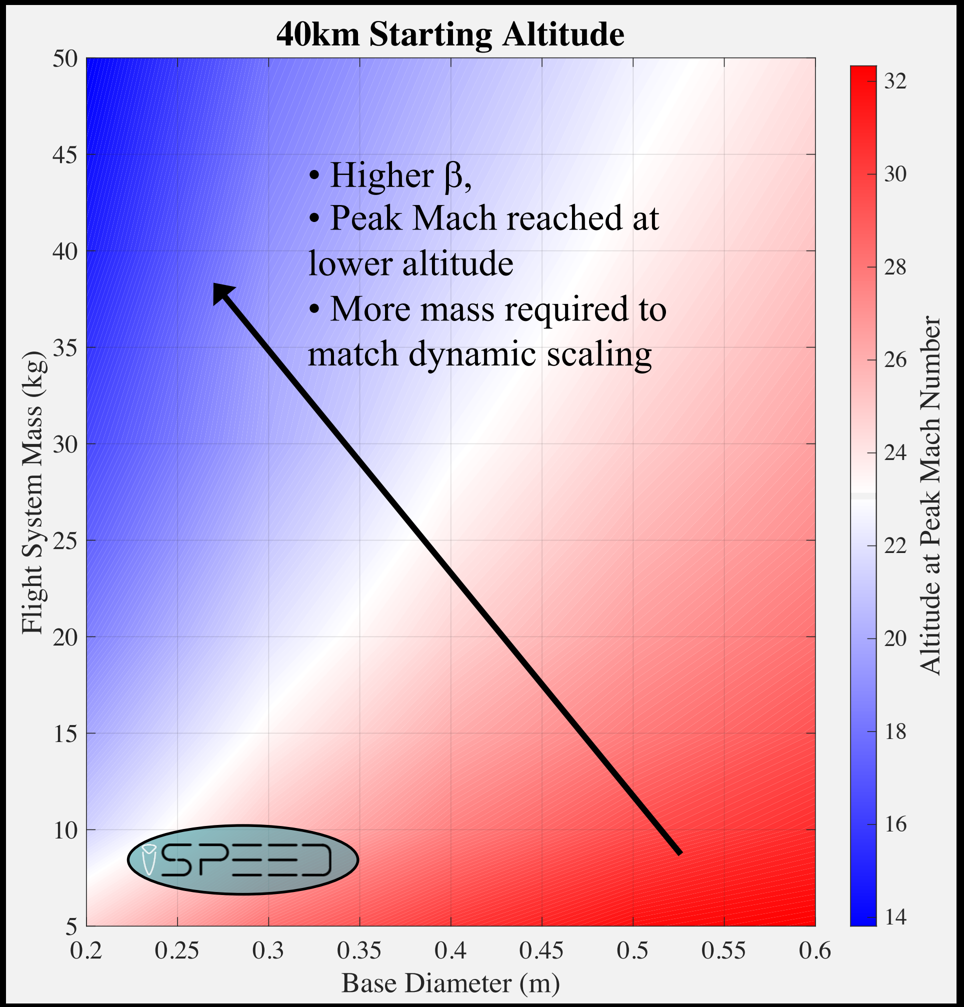

SPEED ConOps
Projectile
Capsule
Balloon
40000
30000
20000
10000
Altitude [m]
1. Launch
2. Ascent
3. Loiter and Flight System Release
Time from ground until release: up to 4 hours
4. Flight System Freefall
5. Capsule Jettison (Up to Mach 1.75)
6. Capsule Free flight
7. Terminal Descent (Mach ~0.15)
8. Projectile Impact
9. Capsule Touchdown & Recovery


One small
Innovation


Dragonfly Capsule: Drop Alt = 40.0 km, 22.5cm Diameter, 1.3kg
Combined
SPEED Flight
System
Capsule After
Ejection
Alt (km)
Mach
0
0.25
0.5
0.75
1
1.25
1.5
0
5
10
15
20
25
30
35
40

Design Space





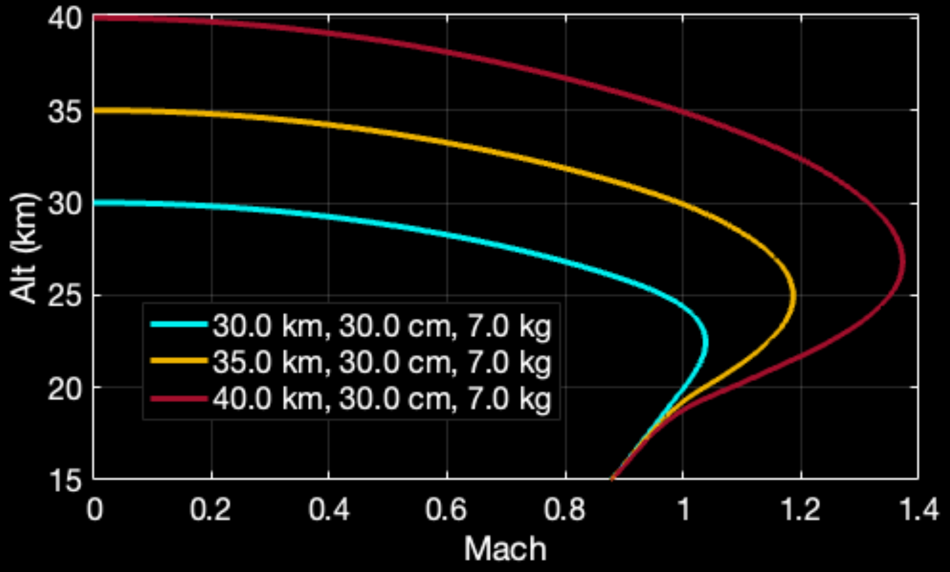
$$m_{model} = m_{flight}\left(\frac{\rho_{model}}{\rho_{flight}}\right)\left(\frac{d_{model}}{d_{flight}}\right)^3$$

Nominal Trajectory and Dynamic Scaling

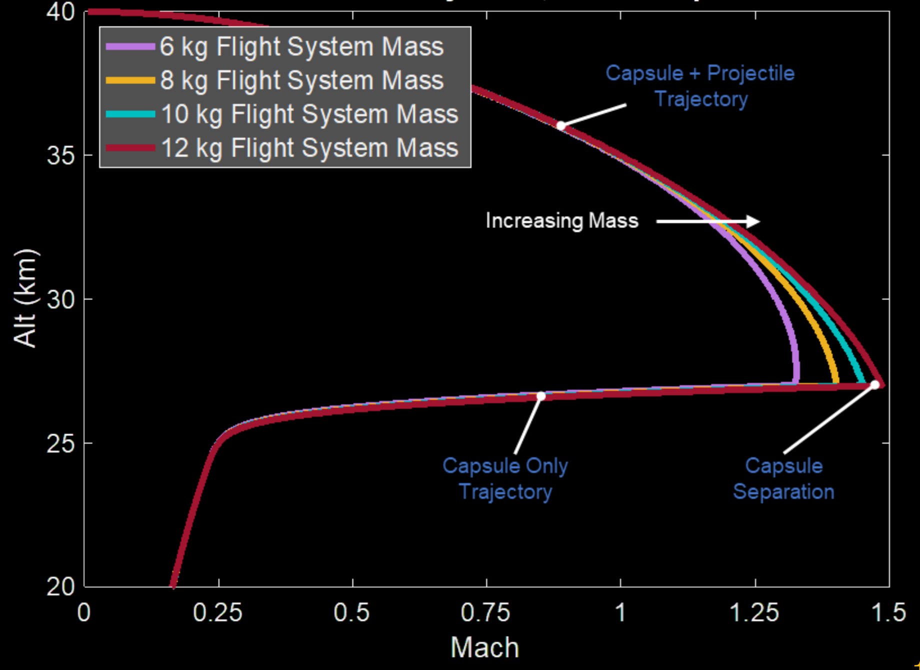
- Architecture can be tailored to meet scaling requirements for most missions (Titan, Mars, Earth) by changing mass properties and separation altitude
- System trade between starting altitude, individual flight system mass, peak Mach number, and number of total payloads that can be flown

Capsule	Drop Alt	Separation Alt	Peak Mach	Flight System Mass	Capsule Diameter	Capsule Mass
MSR EES	40 km	27 km	1.35	6.5 kg	0.25 m	0.7 kg
Dragonfly	40 km	27 km	1.35	7 kg	0.225 m	1.3 kg

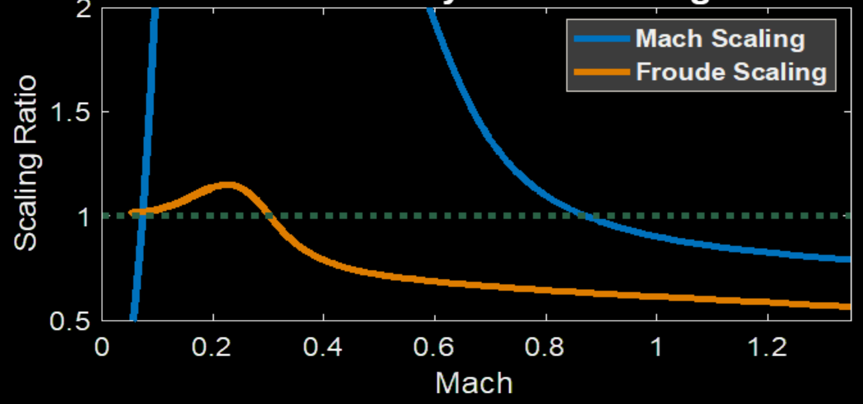
- Dynamic scaling can be closely matched across the regime of interest
  - Mach scaling within ±20% from Mach 1.7 – Mach 0.7
  - Froude scaling within ±20% Mach 0.4 – Terminal Velocity
  - Exceeds capability of ambient ballistic range testing



MSR EES Reference Trajectory: 30 cm Diameter Projectile, 27km Separation

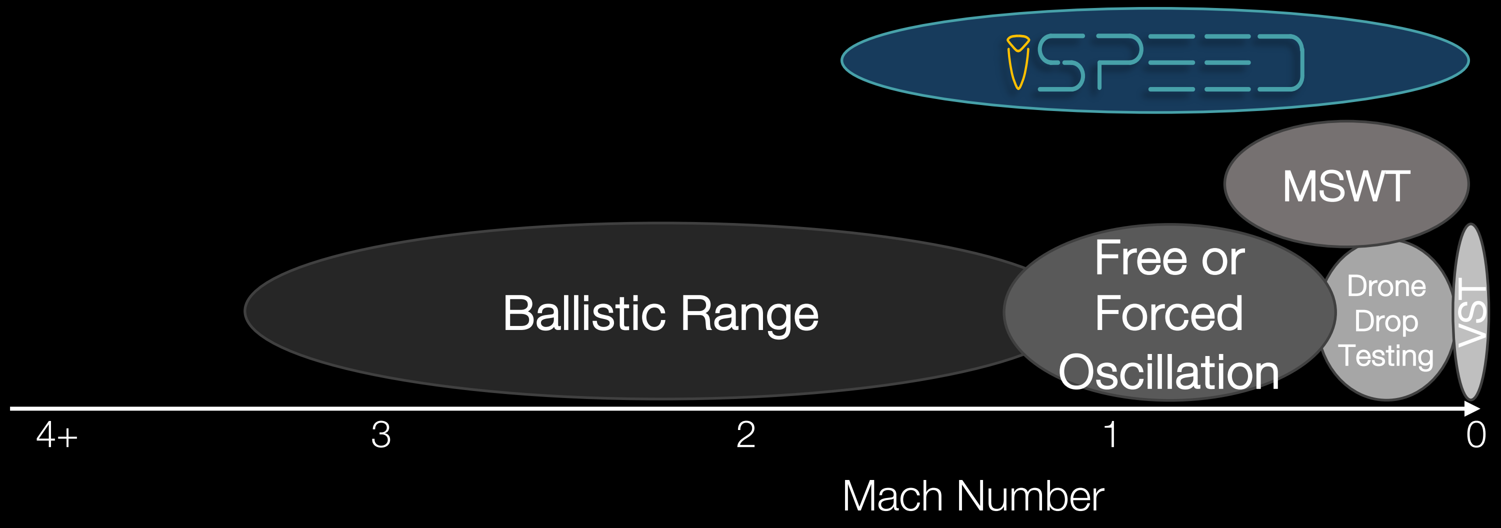


MSR EES Dynamic Scaling



Value Proposition:

- Most flight-like method for obtaining rich, dynamically scaled data
- Many vehicles per flight allows for statistical understanding of vehicle behavior and A/B testing
- Provides coverage over most critical and most difficult to test Mach regime
- Independent data source for comparing predictions from different test facilities and from CFD
- Low-cost and tailorable test capability to complement future aerodatabase generation



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Concept Development

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Development Path

Basic concept development and component testing with

MSR EES Point Design

Drone drop testing of single flight system

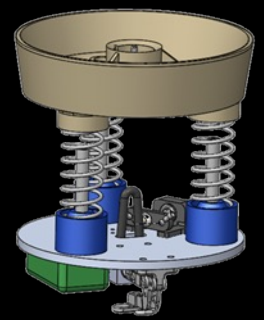
(100m starting altitude)

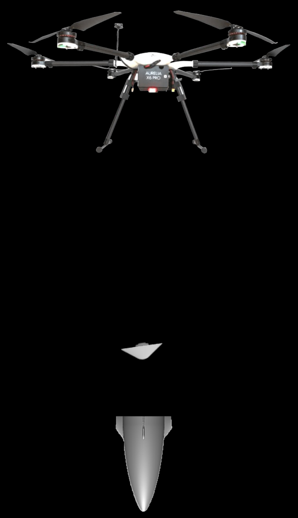
Helicopter drop testing with full fidelity drop + flight system

(600m starting altitude)

First stratospheric balloon demonstration

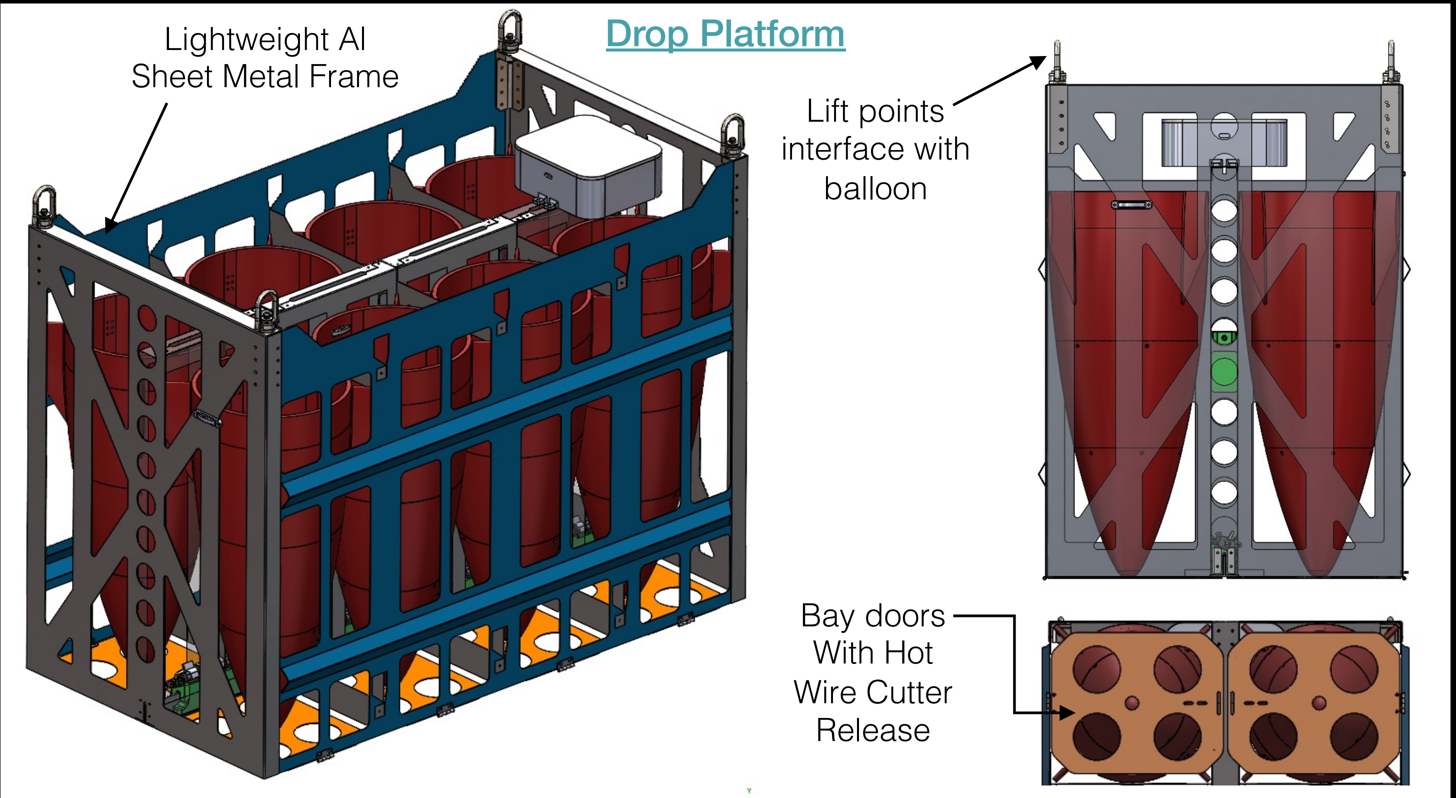
(40 km starting altitude)

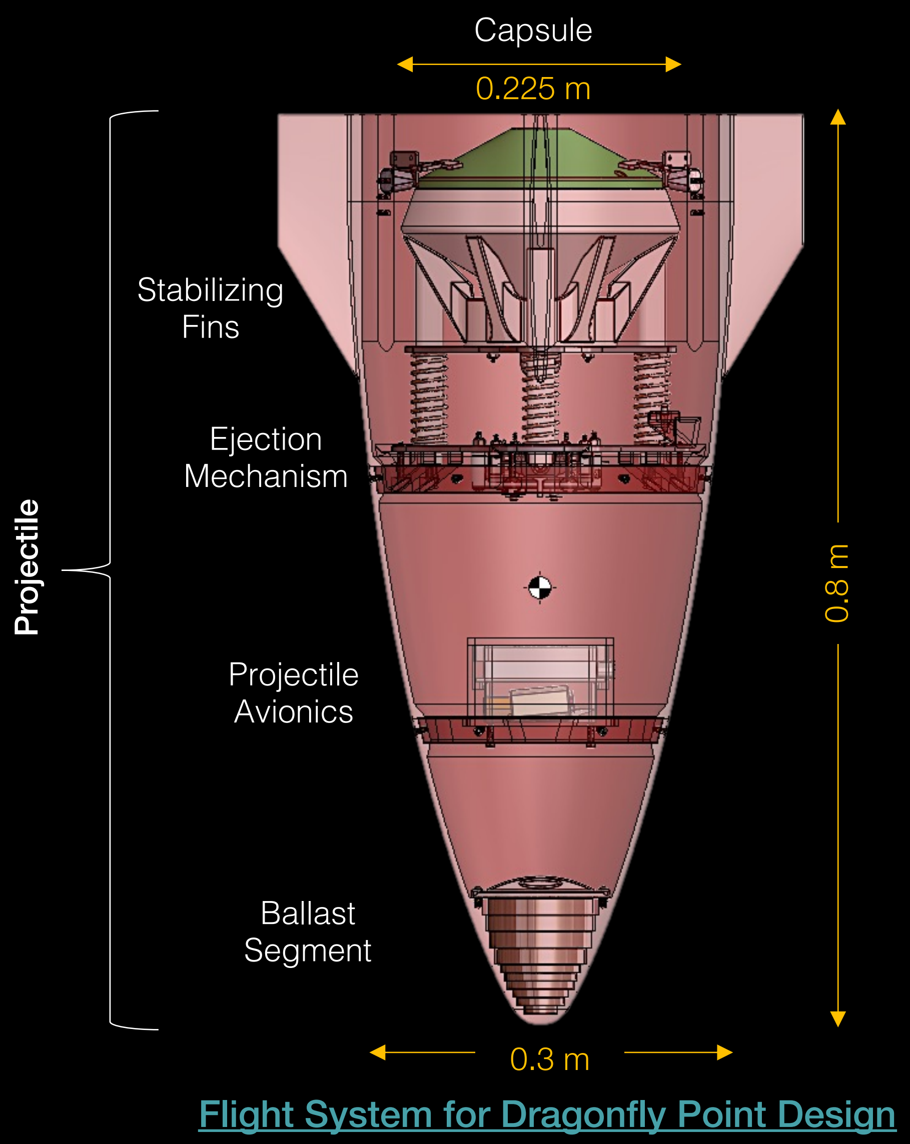




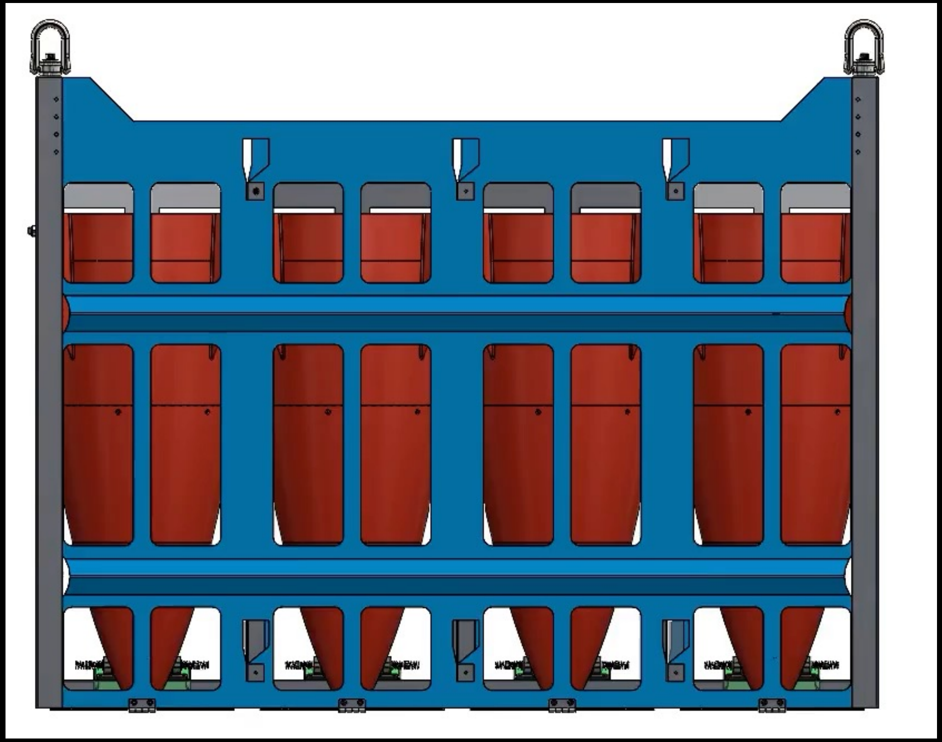
System Overview

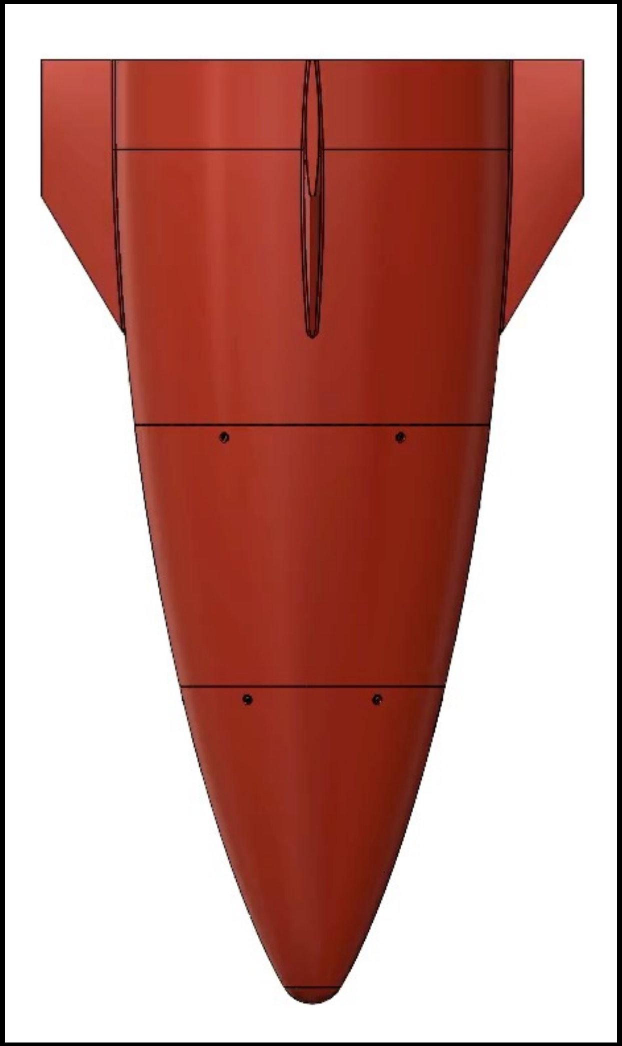
- Three major elements: Drop Platform, Projectile, Capsule
  - 3D printing, COTS instrumentation low-cost materials, and fabrication
  - ~$25k for full system with 8 payloads
- Architecture allows for easy tailoring to different vehicle configurations
  - 3D printed capsule geometries (OMLs, surface features)
  - Initial angle of attack, Mach, altitude
  - Could be reconfigured to test other systems (e.g. parachutes)

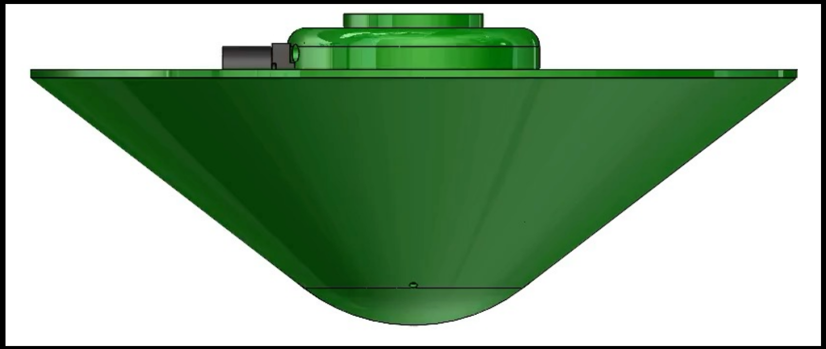


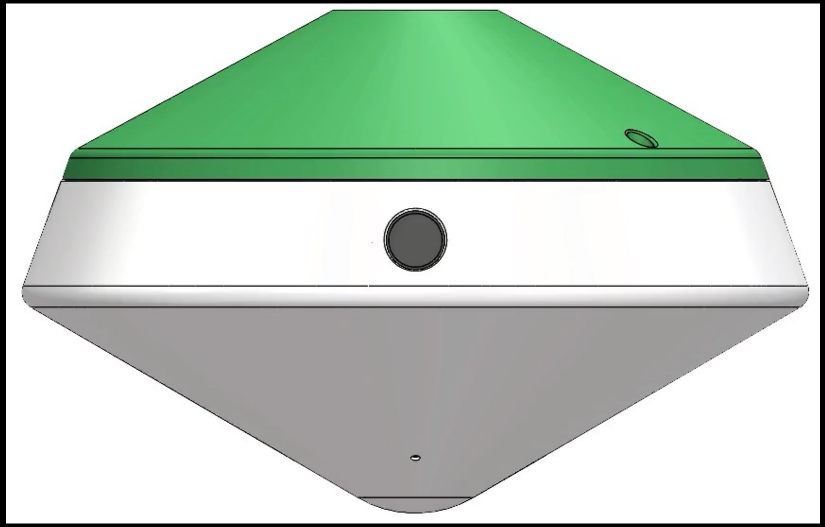


Mechanical Overview

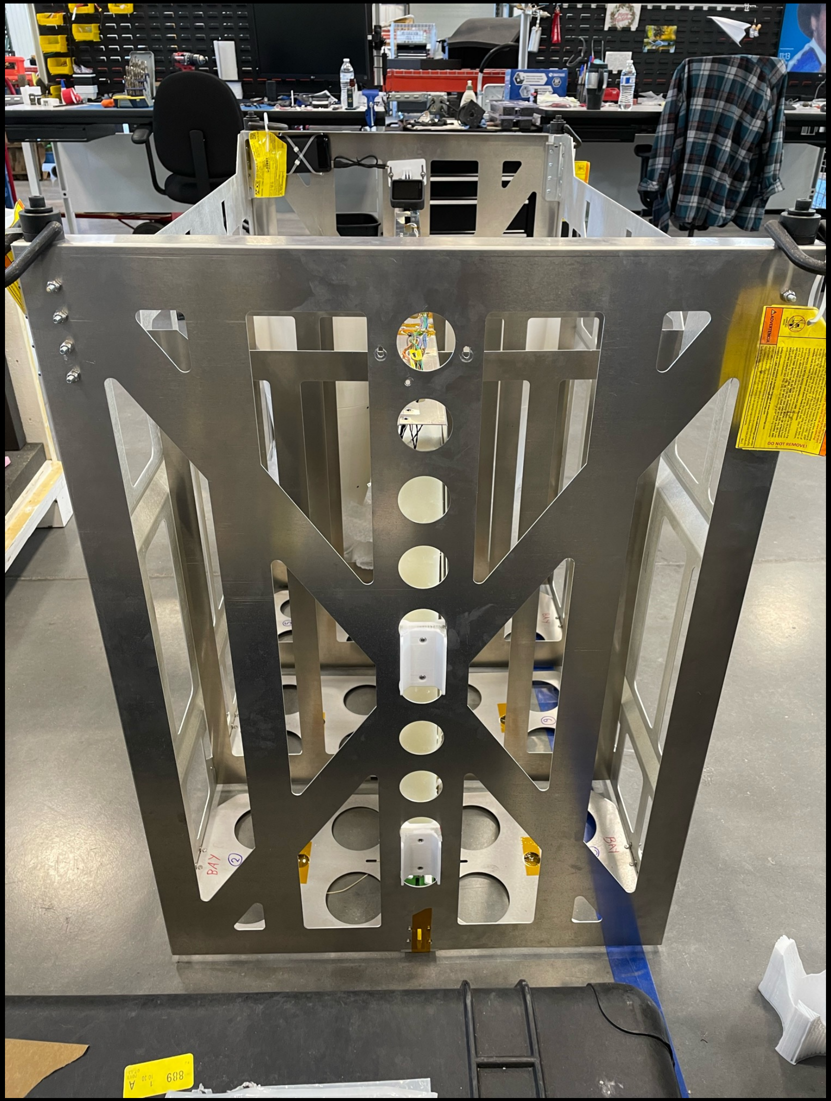


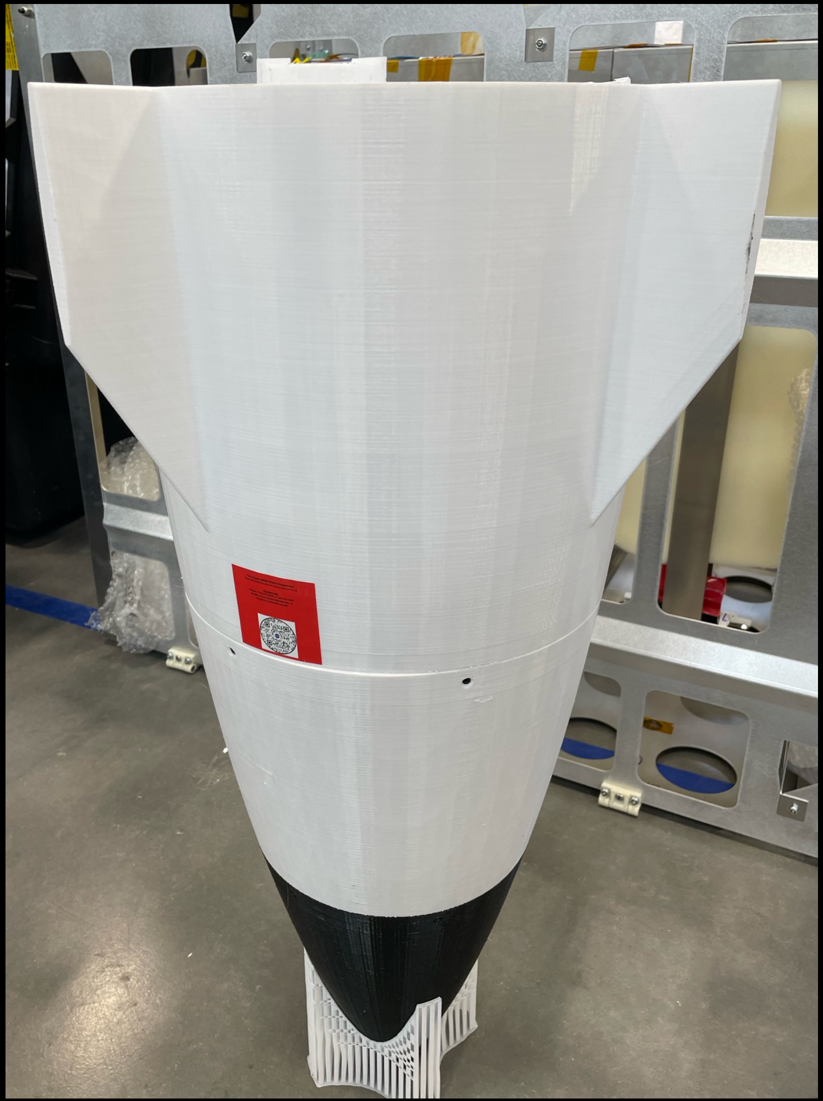


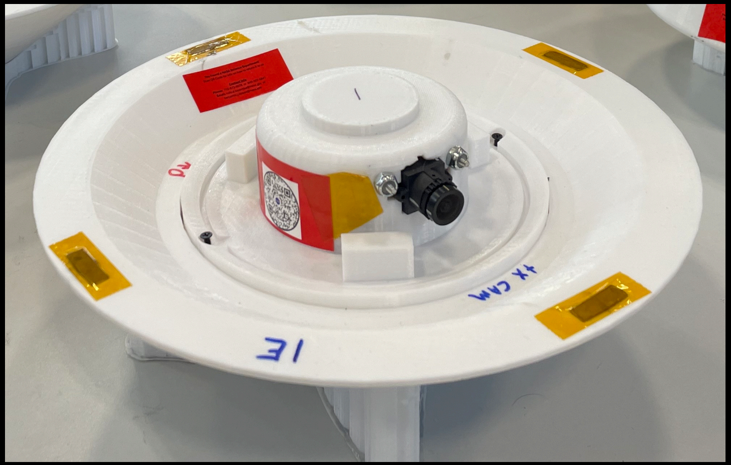




Mechanical Overview



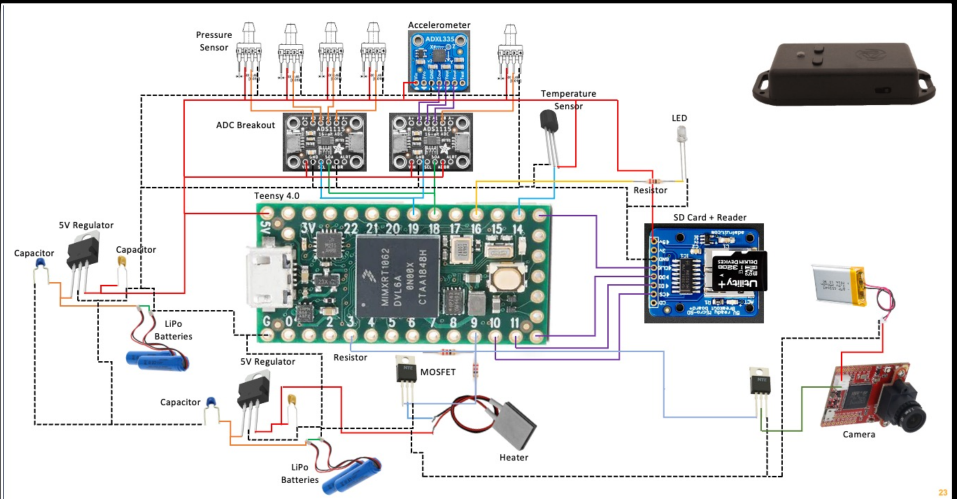


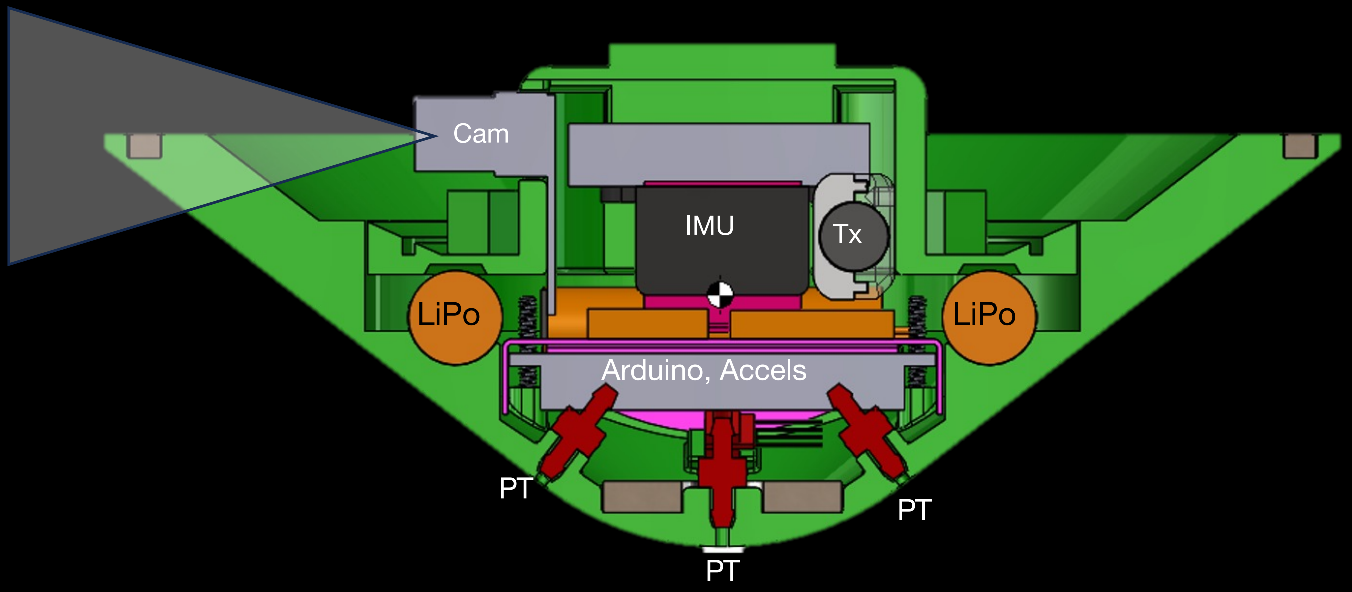


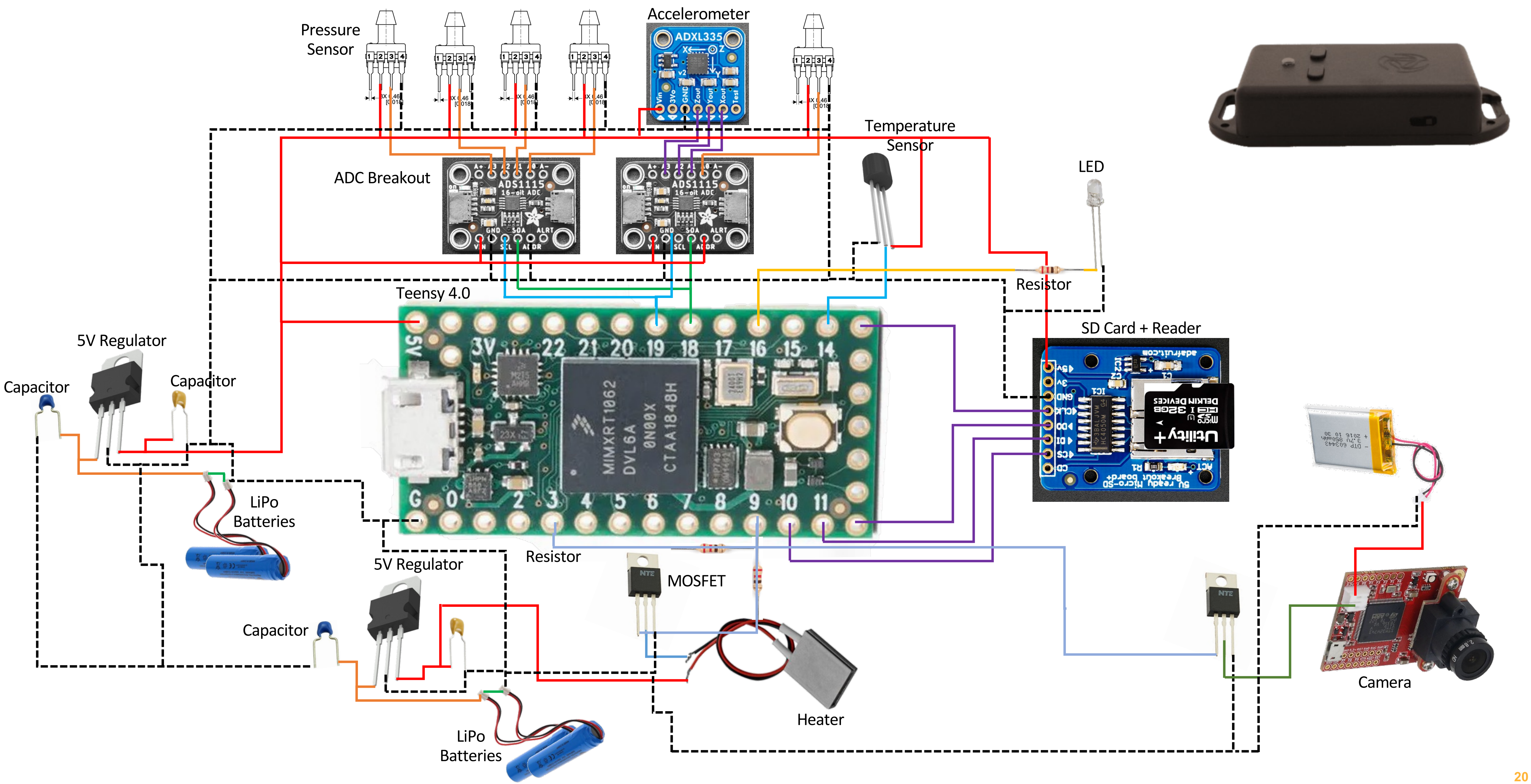
Avionics

- Avionics perform critical functions on each major element in the system
  - Closed-loop thermal control via heaters in each system element
  - <u>Drop Platform:</u> Receive drop signal from balloon and send signal to drop mechanisms in sequence to initiate freefall
  - <u>Projectile:</u> Sense conditions that indicate we are at the desired experimental altitude and initiate capsule ejection
  - <u>Capsule:</u> Measure vehicle and environmental state for downstream data reduction
- Capsule is highly instrumented to provide rich dataset for characterizing flight performance
  - Pressure transducers (5x on forebody, could accommodate aftbody Kulite)
  - 200 Hz IMU, Magnetometer, Secondary Accelerometer
  - Camera
  - Recovery aids
- SD cards on board will be recovered for data extraction and analysis

Capsule Avionics






Pressure Sensor
Accelerometer
ADXL335
ADC Breakout
ADS1115
16-bit ADC
Temperature Sensor
LED
Resistor
Teensy 4.0
SD Card + Reader
5V Regulator
Capacitor
Capacitor
LiPo Batteries
Resistor
MOSFET
5V Regulator
Capacitor
Heater
LiPo Batteries
Camera

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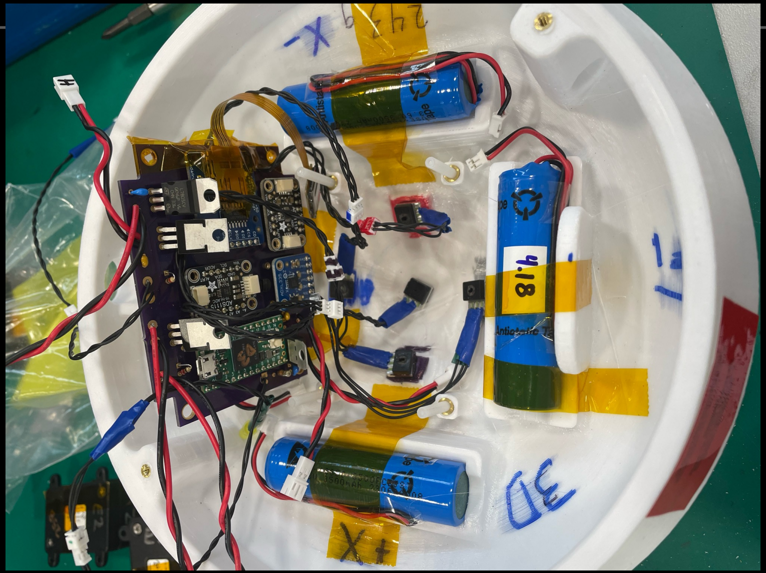

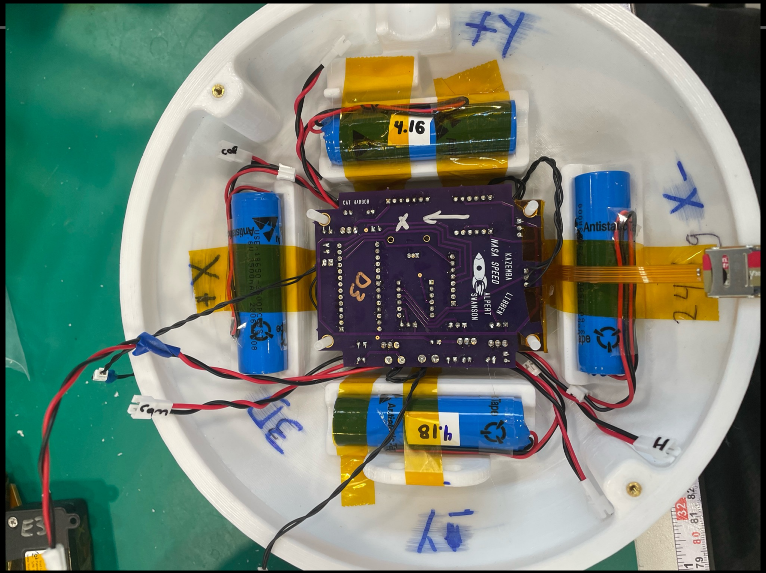

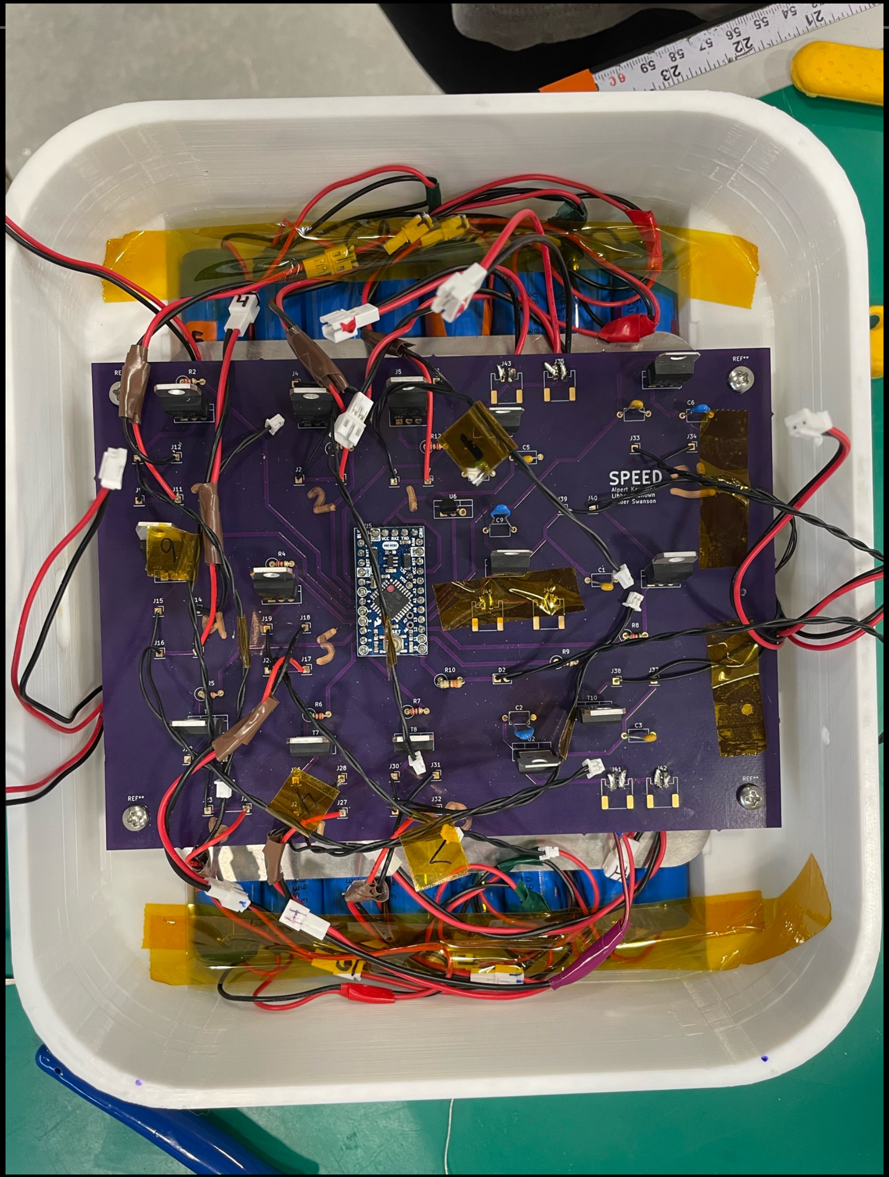

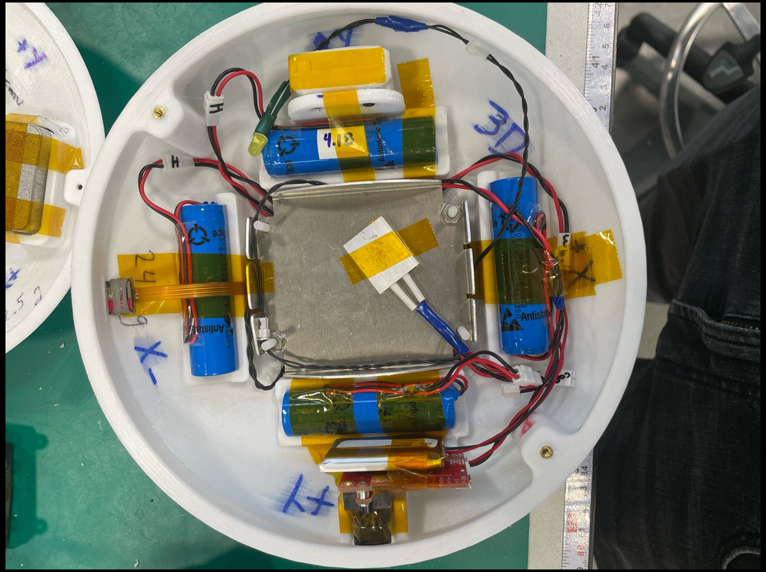

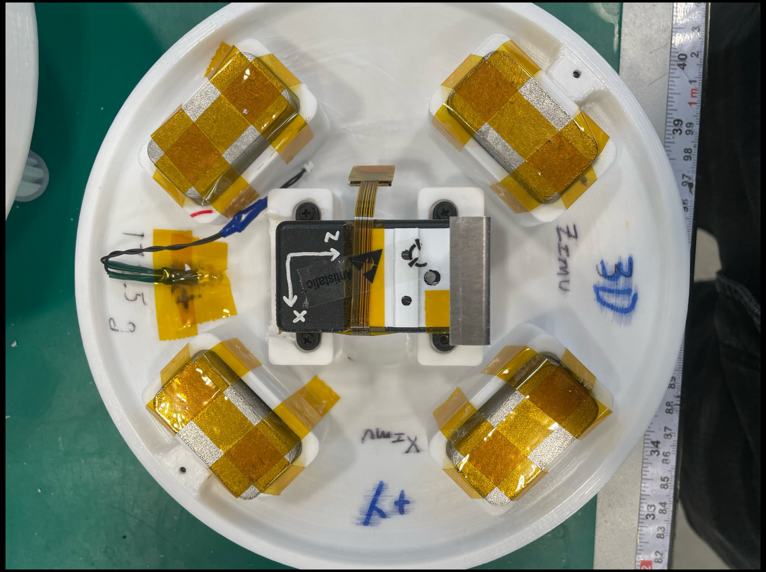

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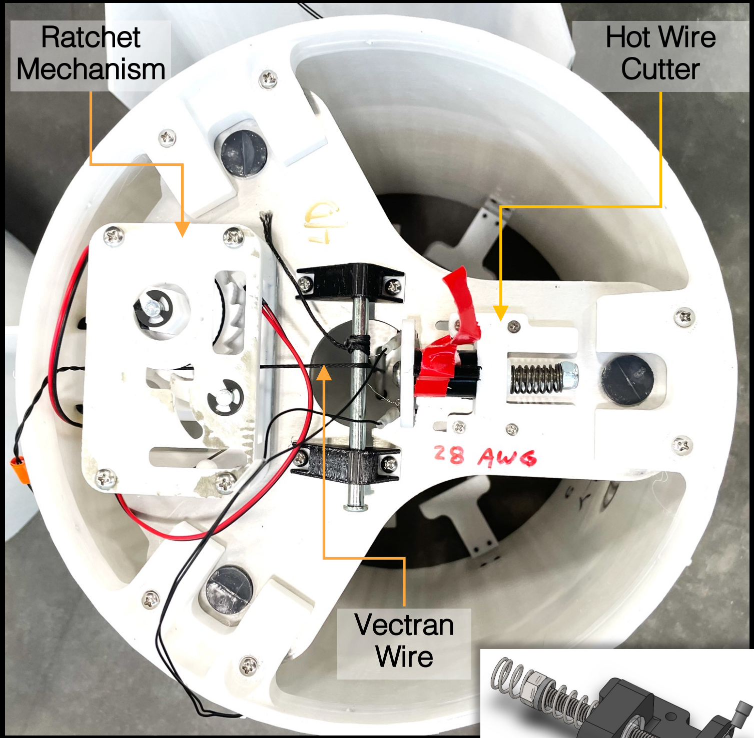
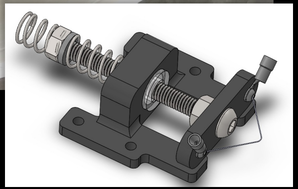
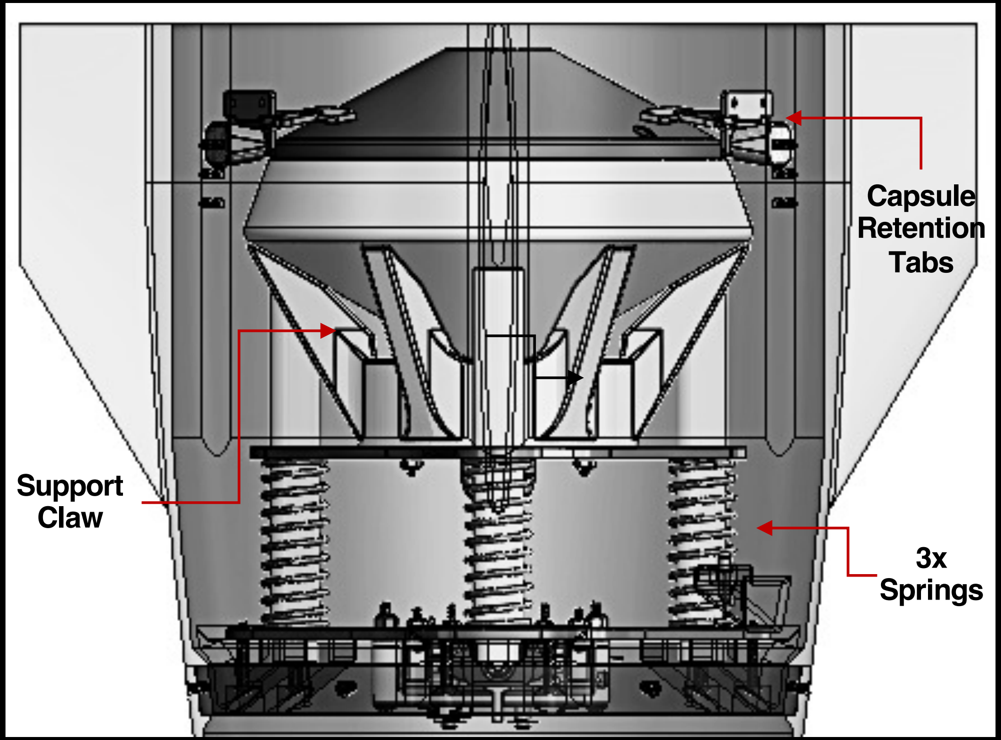
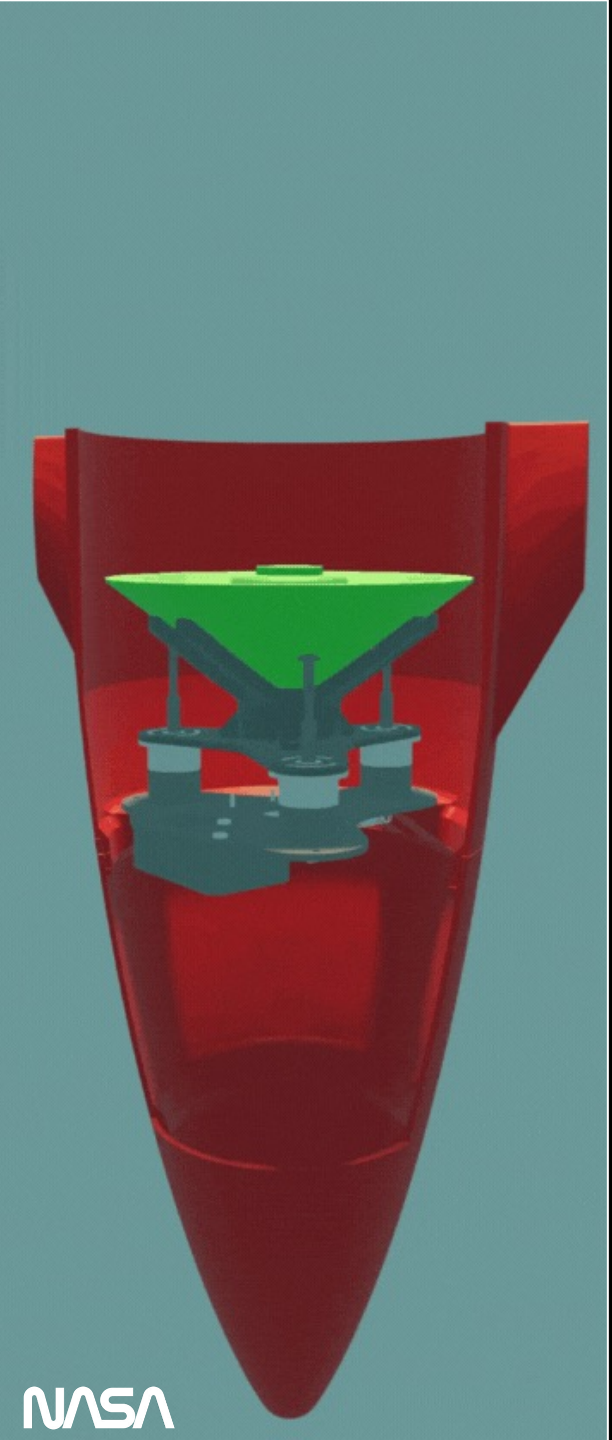
Ejection Mechanism

- Custom ratchet mechanism tightens a 400lb Vectran cord to compress 3x springs
- Capsule retention tabs use friction hinges to provide positive retention during ascent and initial freefall
- Avionics on board the projectile: detect a drop signal from balloon, start a timer for ejection, send current to power a hot-wire cutter that cuts Vectran initiates an ejection of the capsule
- Claw, guide posts, and end-of-travel devices maintain uniform ejection to minimize tip off









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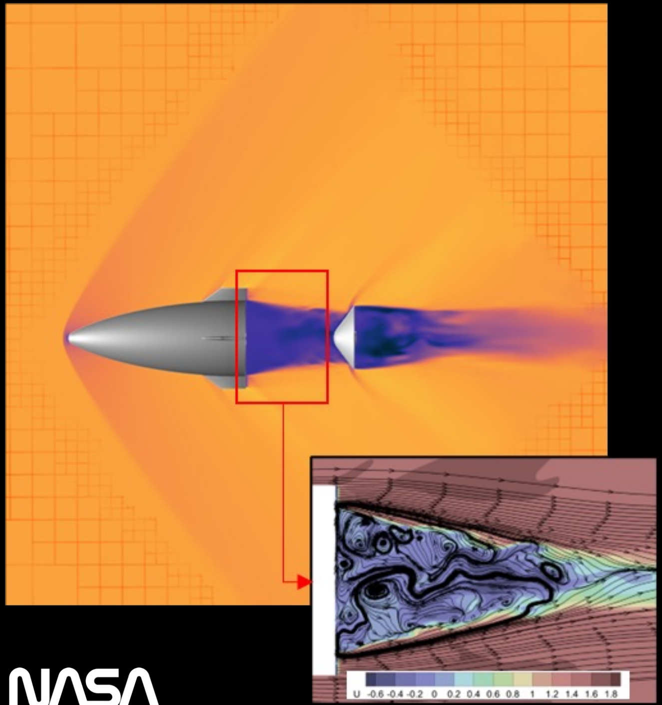
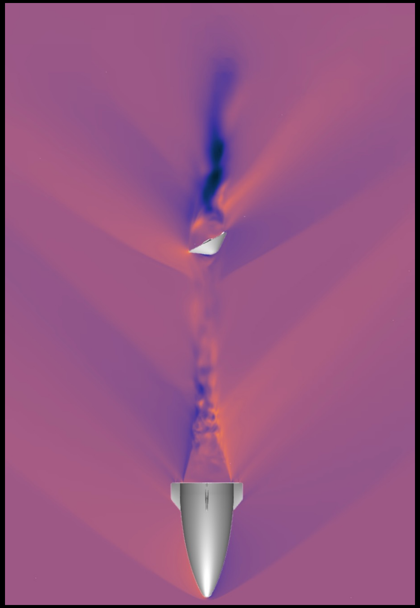
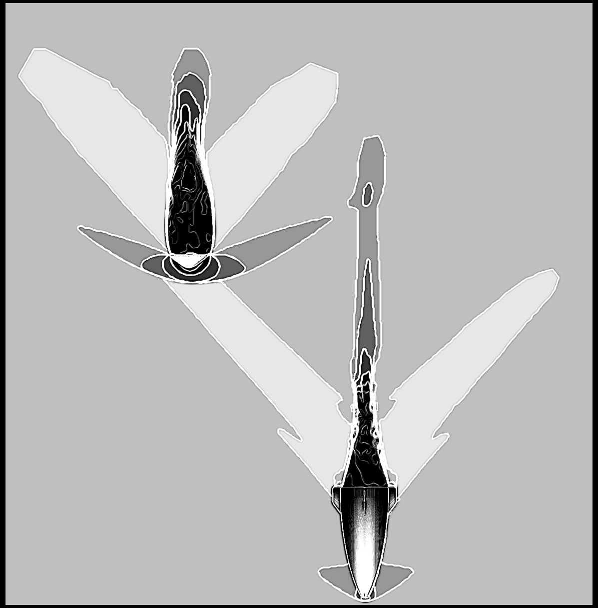
Separation Event

- <u>Key Risk Addressed in Supersonic Flight Test:</u>
  - Do the ejection mechanism and unsteady wake behind the projectile disturb the capsule to an unacceptable degree at the start of the experiment?
  - How long after separation is the capsule in a representative free-flight environment where data is valid?
- Two-body static CFD assessment indicates capsule aero asymptotes after getting ~2 projectile lengths behind projectile
- Capturing dynamics of the capsule during and immediately following the separation will be assessed in maiden flight

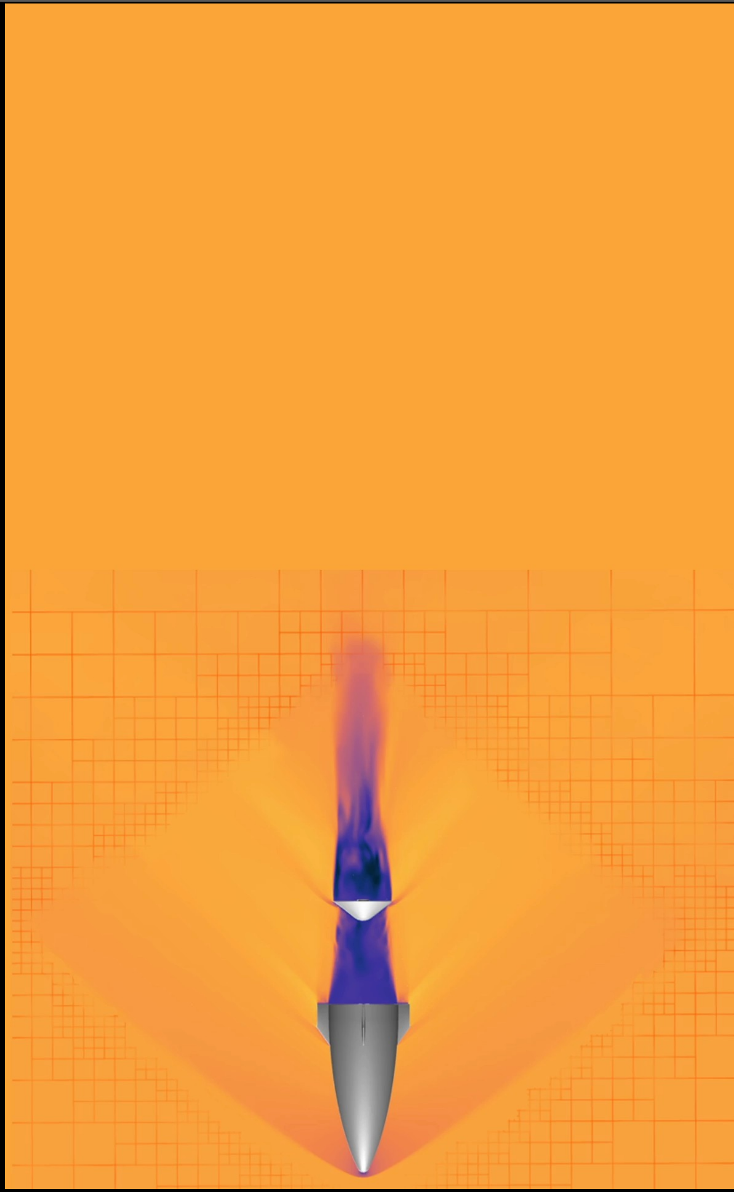




At Angle of Attack



With Lateral Offset



Thermal

- Ascent to stratosphere requires long dwell in temperatures as cold as -60°C
  - Affects survival capability of sensors
  - Longevity of batteries
  - Battery current capacity for Hot Wire Cutters
- Mitigations in design include:
  - Closed loop thermal control with resistive heaters
  - Radiator plates to distribute heater energy
  - Passive heating using hand warmers (low alt)
- Validated design via altitude chamber at Ames
  - Demonstrated heater performance, battery life, ability to function HWC at temperature
- Once at altitude, radiative heating due to solar exposure is a risk
  - Implemented reflective Mylar closeout blanket around entire drop platform