National Aeronautics and Space Administration

Mars Sample Return Earth Entry System Helicopter Drop Test Reconstruction

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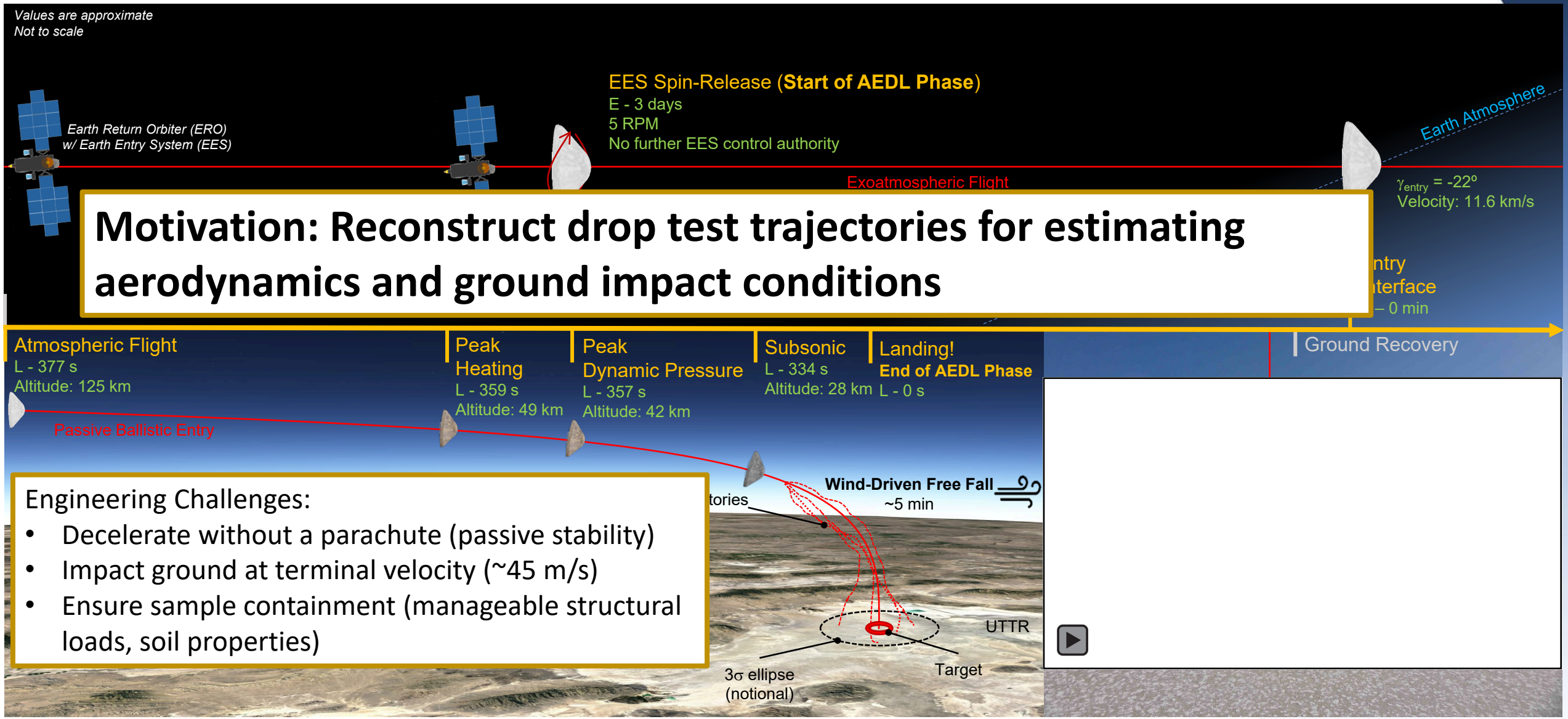
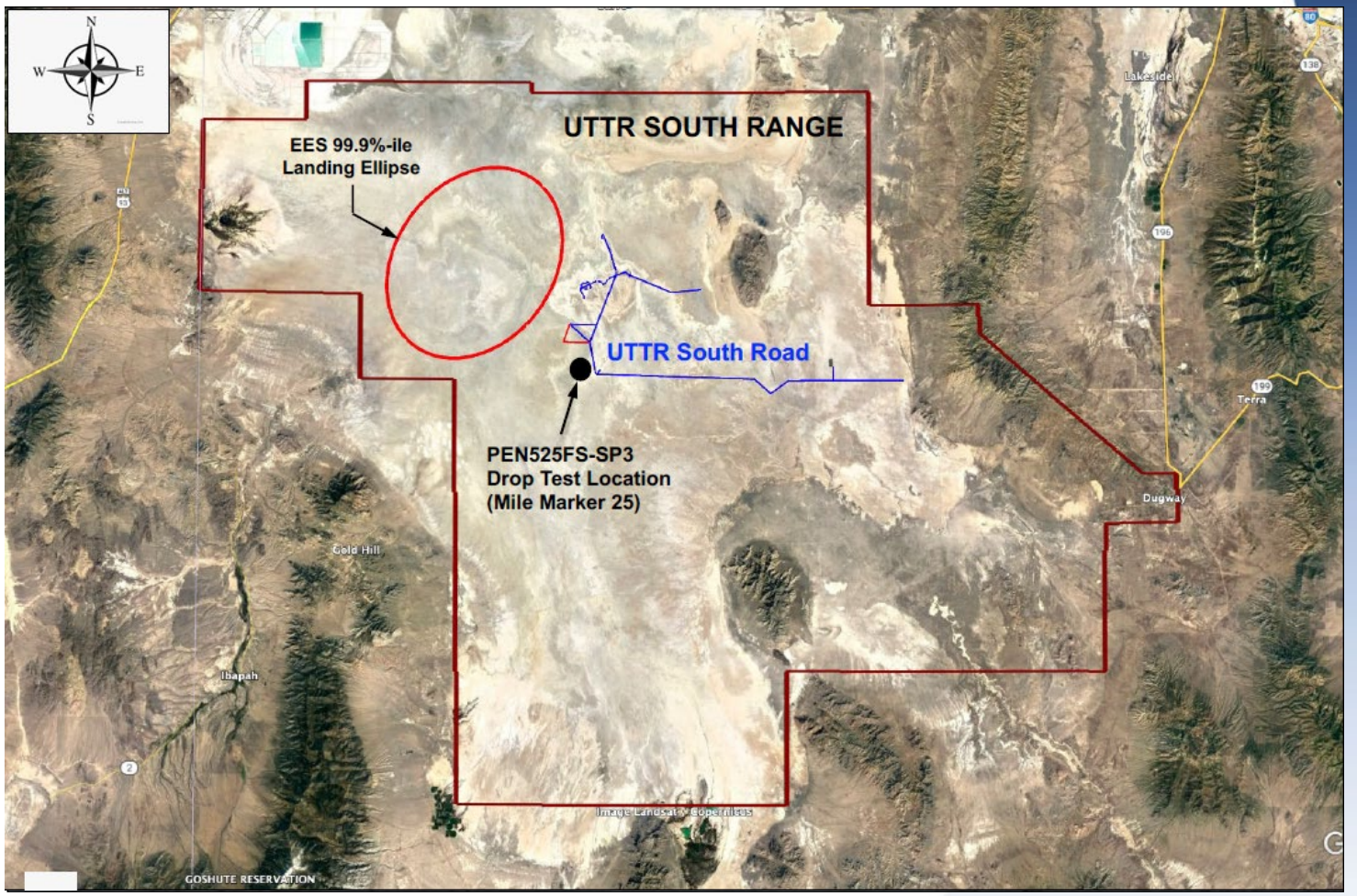
Mars Sample Return mission is currently undergoing a re-architecture. The work presented in this talk is reflective of mission presented at return system PDR December 2023.

Mars Sample Return Earth Entry System: Approach, Entry, Descent, and Landing



Helicopter Drop Test

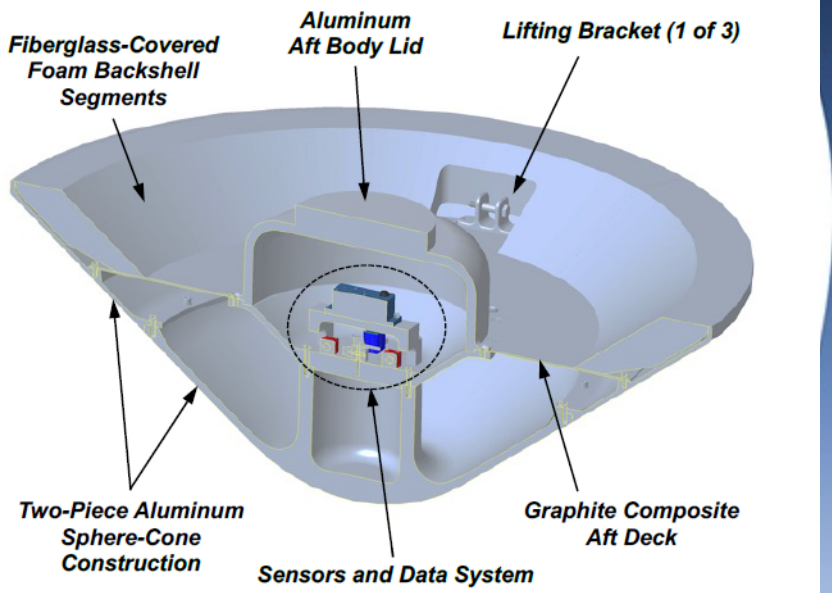
- ***Helicopter drop tests conducted at the Utah Test and Training Range (UTTR), October 2023***
- ***Test objectives***
  - Acquire free-fall flight data for characterization of subsonic aerodynamic properties
  - Acquire ground impact data to support structural modeling
- ***Test Location***
  - Similar Playa soil as EES landing ellipse
  - Close to UTTR South Road helps with transportation logistics



Test Article Configuration

Test article configuration

- Two-piece aluminum 52.5 deg sphere cone structure
- Designed to withstand multiple drop tests at UTTR with off-vertical impact angles up to 15 deg
- Full scale test article (1.273 m diameter)



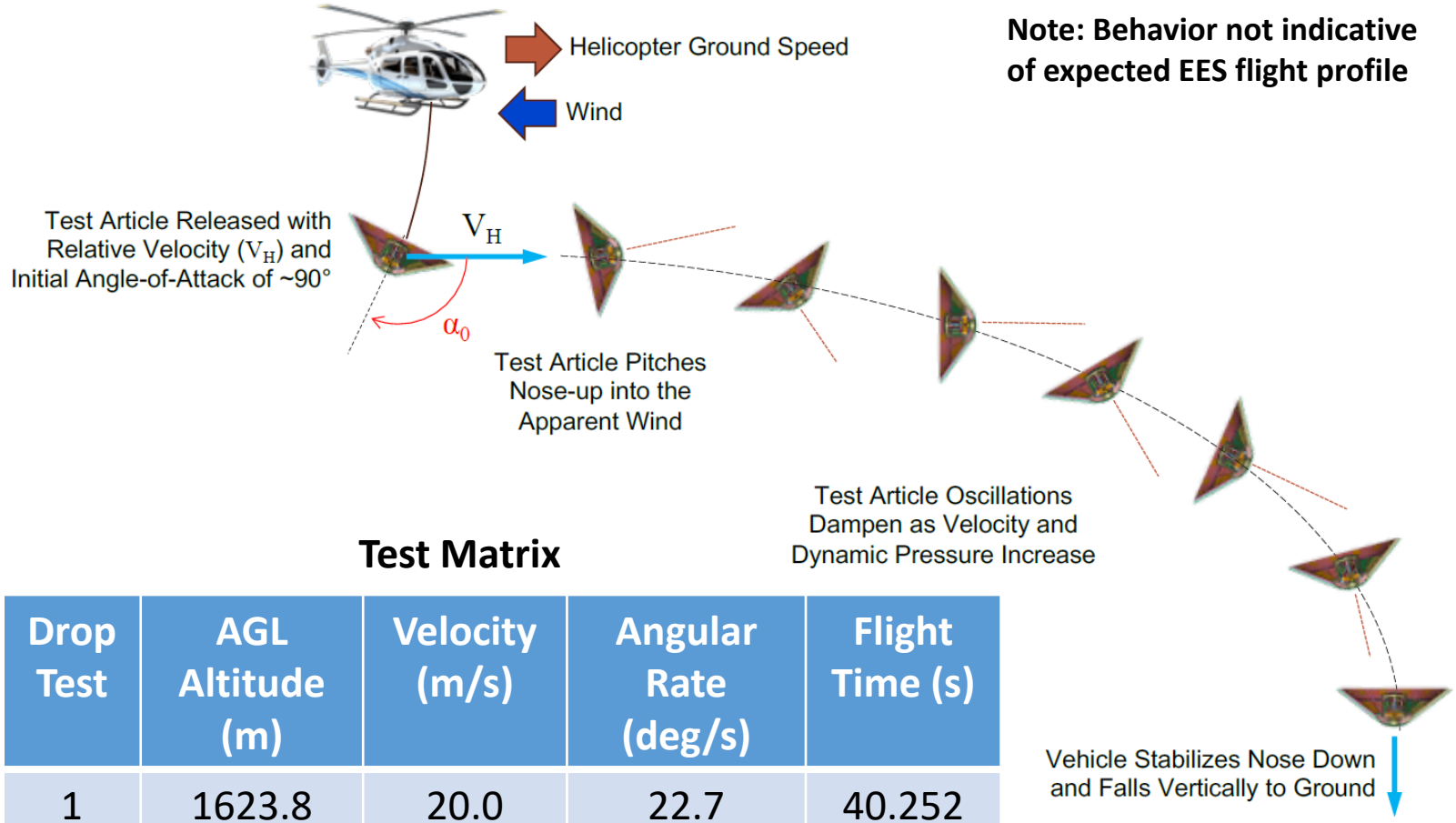
On-Board Instrumentation

Instrument	Use Case
Texense 6DOF IMU Sensor	Free-Fall Flight Dynamics
Flysight GPS	Position/Velocity Along Trajectory
Sony 4K Video Cameras	Record Footage of Drop
High-G Accelerometers	Impact Accelerations
DTS Digital Acquisition System	Handling of Sensor Measurements

Helicopter Drop Test Overview

Testing Procedure

- Select a target release velocity to create desired pitch dynamics
- Launch radiosonde ~15 min prior to drop test to measure wind speed and direction
- Based on wind data, select a heading, ground speed, and altitude for the drop to match the desired release velocity
- Quick-look at data to guide the next test



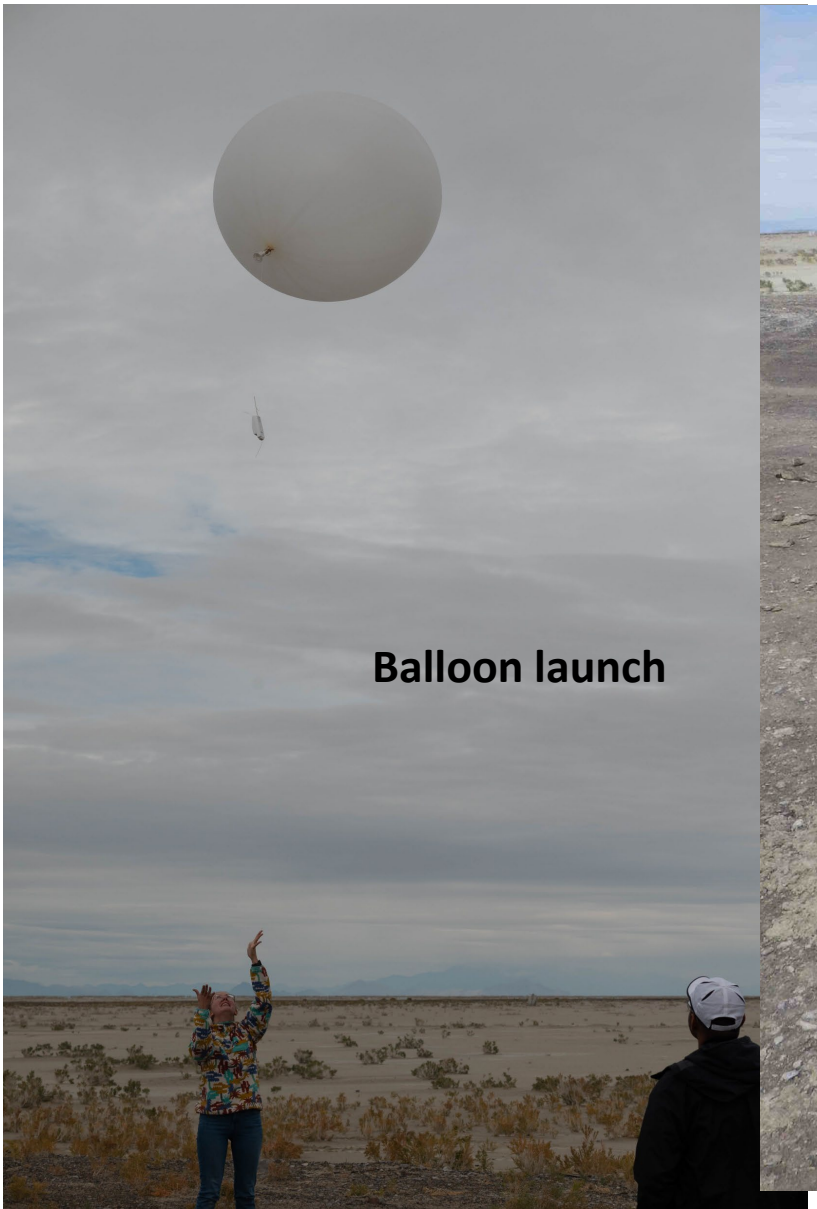
Note: Behavior not indicative of expected EES flight profile

Test Matrix

Drop Test	AGL Altitude (m)	Velocity (m/s)	Angular Rate (deg/s)	Flight Time (s)
1	1623.8	20.0	22.7	40.252
2	1195.8	7.2	7.8	30.906
3	1567.6	6.4	6.4	38.932
4	1588.6	4.3	4.3	40.008

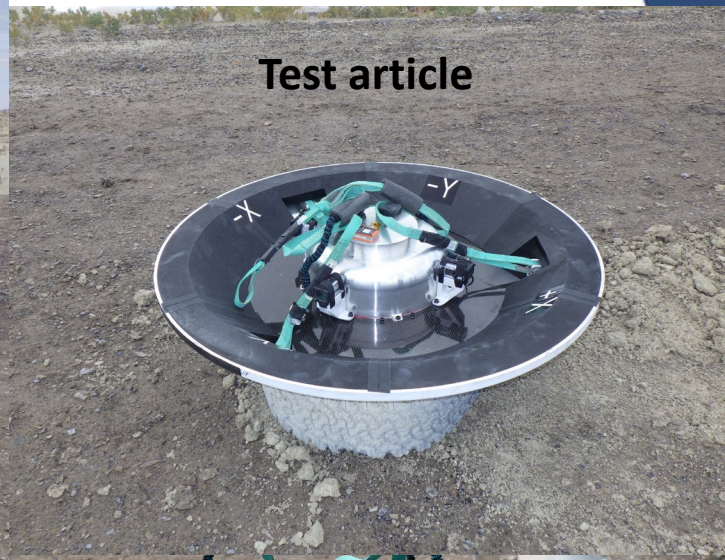
Test Preparation

Image credits: E. Shellabarger



Balloon launch

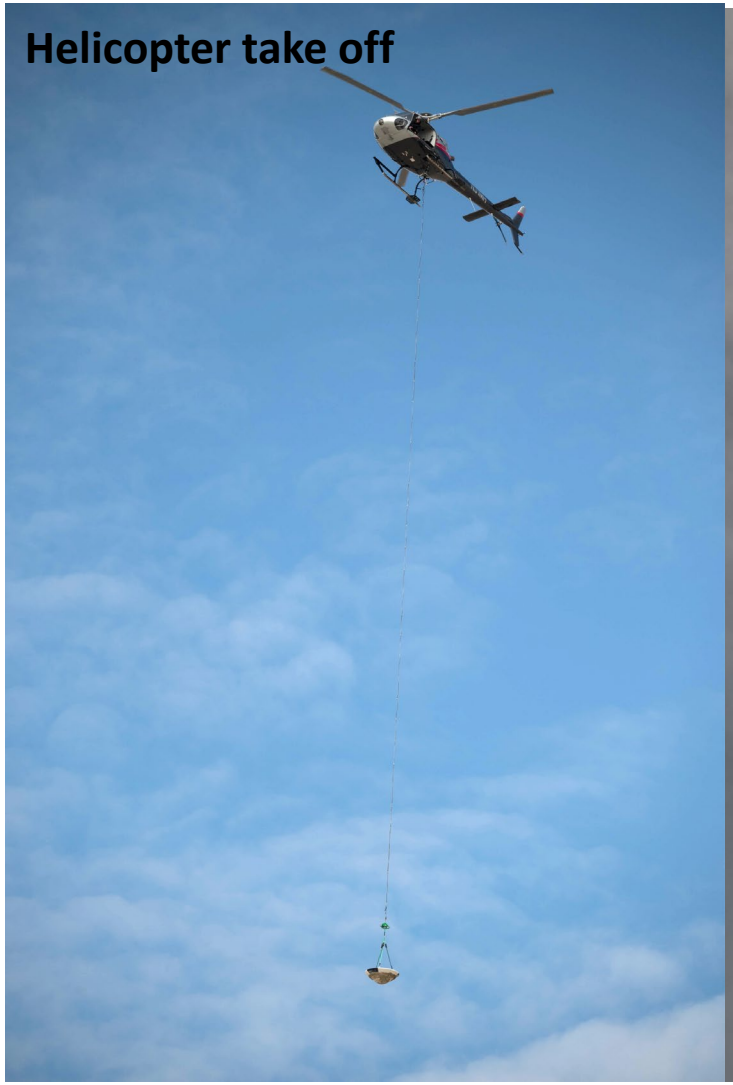
Helicopter and test article



Test article

Hooking up the test article

Helicopter Drop Test



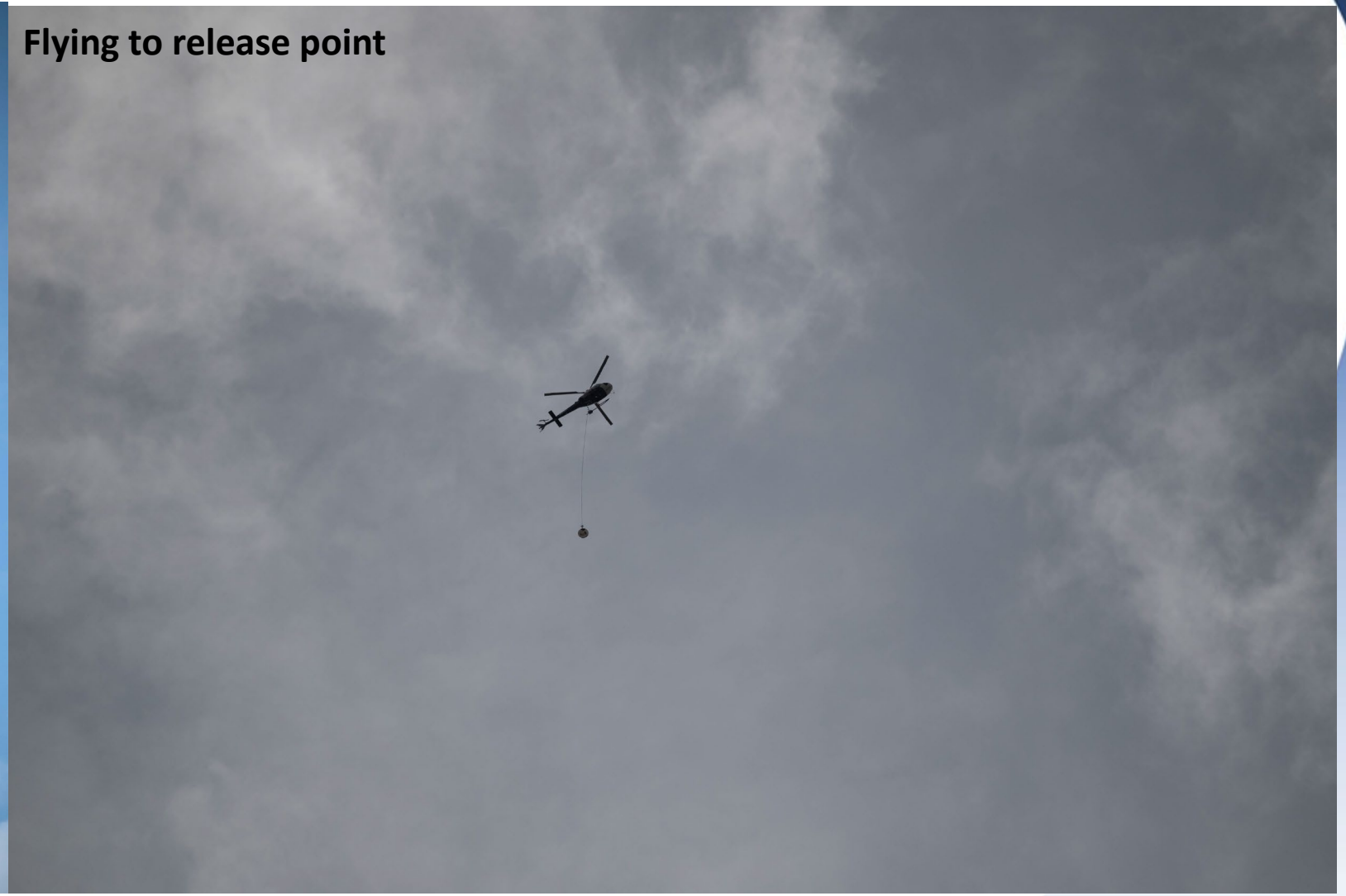
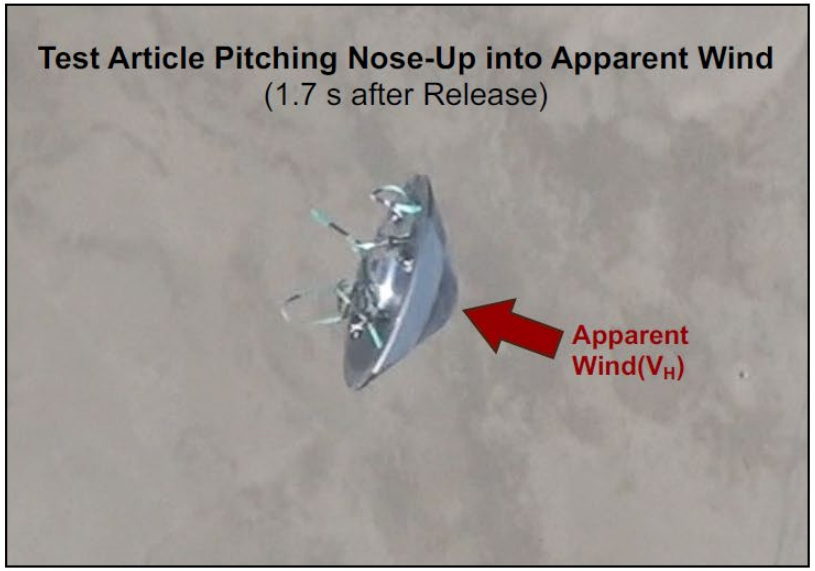


Image credits: E. Shellabarger

Helicopter Drop Test



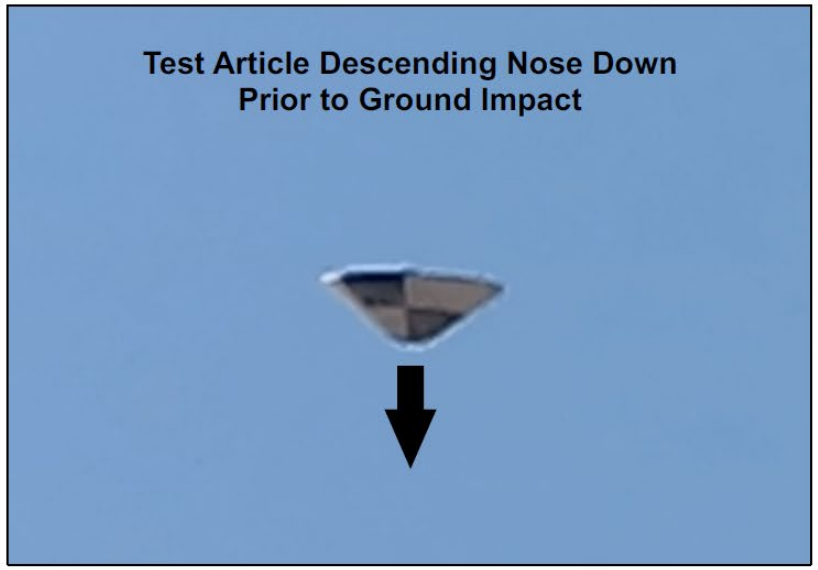
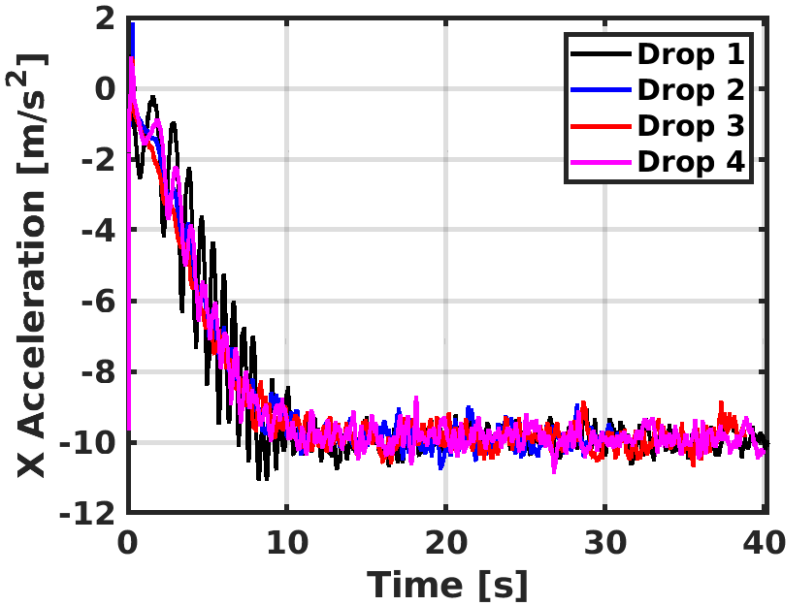


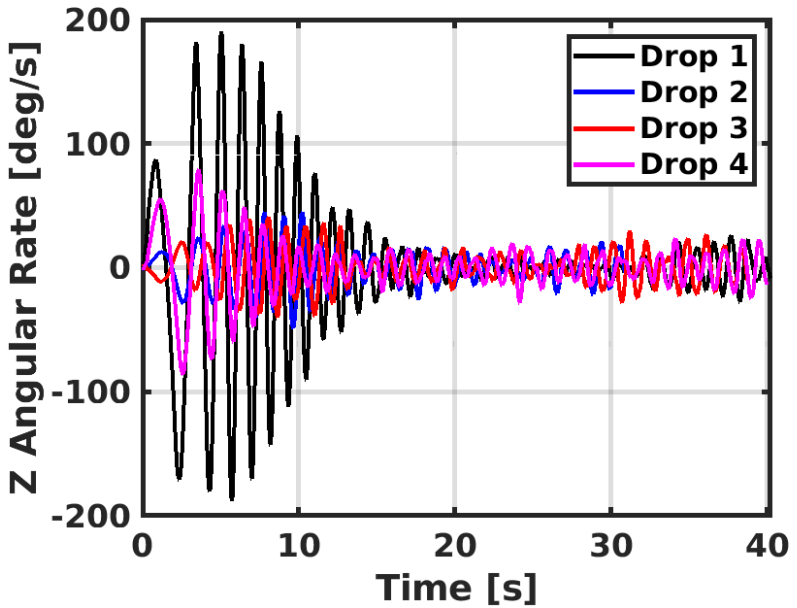
Image credits: E. Shellabarger

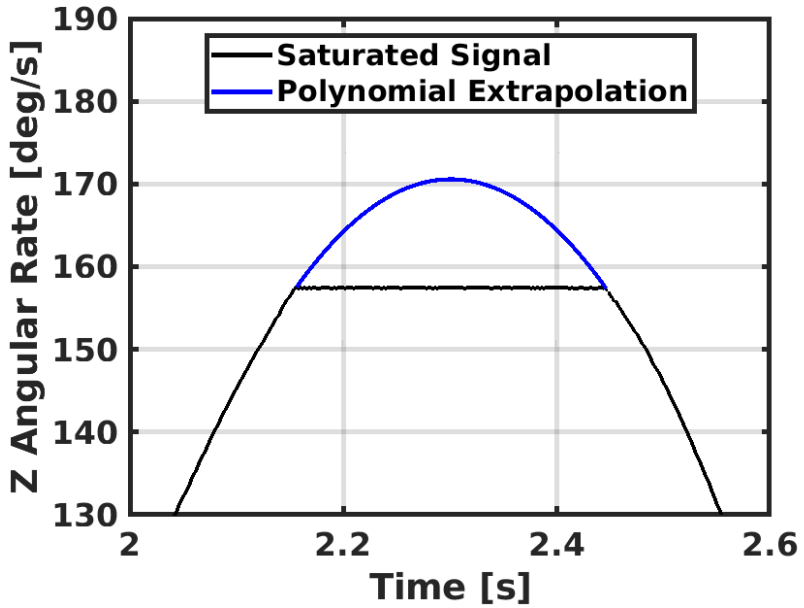
Test Article Recovery

Image credits: E. Shellabarger

Inertial Measurement Unit

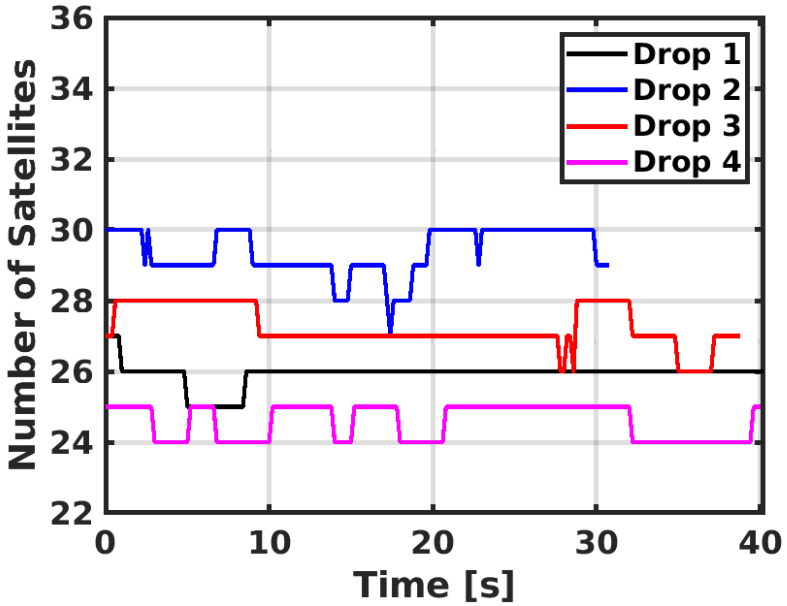


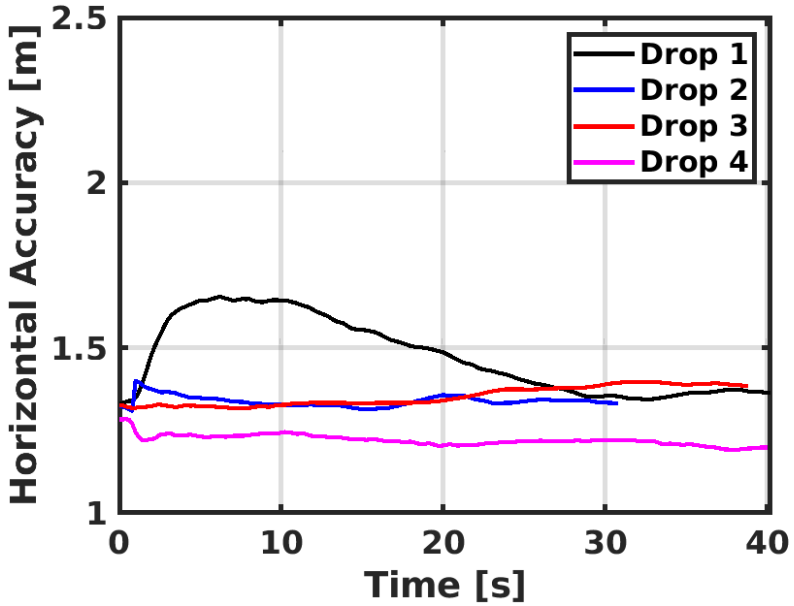




- ***Texense IB6 IMU***
  - Sample rate 50 kHz, filtered and downsampled to 500 Hz for data analysis
  - Drop test 1 saturated the yaw rate sensor in 5 places – yaw rate was extrapolated from a quadratic polynomial fit

Global Positioning System

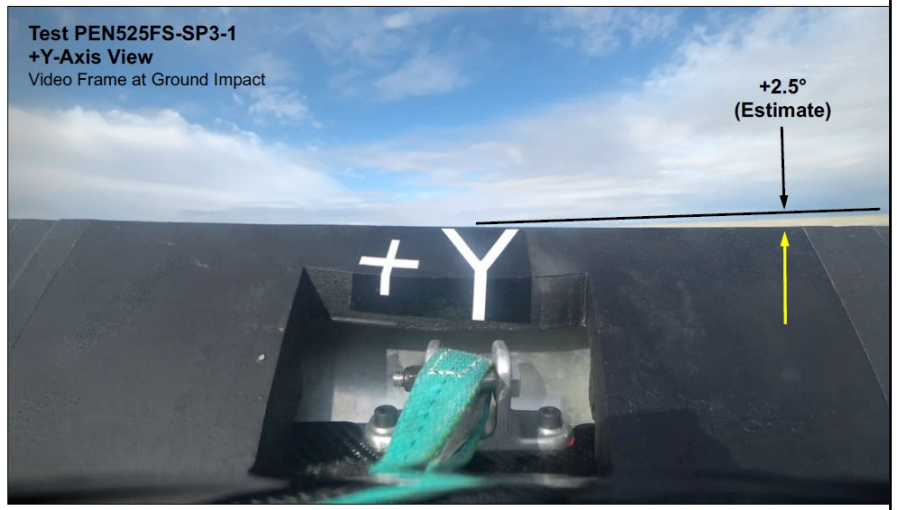




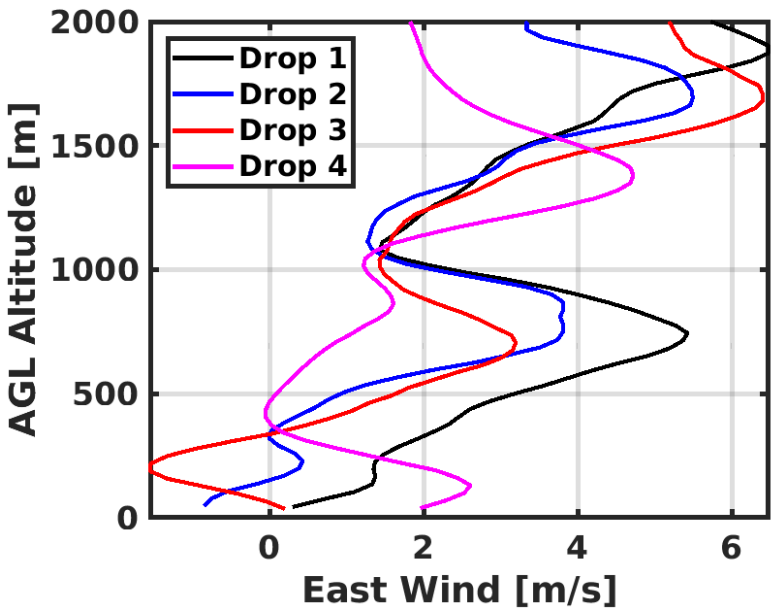
- ***Bionic Avionics Flysight GPS***
  - Sample rate of 5 Hz
  - Produces geodetic position, north-east-down (NED) velocities, and accuracy estimates
  - Accuracy estimates included horizontal and vertical position components and one speed accuracy. The speed accuracy was assumed to apply to each NED component
  - The GPS unit was not G-hardened: signal was erratic immediately after ground impact but stabilized after several seconds

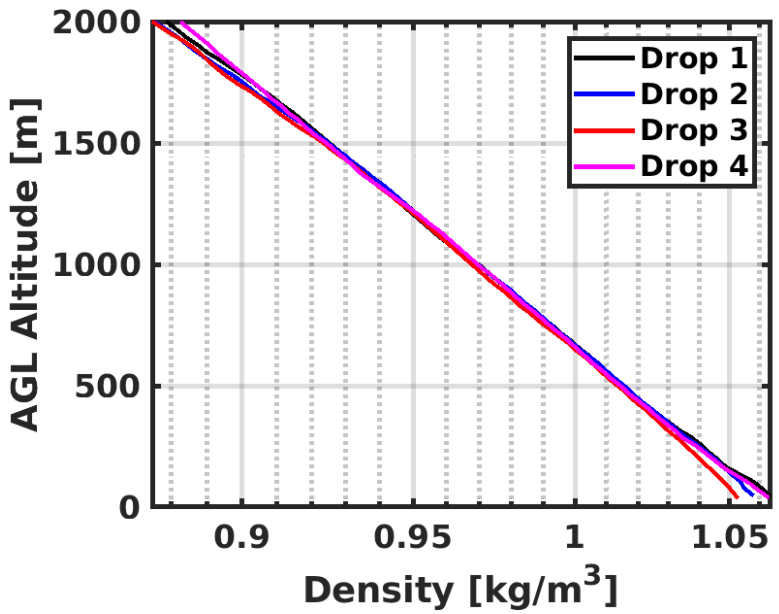
On-Board Video

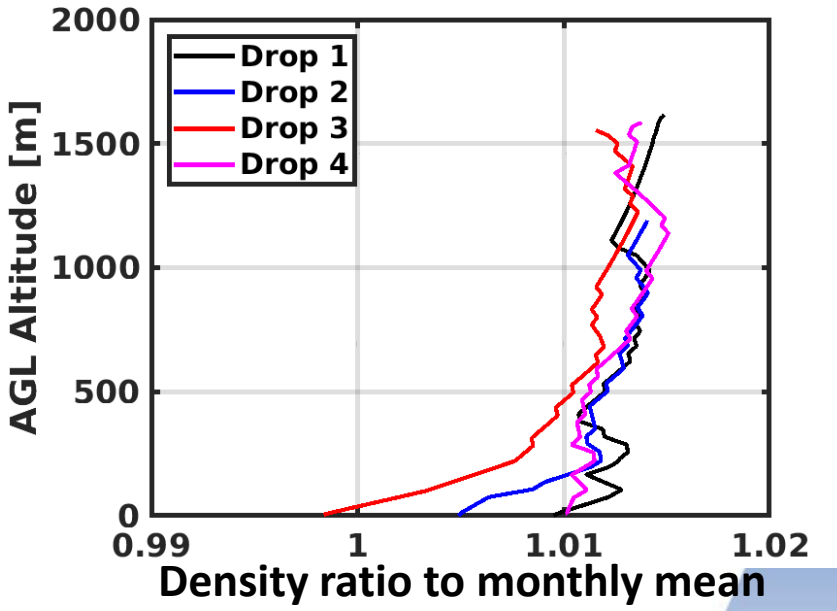
- ***Sony 4k resolution video at 30 fps***



Weather Balloons







- ***Weather balloons were used to measure the atmosphere for both test planning and post-flight reconstruction***
- ***One balloon was launched prior to each test to provide wind data that were used to determine the drop altitude, ground speed, and heading***
- ***The balloon measured densities ~1% higher than the monthly mean***
- ***Balloon data were integrated into post-flight reconstruction and simulations***

Trajectory Reconstruction Approach

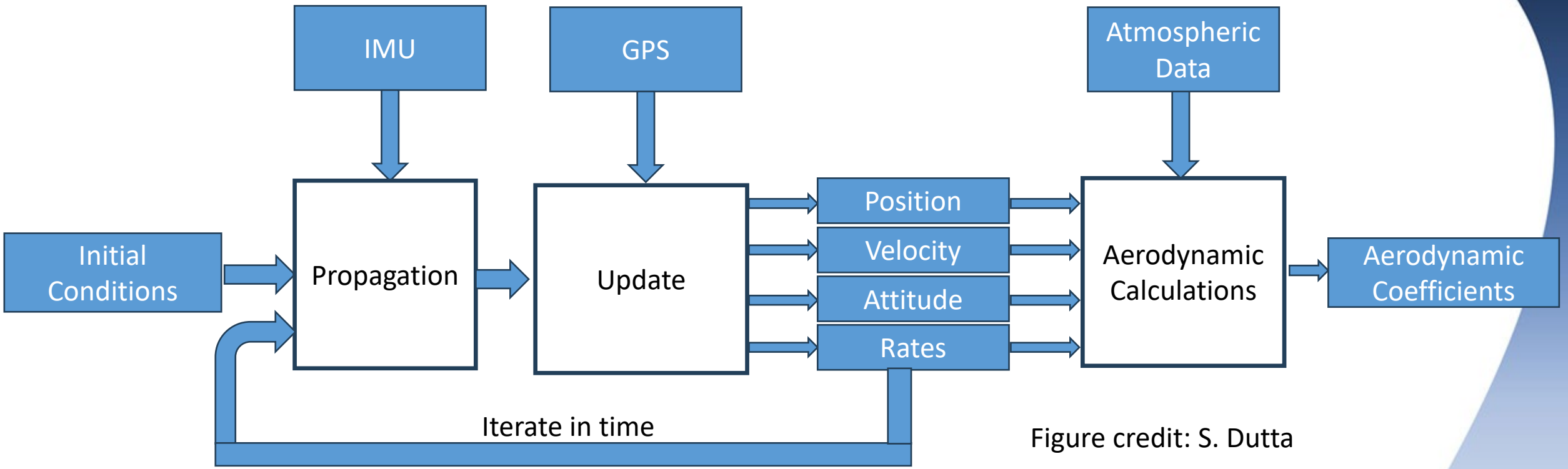
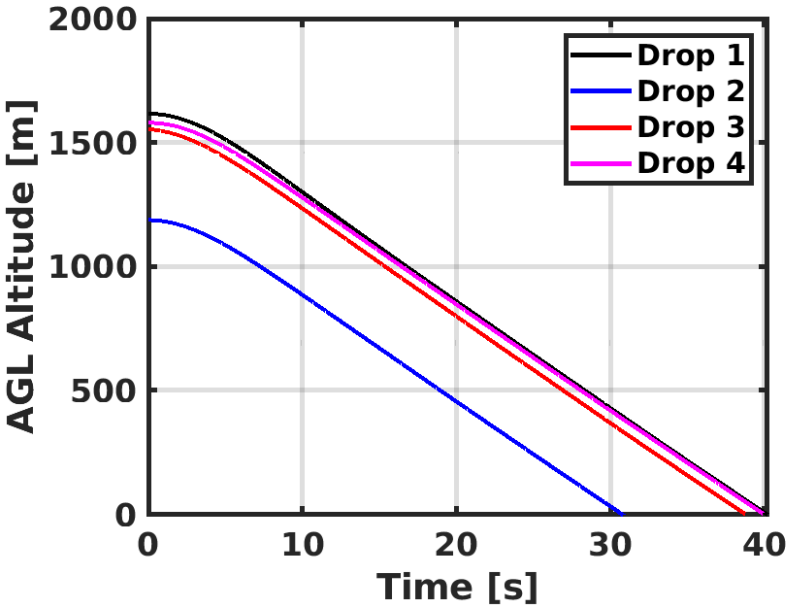
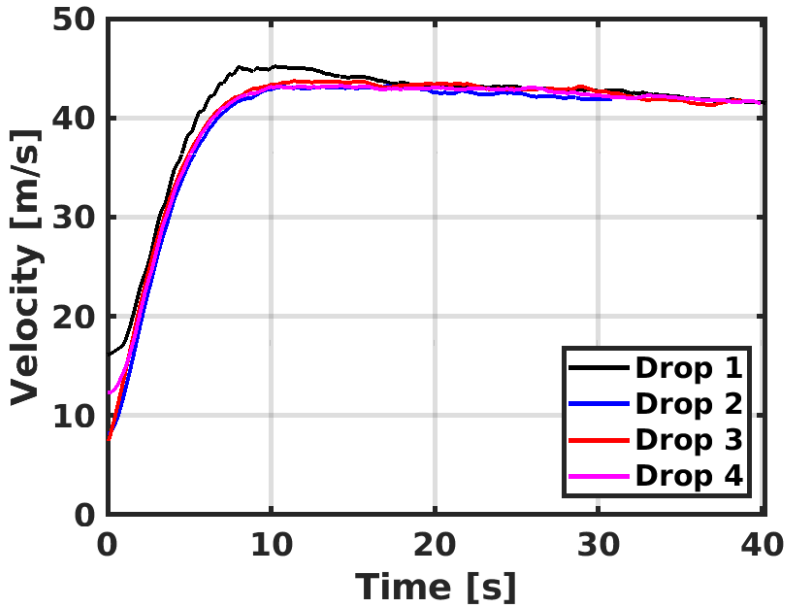


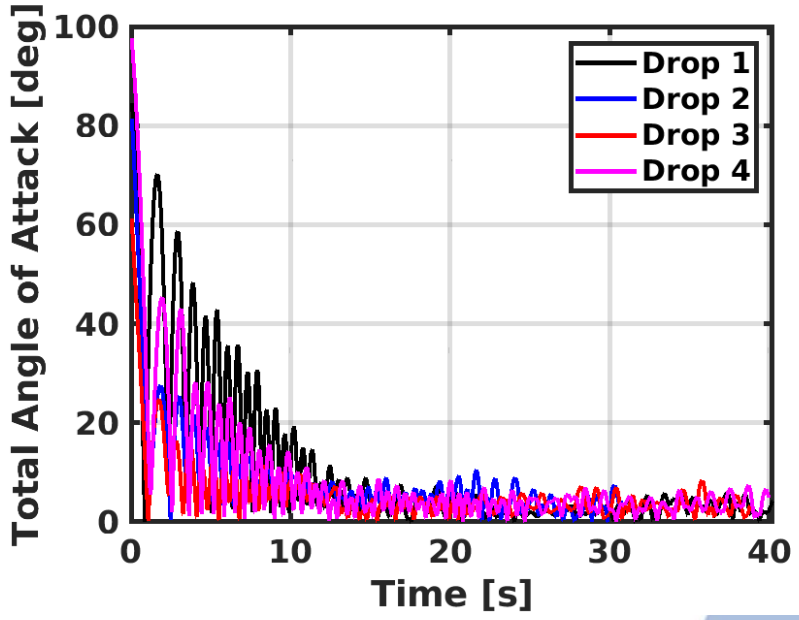
Figure credit: S. Dutta

- ***New Statistical Trajectory Estimation Program (NewSTEP)***
  - Iterative Extended Kalman Filter/Smoother formulated for solving trajectory reconstruction problems

Trajectory Reconstruction Results







- ***Reconstructed impact conditions used for impact structural dynamics analysis (not documented here)***

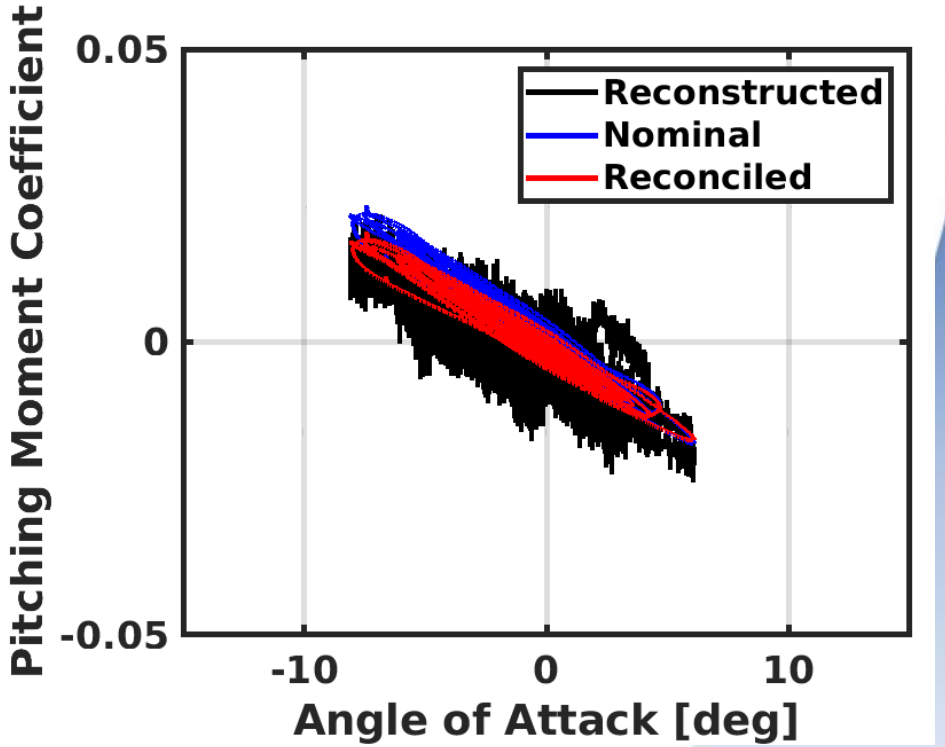
Reconstructed Impact Conditions

Drop Test	Velocity (m/s)	Flight Path Angle (deg)	Off-Nadir angle (deg)
1	41.87	-82.78	3.19
2	41.98	-86.33	3.48
3	41.81	-88.06	3.68
4	41.50	-86.50	1.79

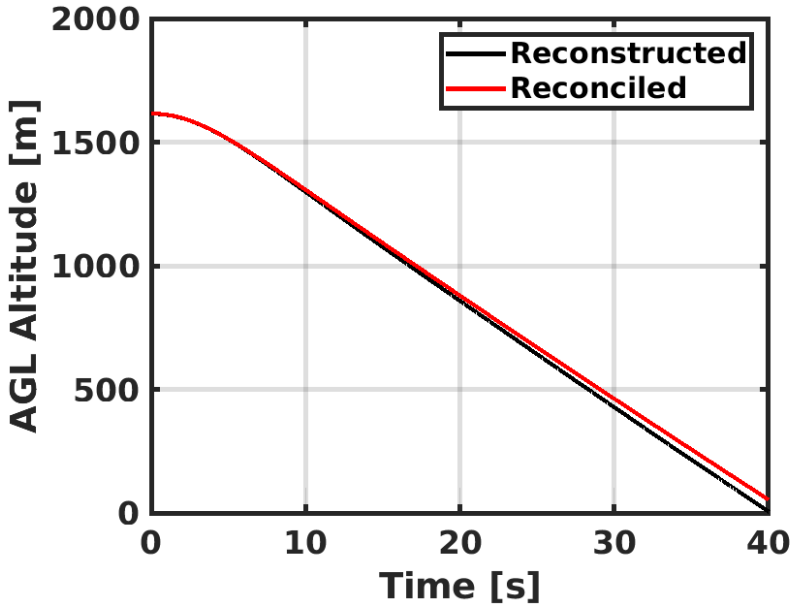
Aerodynamic Reconstruction Results

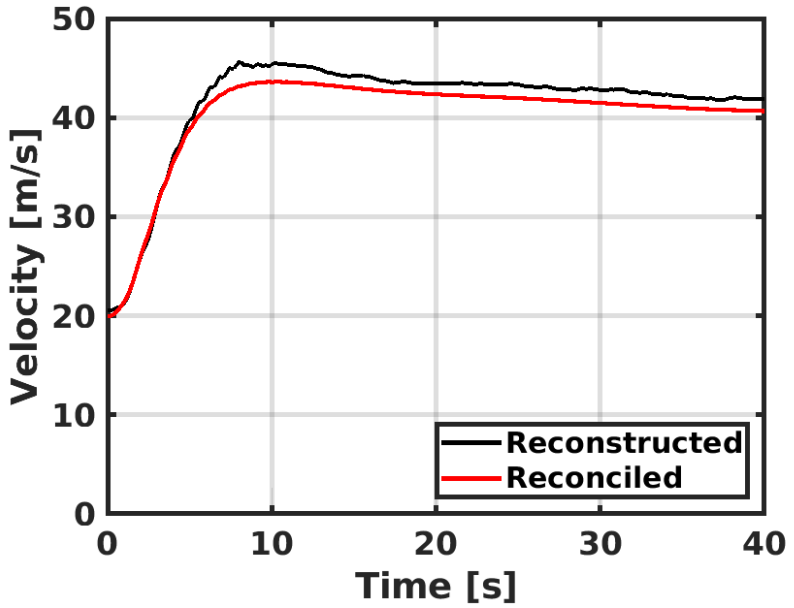
	C_A Multiplier	C_N Adder	C_N/C_Y Multiplier	C_Y Adder	C_m Adder	C_m/C_n Multiplier	C_n Adder
Estimate	0.1641	-0.5860	-0.6577	-0.3115	-0.3949	-0.6476	0.6854
3σ	0.0030	0.0040	0.0123	0.0267	0.0594	0.0641	0.0595

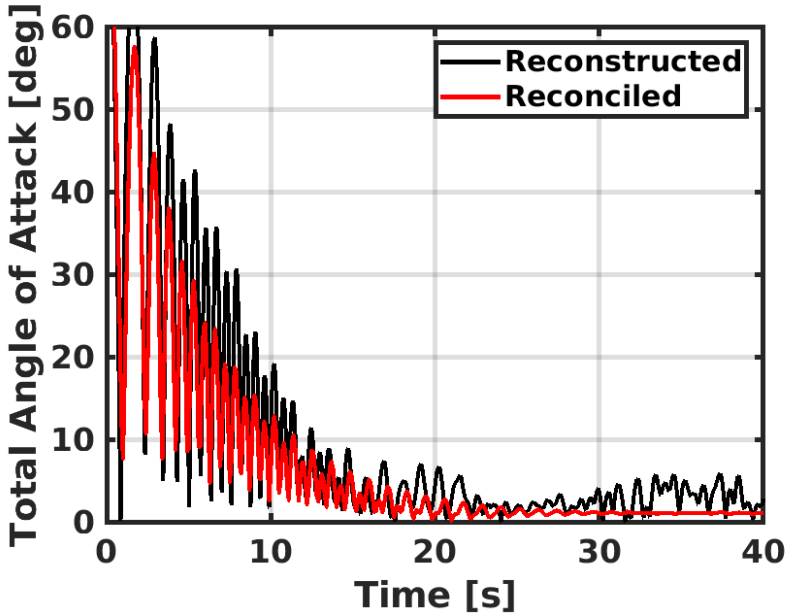
- ***Reconstructed aerodynamic coefficients were computed from sensed accelerations and rates, dynamic pressure, and mass properties***
- ***Reconciled aerodatabase was computed as a best fit to the reconstruction in a process involving all four drop tests simultaneously***
- ***Unsuccessful at estimating dynamic stability***
  - The dynamics model in the aerodatabase does not capture persistent low-amplitude oscillations in the reconstructed angle of attack



Comparison with Simulation – Drop 1



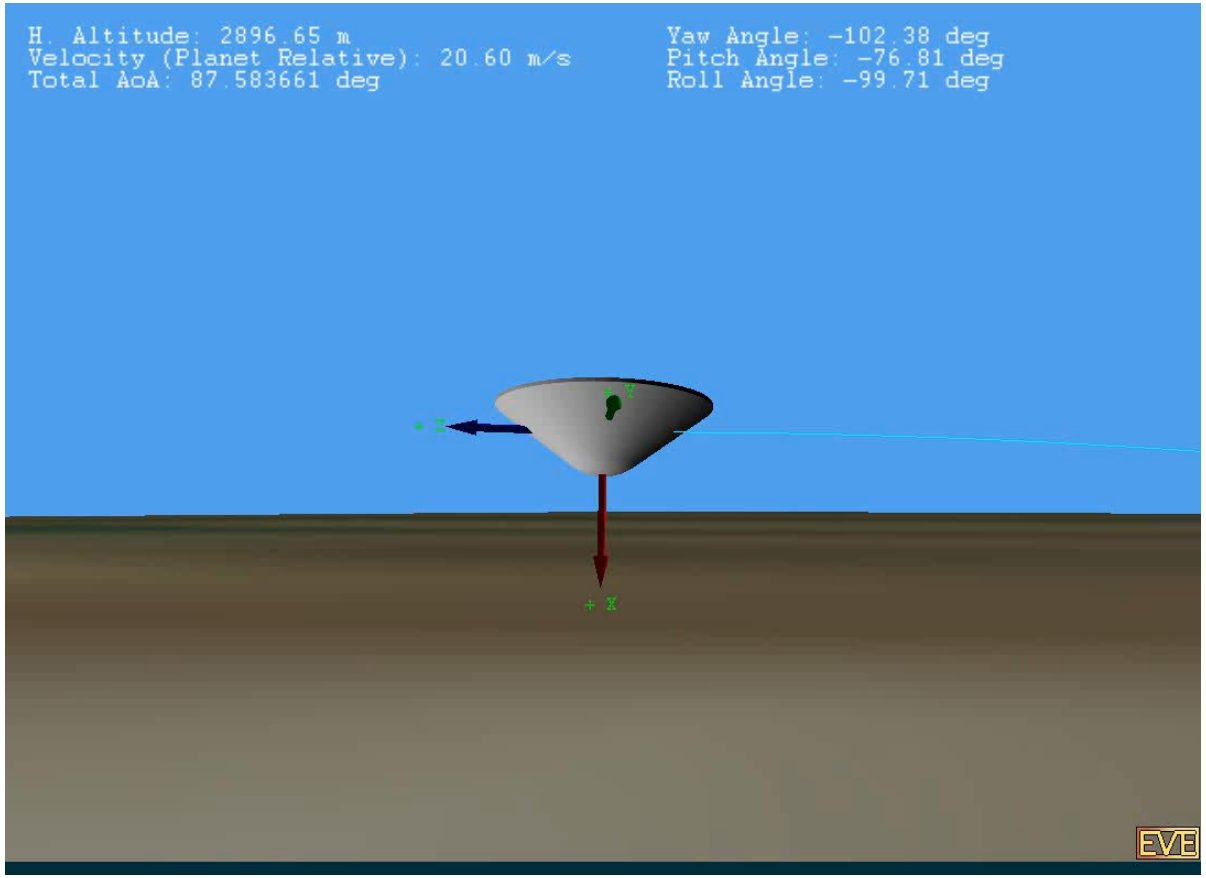




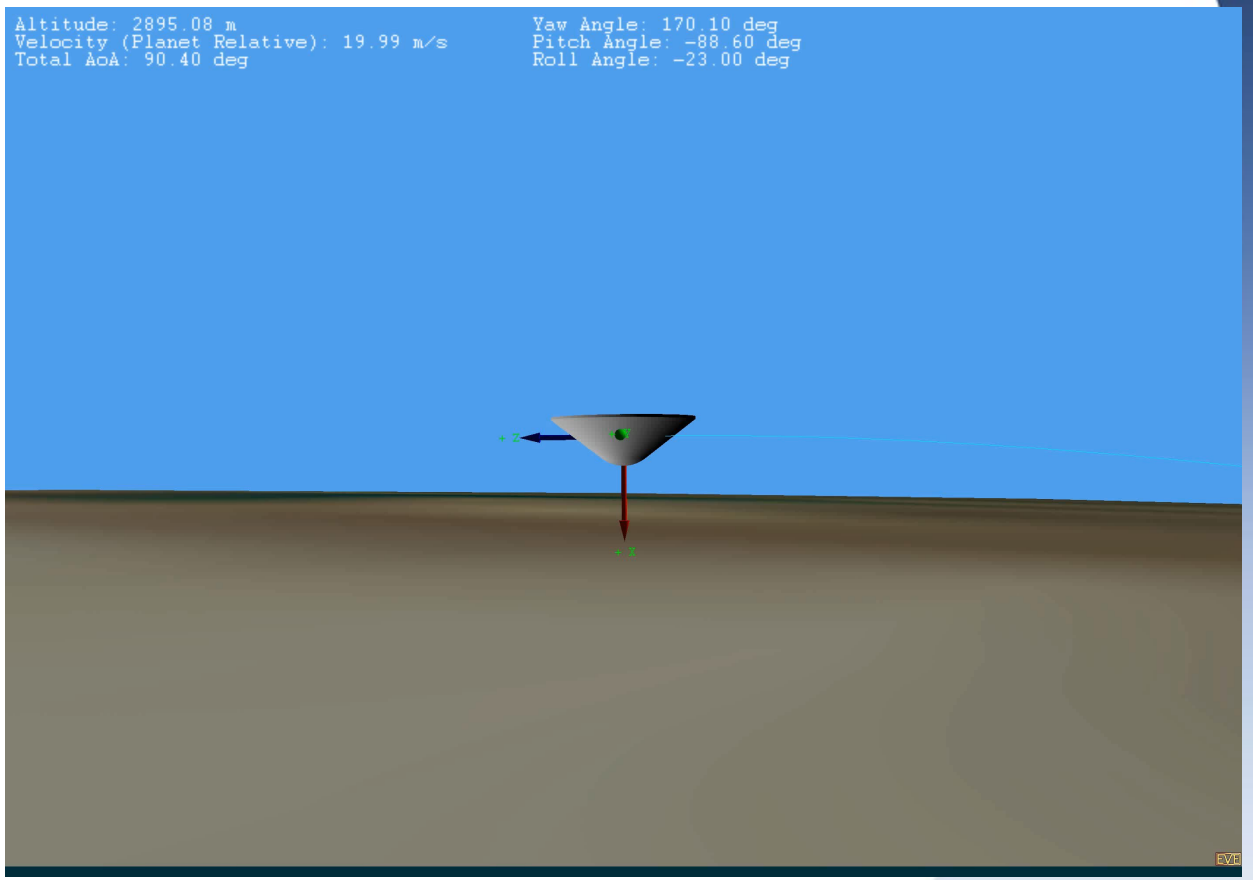
- ***Program to Optimize Simulated Trajectories II (POST2) simulation was updated with the as-flown atmosphere, aerodynamics, and initial conditions to produce the reconciled trajectory***
- ***Simulations predict slightly lower impact velocity, longer flight time, and lower angle of attack – consistently for all drops***
- ***Persistent angle of attack motion in terminal flight is not captured in the simulation***
  - Possible causes: winds, low-amplitude pitch damping characteristics

Animation

Reconstruction



Simulation



- ***Animations created using the Exploration Visualization Environment (EVE)***

Summary

- ***Earth Entry System conducted 4 successful drop tests at UTTR***
- ***On-board instrumentation was used to reconstruct the as-flown trajectory and aerodynamics using NewSTEP***
- ***Test objectives were met***
  - Acquired aerodynamic data
  - Estimate of ground impact conditions
- ***Findings:***
  - Extracted a set of static aerodynamic parameters that are within the uncertainties of the aerodynamic database
  - Evidence of low-amplitude attitude oscillations that are not captured in simulations
  - Reconstructed trajectories have a higher angle of attack, higher impact velocity and shorter flight time than simulation results
  - Determined ground impact conditions

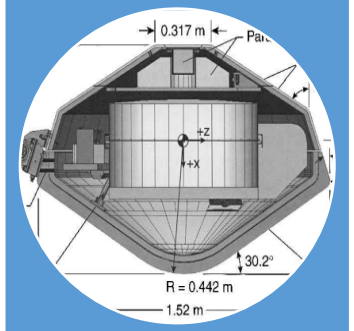
Acknowledgements

➢ ***Special thanks to the entire EES drop-test team and Dugway Proving Grounds/UTTR support team***

Questions?

BACKUP

Comparison of EES to other Earth Return Vehicles



Genesis (2001)

- Spin Stabilized (15 RPM)
- Entry: 11 km/s, -8.3°
- 1.5m Diameter, 60° sphere-cone
- Parachute Descent
- Peak Deceleration: 30 G
- 48 x 15 km landing ellipse

Stardust (2006)

- Spin Stabilized (13.5 RPM)
- Entry: 12.8 km/s, -8.2°
- 0.8 m Diameter, 60° sphere-cone
- Parachute Descent
- Peak Deceleration: 40 G
- 44 x 76 km landing ellipse

OSIRIS-Rex (2023)

- Spin Stabilized (12 RPM)
- Entry: 12.7 km/s, -8.2°
- 0.8m Diameter, 60° sphere-cone
- Parachute Descent
- Peak Deceleration: 40 G
- 58 x 14 km landing ellipse

MSR EES (Current)

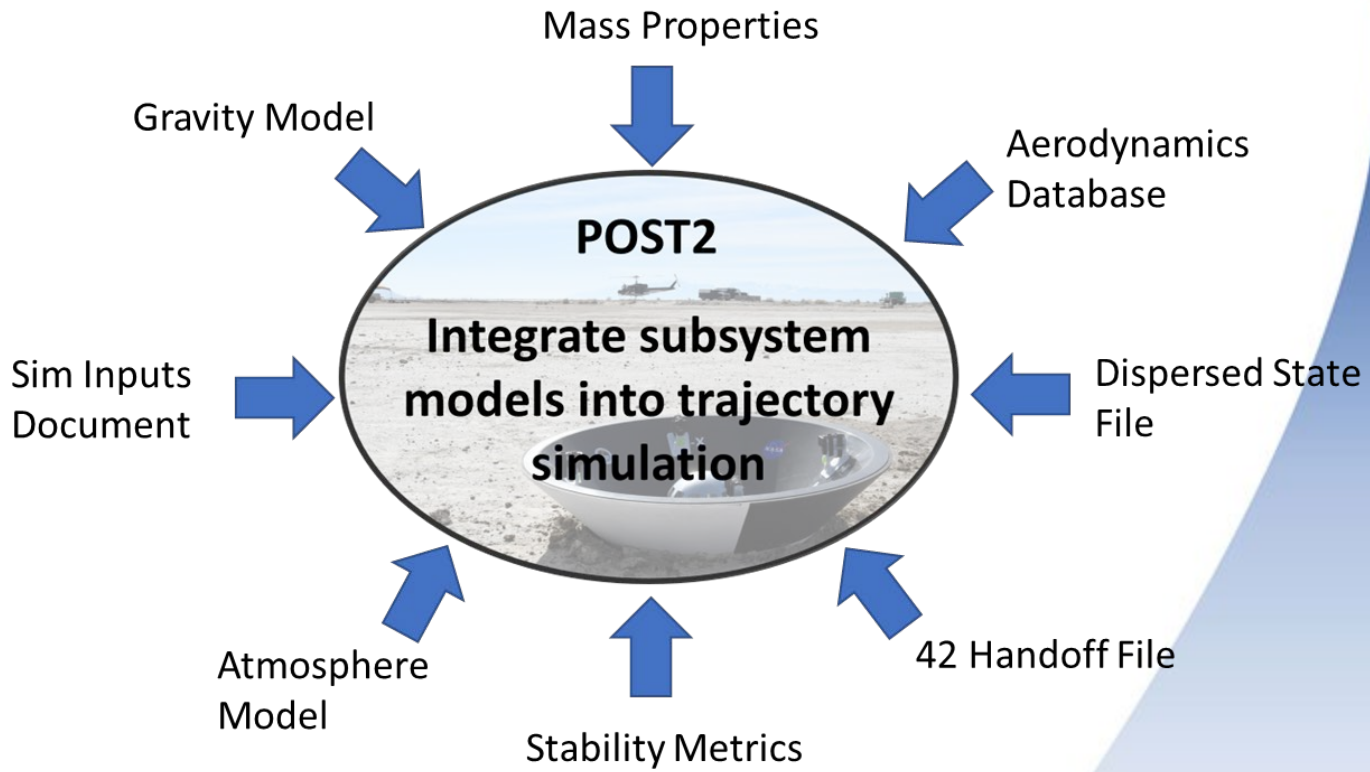
- Spin Stabilized (5 RPM)
- Entry: 11.6 km/s, -22°
- 1.25 m Diameter, 52.5° sphere-cone
- No Parachute
- Peak Deceleration 123 G
- 22 x 17 km landing ellipse

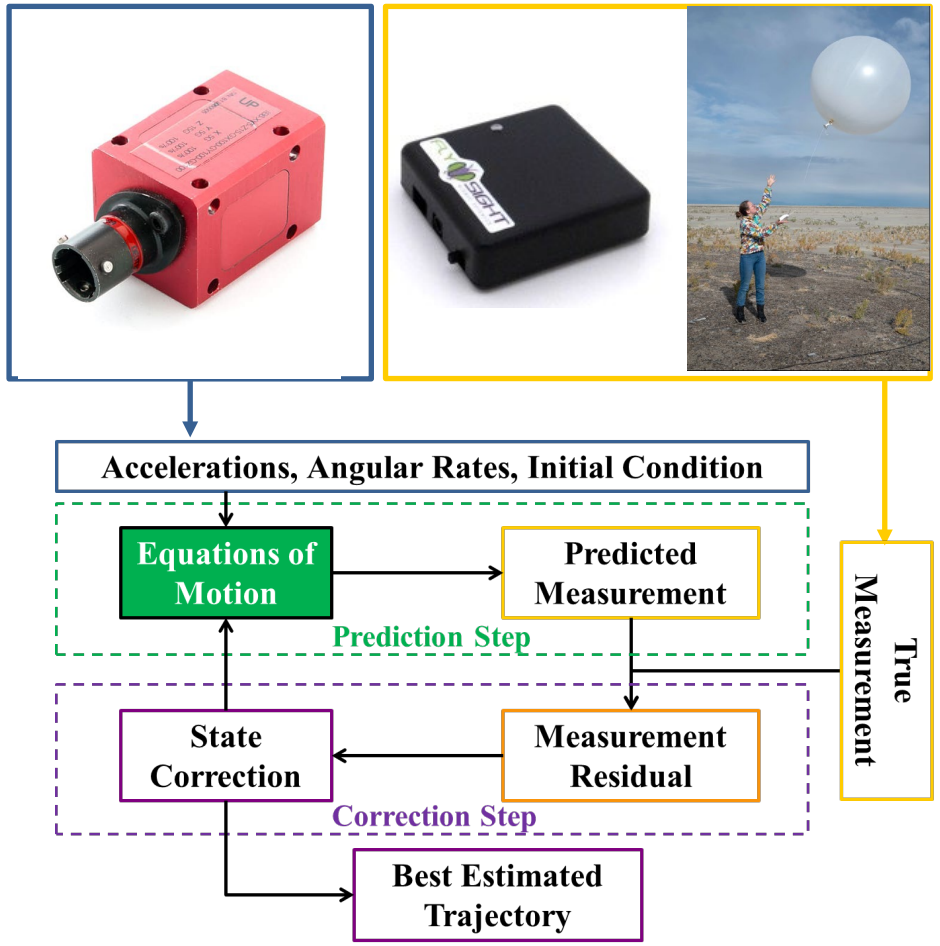
Not Included: Varda (2023)

- **EES does not utilize a stabilizing parachute**
  - Aeroshell cone angle modified to balance volume and aerodynamic stability
- **EES has a very steep Entry Flight Path angle**
  - Done to reduce landing ellipse; but at expense of high heating/deceleration environment

POST2 Simulation Architecture

- **POST2 integrates various subsystem models into flight mechanics sim**
  - Models are checked out with developers
  - Simulation Inputs Document provides centralized document for initializing sim inputs
  - Configure simulation to desired Monte Carlo scenario
  - Outputs post-processed for engineering analysis (e.g. aerothermal) and scorecard generation





Parameter estimation approach

$$\min_{\boldsymbol{u}} \sum_{k=1}^{N} \left[C_k - C\left(M_k, \alpha_k, \beta_k, \boldsymbol{u}\right) \right]^2$$