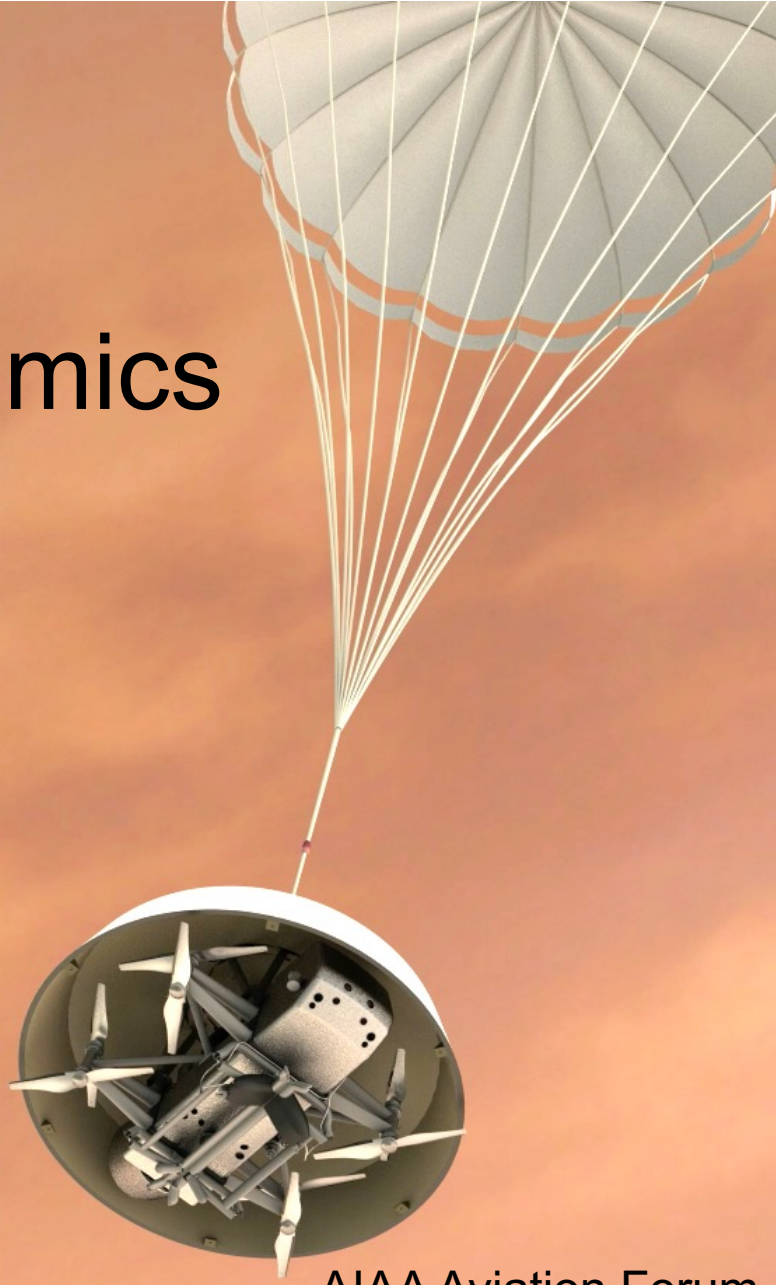
An Investigation of the Dragonfly Mission Aeroshell/Parachute Dynamics through Subscale Drop Tests



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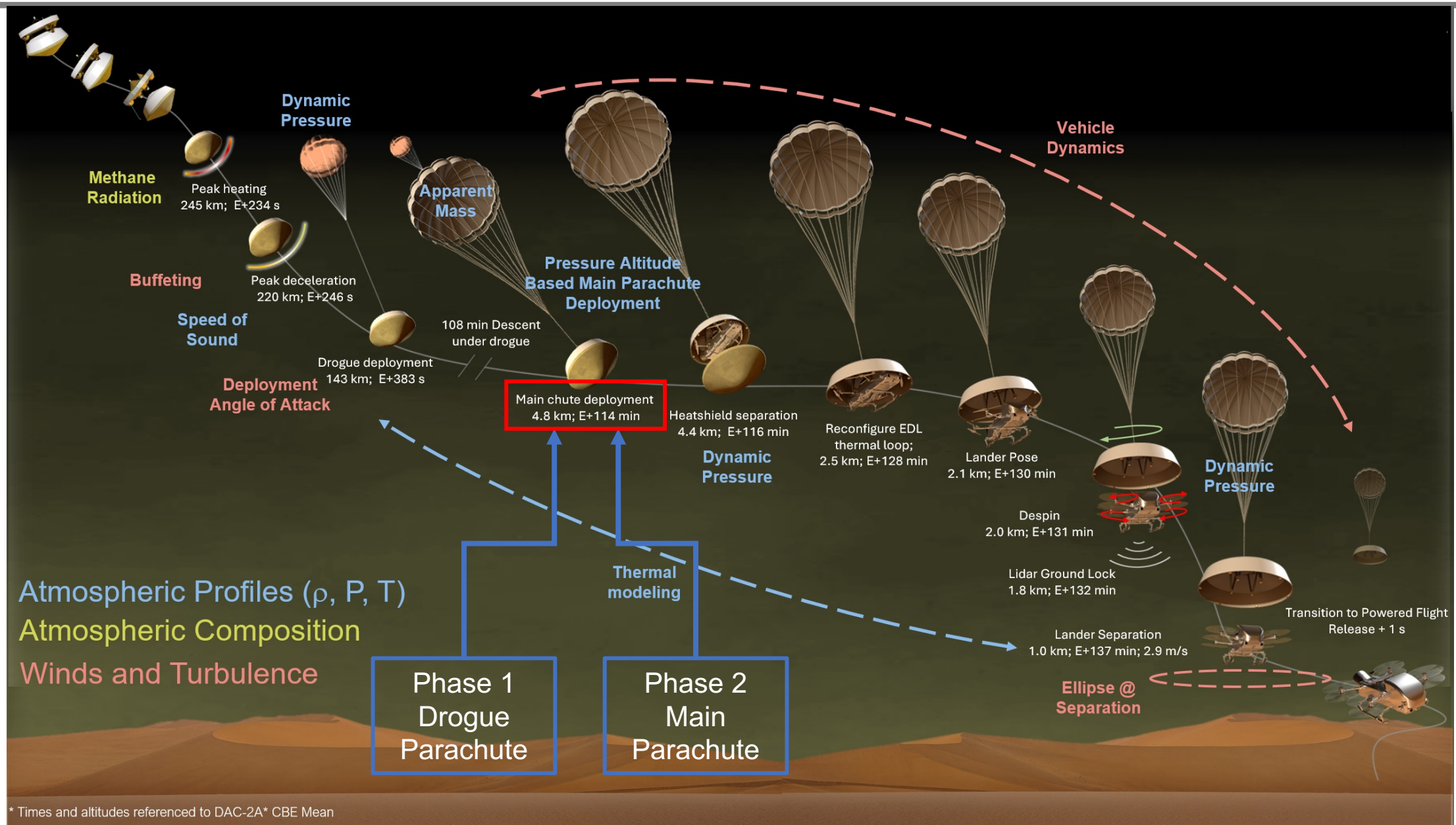
The Dragonfly Mission

- Dragonfly Mission
  - Place a rotorcraft lander on the surface of Titan (Saturn's largest moon)
  - Study prebiotic chemistry and habitability
  - Launch 2028, arrival at Titan by 2034
  - The dense, cryogenic atmosphere poses many design challenges for the entry, descent, and landing (EDL) system

Dragonfly Concept of Operations



* Times and altitudes referenced to DAC-2A* CBE Mean

Test Objectives

- Quantify the dynamics of the Dragonfly aeroshell/parachute system at 4 km Titan altitude
  - Ability to recover from extreme initial conditions (e.g., inverted aeroshell) and settle to “small” angle oscillations
  - Quasi steady-state Euler angles (roll (ϕ), pitch (θ), and nadir (Θ) angles) of the aeroshell
  - Quasi steady-state rotation rates (roll (p), pitch (q), and RMS (Ω) rates) of the aeroshell
- Phase I examines the aeroshell/**drogue parachute** dynamics
- Phase II examines the aeroshell/**main parachute** dynamics

Outline

- The Dragonfly Mission
- Dragonfly Concept of Operations
- Test Objectives
- Test Design
- Dynamically-Scaled Drop Test
- Drop Test Configurations
- Instrumentation
- Test Operations
- Data Analysis
- Conclusions

Test Design

- Dynamically scaled drone drop test of the aeroshell/parachute systems at a 200 acre field
- Split into drogue phase (Dec. 2022) and main phase (Nov. 2023)
- Mount the aeroshell onto an Alta-X drone with a purpose-built container that stages the parachute as the aeroshell drops
- Release the aeroshell at an altitude of 350 m
- Aeroshell and parachute descend for ~45 s drogue, ~65 s main
- Onboard IMUs record quantities of interest to capture dynamics
- Need at least 10 drops per configuration

Dynamically-Scaled Drop Test

- Dynamic-scaling preserves the ratio of aerodynamic to gravitational forces between the model (M) @ Earth sea-level and full-scale (F) @ Titan 4 km

- Given the **environmental** scale factors
  - Density factor, $N_\rho = \frac{\rho_\mathrm{M}}{\rho_\mathrm{F}}$,
  - Gravitational factor, $N_g = \frac{g_\mathrm{M}}{g_\mathrm{F}}$

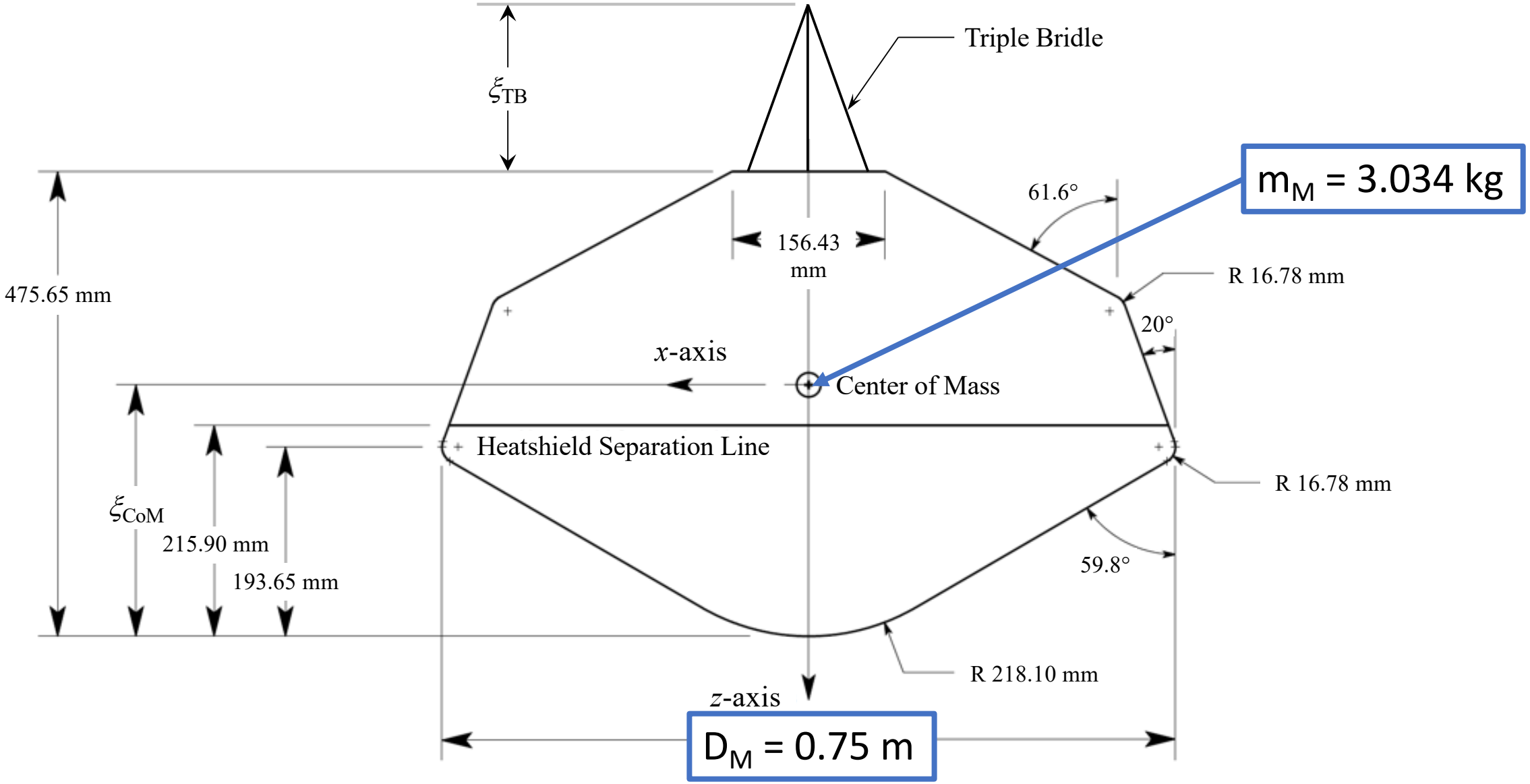
- Choose the **geometric** scale factor $N_L = \frac{L_\mathrm{M}}{L_\mathrm{F}} = 0.1667$ for this test

- Build to the required **mass** scale factors
  - Mass factor, $N_m = \frac{m_\mathrm{M}}{m_\mathrm{F}} = N_\rho N_L^3$,
  - Inertia factor, $N_I = \frac{I_\mathrm{M}}{I_\mathrm{F}} = N_\rho N_L^5$,

Effects of Dynamic Scaling

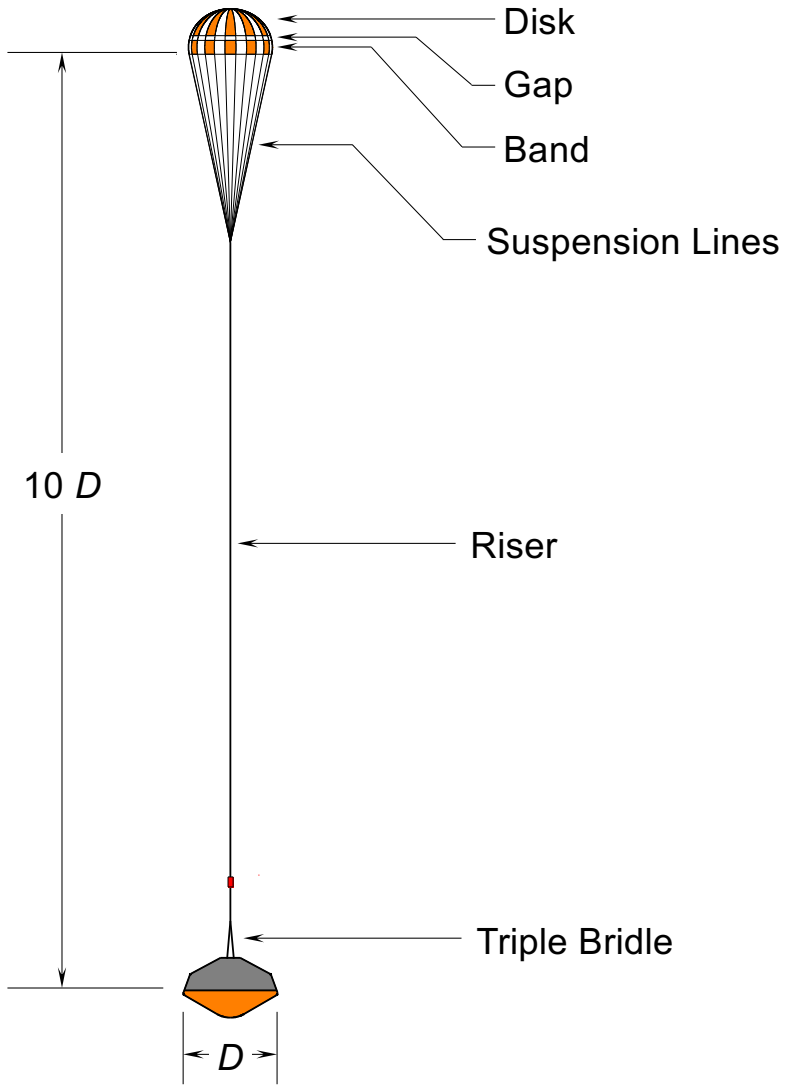
Parameter Type	Scale Factor	Equation	Value	Comment
Geometric	Linear Dimension	$N_L = \frac{L_\mathrm{M}}{L_\mathrm{F}}$	0.1667	16.67 percent scale model
Environment	Atmospheric Density	$N_\rho = \frac{\rho_\mathrm{M}}{\rho_\mathrm{F}}$	0.2625	$\rho_\mathrm{M} = 1.2250\ \mathrm{kg/m^3}$ (Earth sea-level) $\rho_\mathrm{F} = 4.6671\ \mathrm{kg/m^3}$ (Titan at 4 km altitude)
Environment	Acceleration of Gravity	$N_g = \frac{g_\mathrm{M}}{g_\mathrm{F}}$	7.270	$g_\mathrm{M} = 9.807\ \mathrm{m/s^2}$ (Earth sea-level) $g_\mathrm{F} = 1.349\ \mathrm{m/s^2}$ (Titan at 4 km altitude)
Mass	Mass	$N_m = \frac{m_\mathrm{M}}{m_\mathrm{F}} = N_\rho N_L^3$	$1.215 \bullet 10^{-3}$	
Mass	Mass Moment of Inertia	$N_I = \frac{I_\mathrm{M}}{I_\mathrm{F}} = N_\rho N_L^5$	$3.375 \bullet 10^{-5}$	
Time	Time	$N_t = \frac{t_\mathrm{M}}{t_\mathrm{F}} = \sqrt{\frac{N_L}{N_g}}$	0.1514	Time is compressed in model scale ($N_t < 1$).
Time	Rotation Rate	$N_\omega = \frac{\omega_\mathrm{M}}{\omega_\mathrm{F}} = \sqrt{\frac{N_g}{N_L}}$	6.604	Rotation rates of model are larger than full-scale.

16.67% Aeroshell Configuration



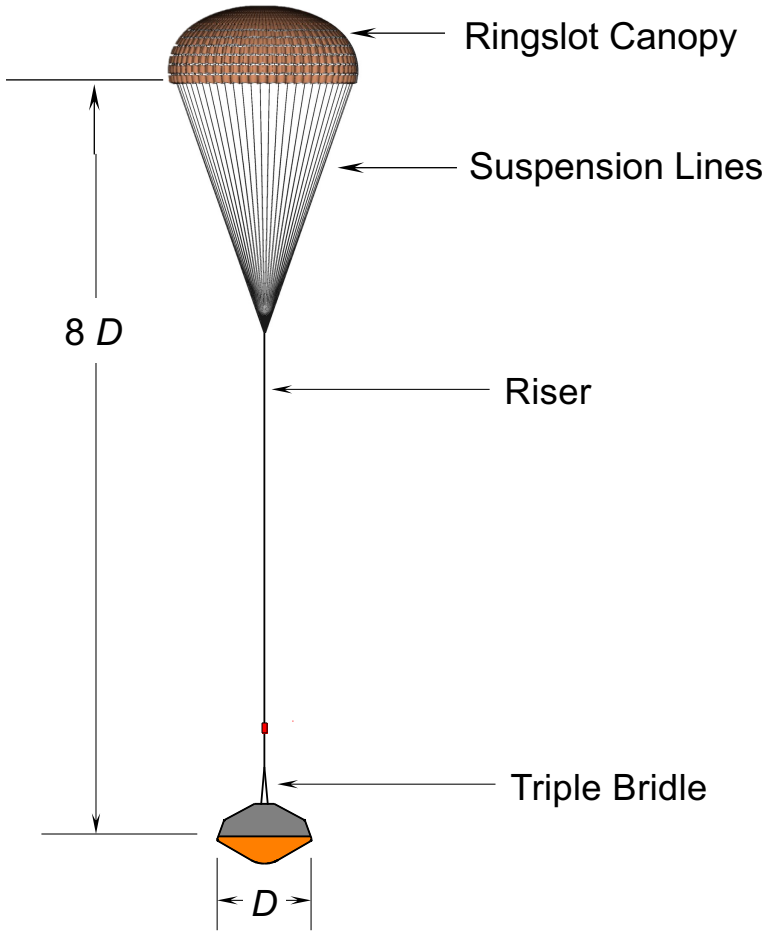
Phase I Parachute Configuration

- Aeroshell with heatshield
- 0.90 m Disk-Gap-Band (DGB) drogue parachute (5.4 m full-scale nominal diameter)
- Geometric scaling of triple bridle, riser, and suspension lines
- 12 drops conducted



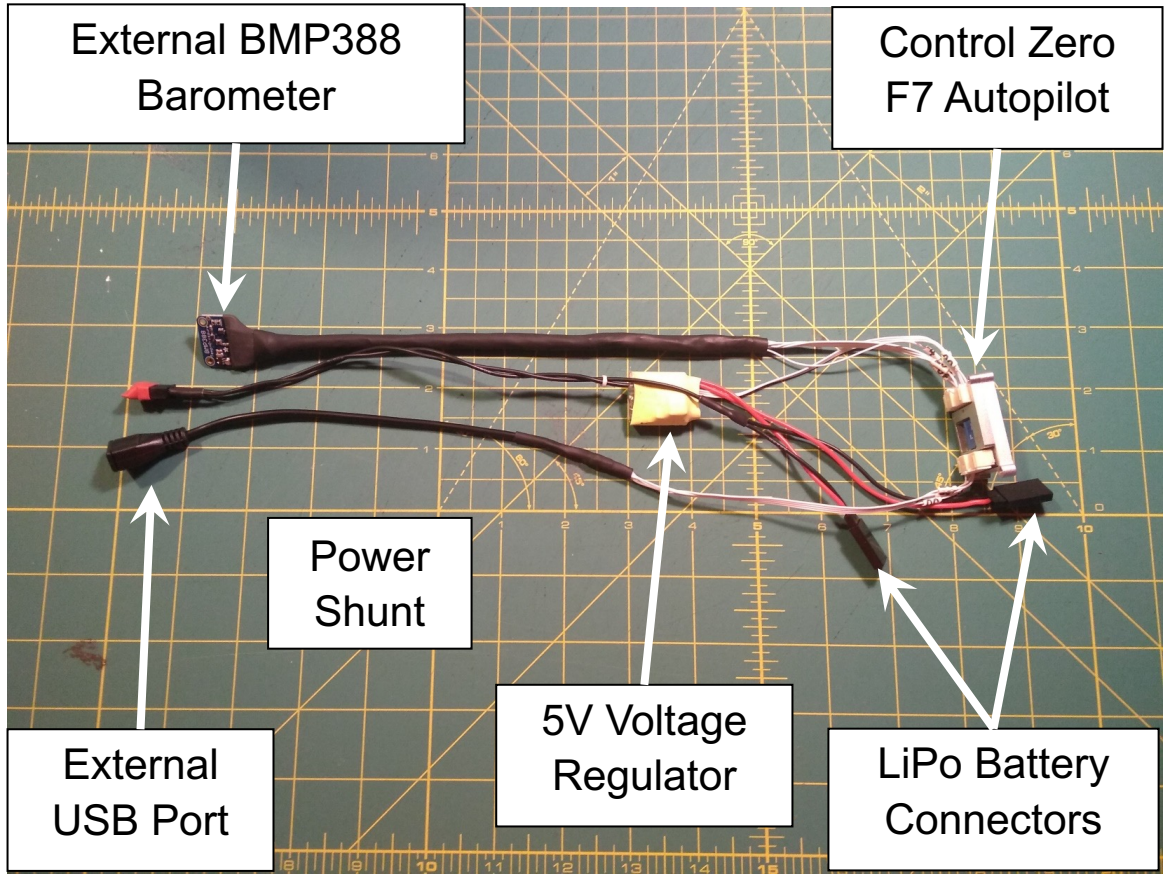
Phase II Parachute Configuration

- Aeroshell with heatshield
- 2.78 m Conical Ringslot main parachute (16.7 m full-scale nominal diameter)
- Geometric scaling of triple bridle, riser, and suspension lines
- Parachute geometric porosity: 13 drops at 20% and 12 drops at 15%



Instrumentation and Data Collection

Measurement	Recording Rate
Accelerometer, 3-axis	215 Hz
Gyroscope, 3-axis	215 Hz
Magnetometer, 3-axis	10 Hz



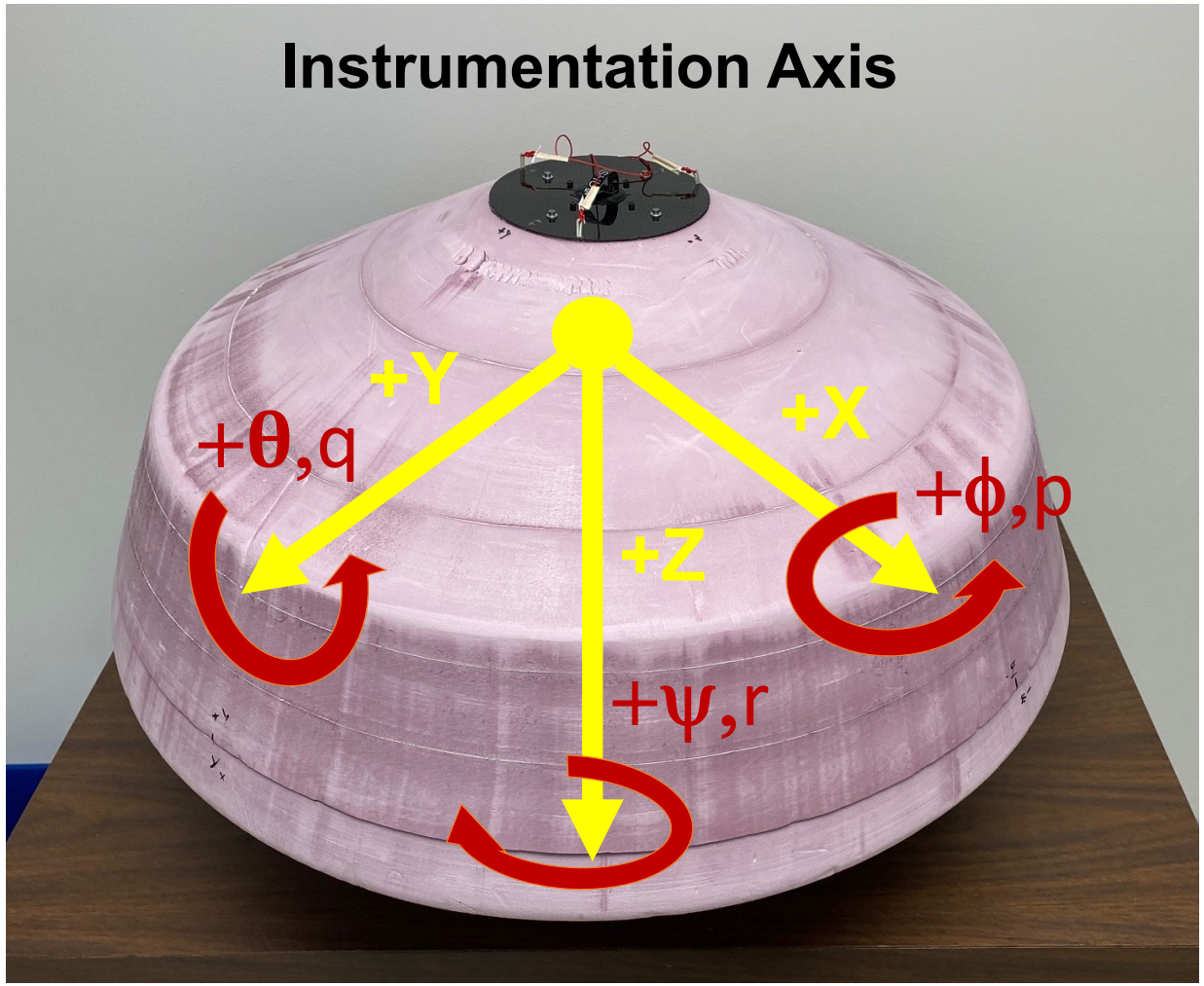
- Euler angles calculated on-board through data fusion @ 10 Hz
- Instrumentation calibrated for temperature variations

Test Operations (1 of 3)

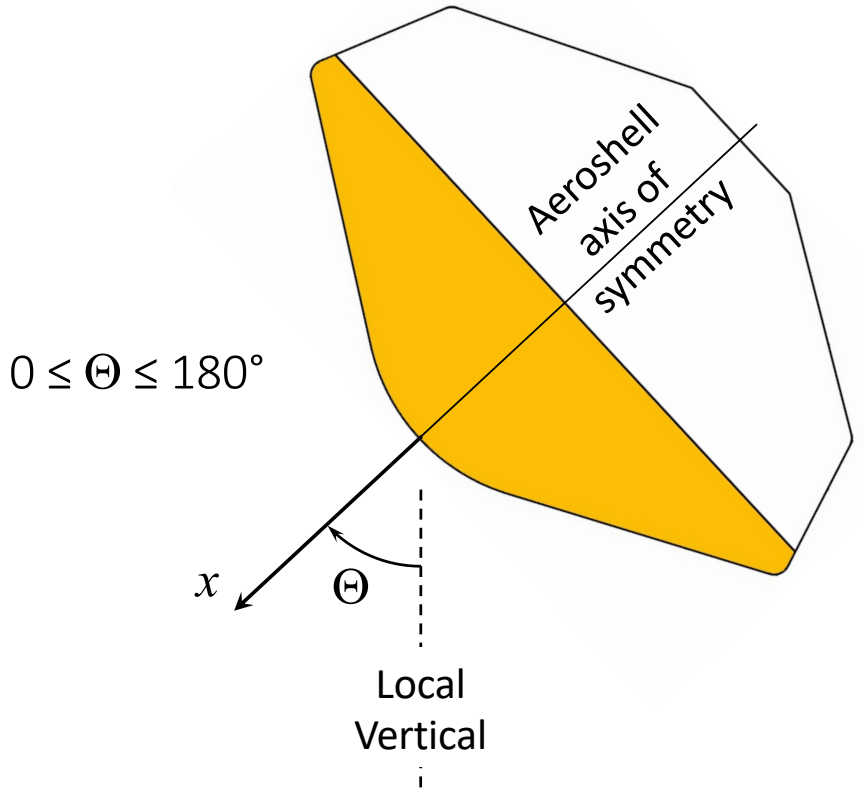
Test Operations (2 of 3)

Test Operations (3 of 3)

Data Analysis (1 of 5)



Nadir Angle, $\Theta = \cos^{-1}(\cos(\theta)\ \cos(\phi))$

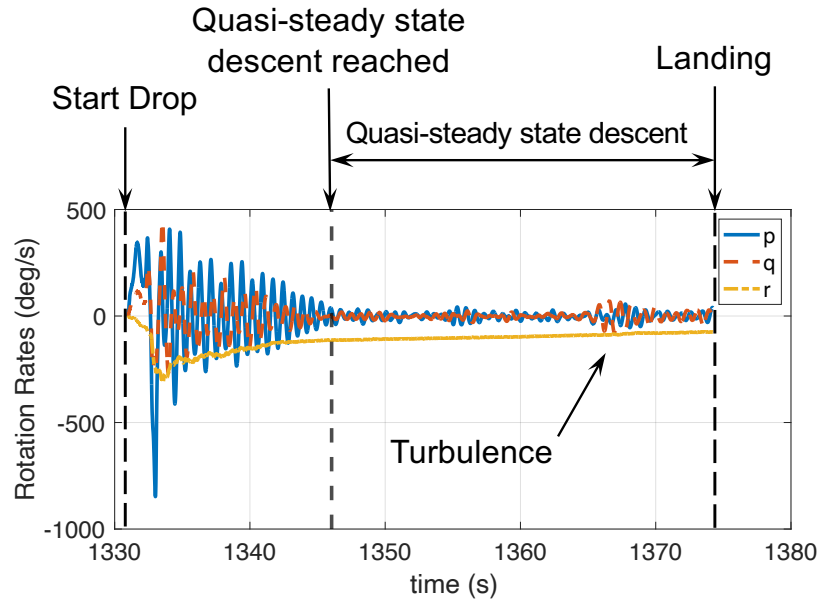


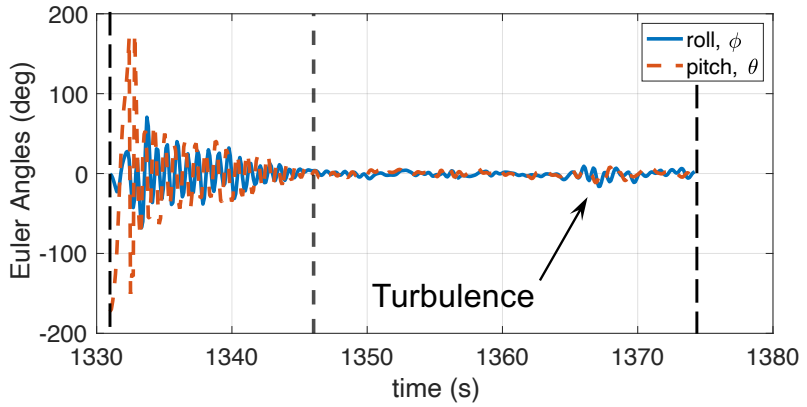
RMS Rotation Rate, $\Omega = \sqrt{q^2 + p^2}$

Data Analysis (2 of 5)

Single Drop | Appended Drops | Statistics I | Statistics II

- Release of the aeroshell and parachute from inverted position
- Initial transient
  - Dynamics rapidly decay after rapid decay initial large oscillation amplitudes
- Defined phase of flight: quasi-steady state descent
  - No further damping of pitch or roll rate
- Low altitude gust disturbances observed in some drops

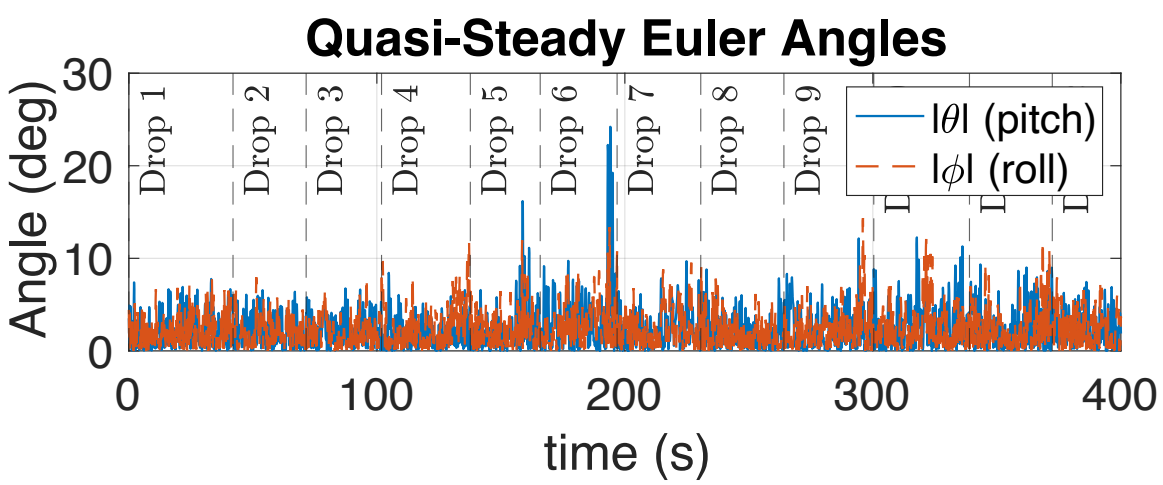


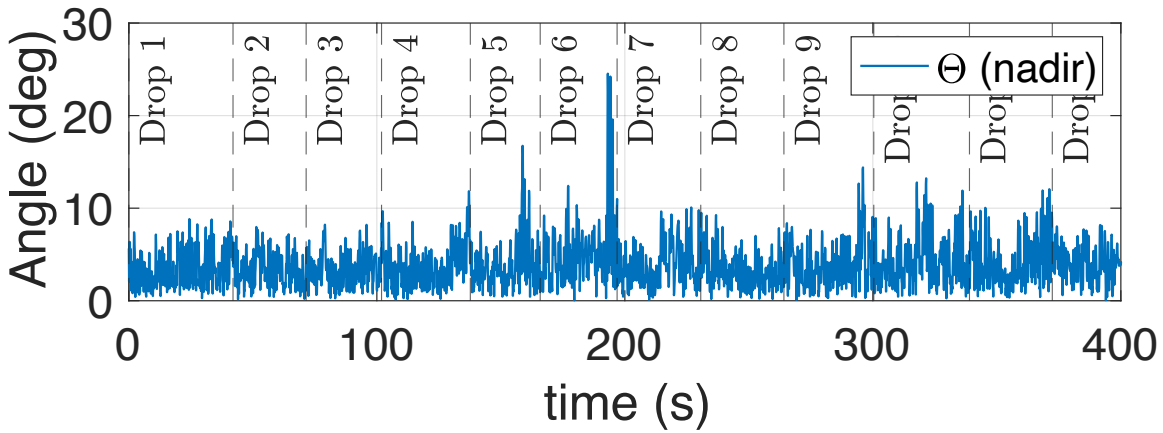


Data Analysis (3 of 5)

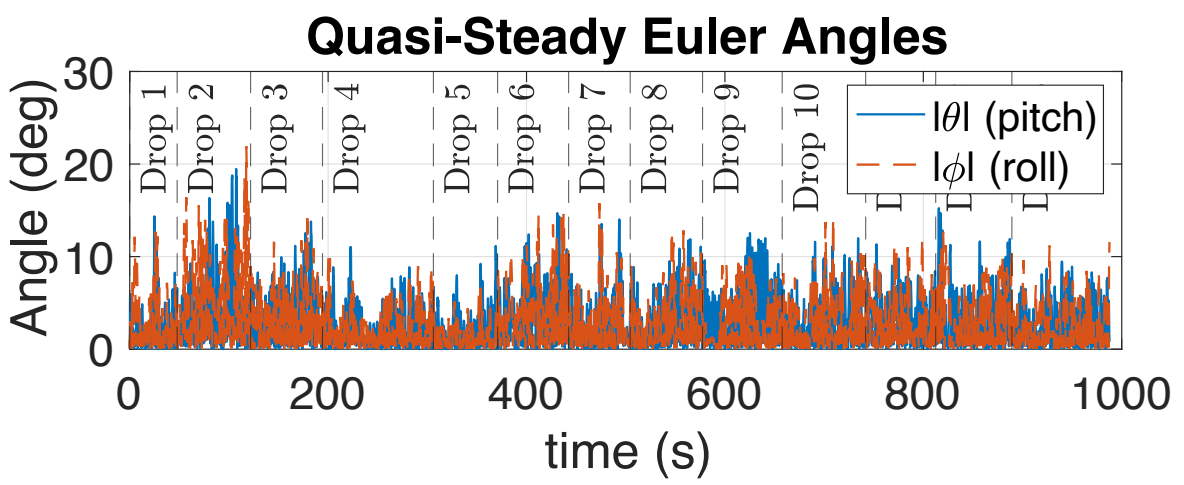
Single Drop | Appended Drops | Statistics I | Statistics II

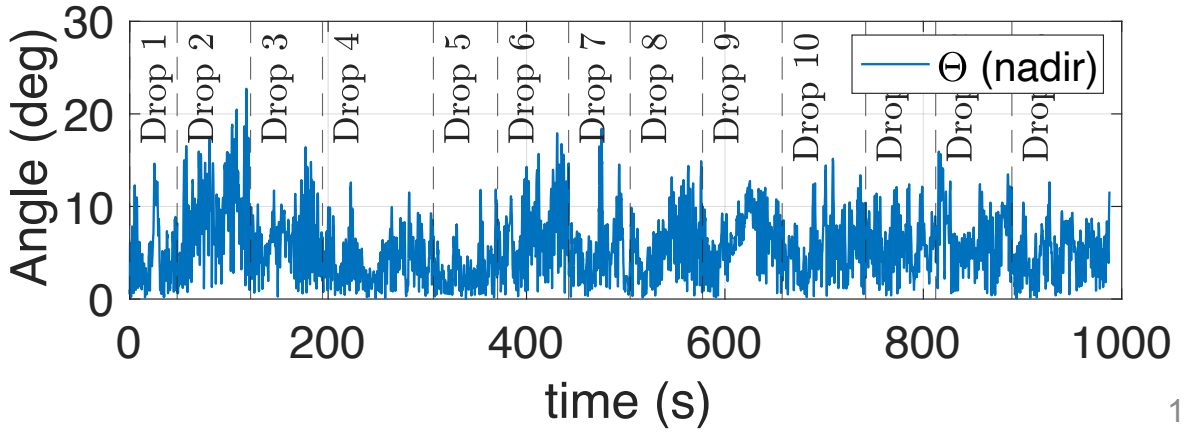
Phase I – Drogue Parachute





Phase II – 20% Main Parachute





Data Analysis (4 of 5)

Single Drop | Appended Drops | Statistics I | Statistics II

Percentile	Phase I			Phase II		
	Drogue Parachute			Main Parachute 20% Geometric Porosity		
	Pitch Angle $\lvert\theta\rvert$ (deg)	Roll Angle $\lvert\phi\rvert$ (deg)	Nadir Angle Θ (deg)	Pitch Angle $\lvert\theta\rvert$ (deg)	Roll Angle $\lvert\phi\rvert$ (deg)	Nadir Angle Θ (deg)
50%-tile	2.0	2.0	3.6	2.9	3.3	5.5
90%-tile	5.2	5.4	7.0	8.0	7.7	10.6
99%-tile	**9.4**	**9.3**	**11.4**	**13.1**	**12.7**	**15.4**
Maximum	14.3	24.2	24.5	21.9	19.5	22.7

Data Analysis (5 of 5)

Single Drop | Appended Drops | Statistics I | Statistics II

Percentile	Phase I			Phase II		
	Drogue Parachute			Main Parachute 20% Geometric Porosity		
	Pitch Rate $\lvert q \rvert$ (deg/s)	Roll Rate $\lvert p \rvert$ (deg/s)	Combined Pitch and Roll Rates Ω (deg/s)	Pitch Rate $\lvert q \rvert$ (deg/s)	Roll Rate $\lvert p \rvert$ (deg/s)	Combined Pitch and Roll Rates Ω (deg/s)
50%-tile	1.6	1.7	2.8	0.8	0.7	1.3
90%-tile	4.1	4.1	5.4	1.9	1.9	2.6
99%-tile	**7.7**	**6.9**	**9.2**	**3.4**	**3.4**	**4.2**
Maximum	19.9	10.6	20.0	6.3	6.6	7.7

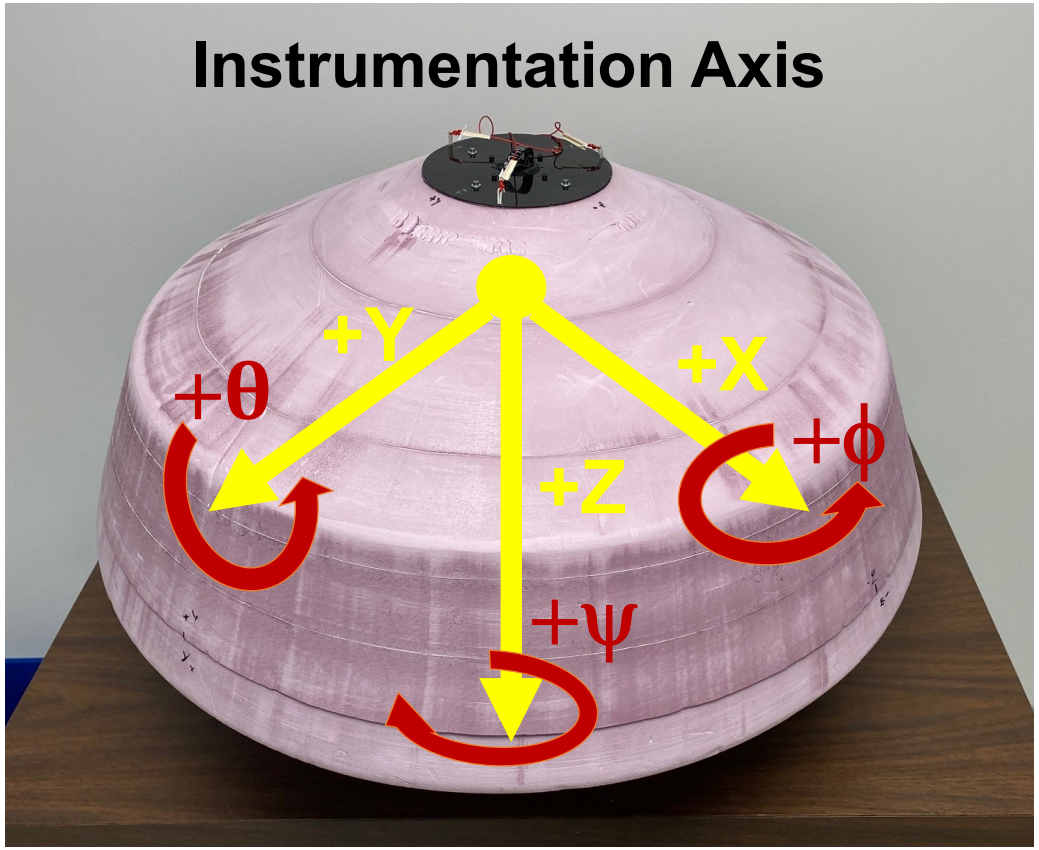
*All rates are in full-scale (full-scale rates = model scale rates / 6.604).

Conclusions

- Analysis shows the aeroshell consistently recovers from initial inverted position and settles into a quasi-steady state
- The drogue parachute had lower values of $|\theta|$, $|\phi|$, and Θ than the main parachutes
- The drogue parachute had higher values of $|q|$, $|p|$, and Ω than the main parachutes
- For all parachutes, the values of $|q|$, $|p|$, and Ω were considered low in full-scale time from the standpoint of the Dragonfly mission
- Currently using the statistical data to compare to flight mechanics simulations of the same configurations
- Since conducting the test, the nominal full-scale diameter of the drogue parachute has increased from 5.4 m to 8.25 m. Therefore, the results from Phase I are considered conservative


DRAGONFLY

Backup Chart: Instrumentation Axis

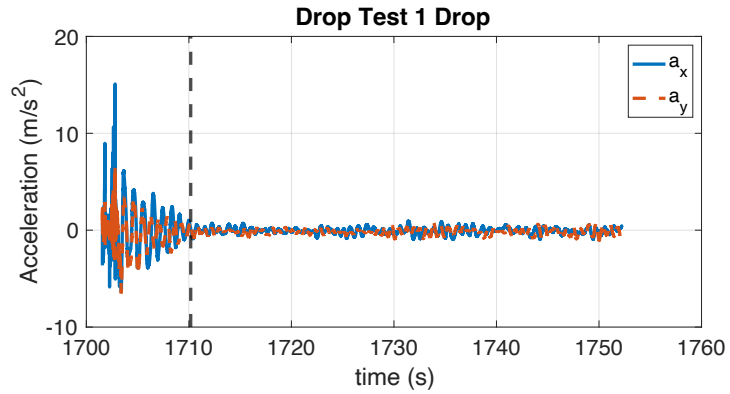


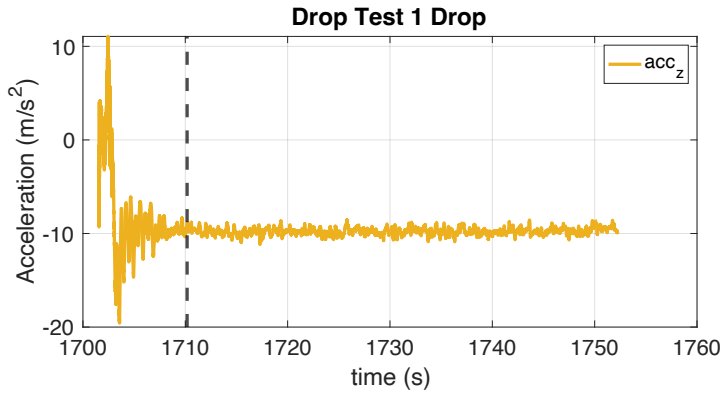
IMU Corrections

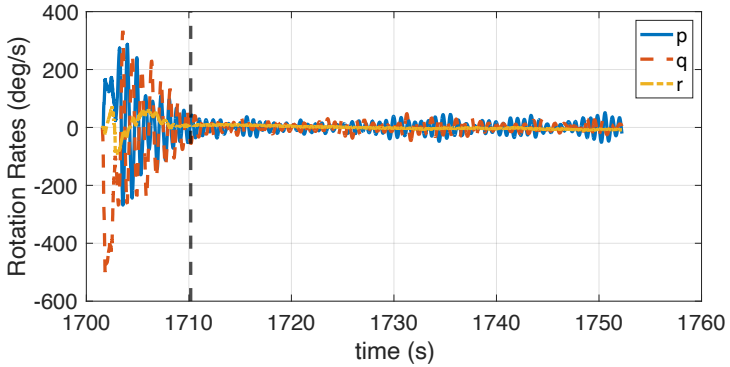
- Pretest temperature calibration of IMU (improves accuracy!)
- Accelerometer
  - < $1x10^{-4}$ m/s^3 drift pre/post flight
  - Global multiplier to bring $|acc| = |g_{earth}|$
- Gyro
  - < $1x10^{-4}$ deg/s^2 drift pre/post flight
  - Each component had individual bias offset applied
- No corrections to static pressure

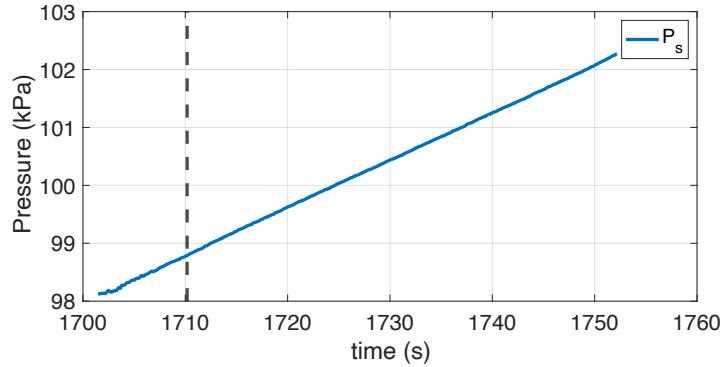
Drop Test 1 Calibration Post Impact Hold Mean Values			
Mean Value	Raw Signal	Cal Signal	Units
$\|acc\|$	9.7934	9.8066	m/s^2
$d\|acc\|/dt$	-2.9E-5	-2.9E-5	m/s^3
p	-5.9E-2	-1.7E-16	deg/s
q	8.2E-2	2.2E-17	deg/s
r	1.0E-2	2.9E-17	deg/s
dp/dt	-3.4E-5	-3.4E-5	deg/s^2
dq/dt	-7.5E-5	-7.5E-5	deg/s^2
dr/dt	-7.1E-5	-7.1E-5	deg/s^2

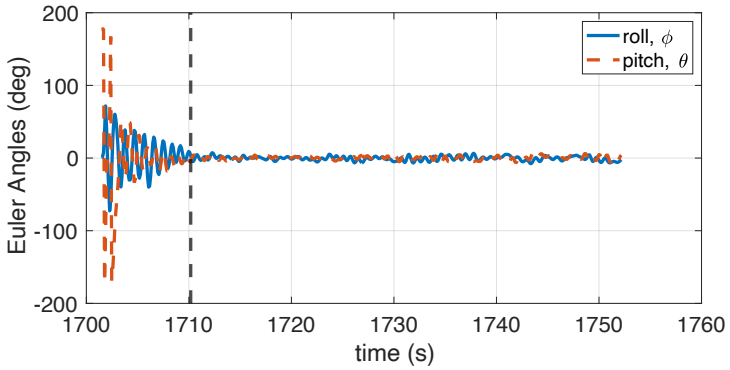
Backup Chart: Drop 1 Data Streams

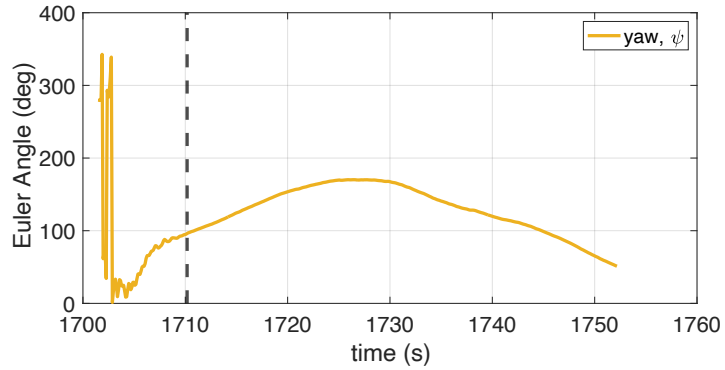




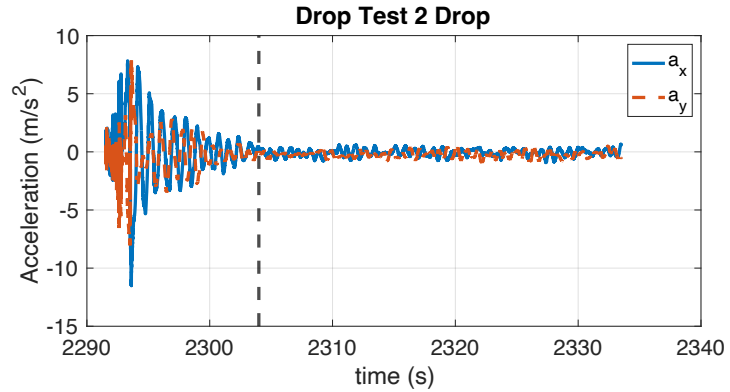


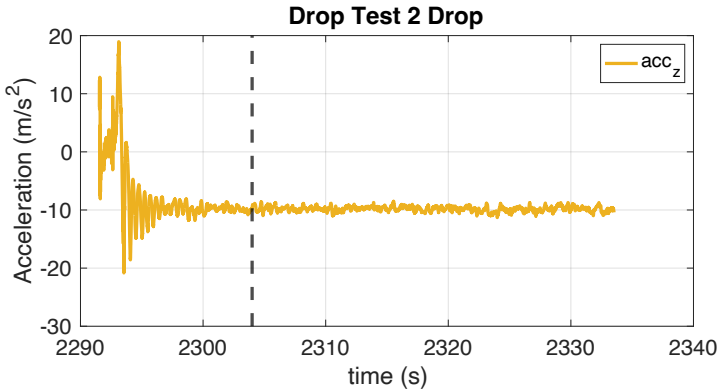


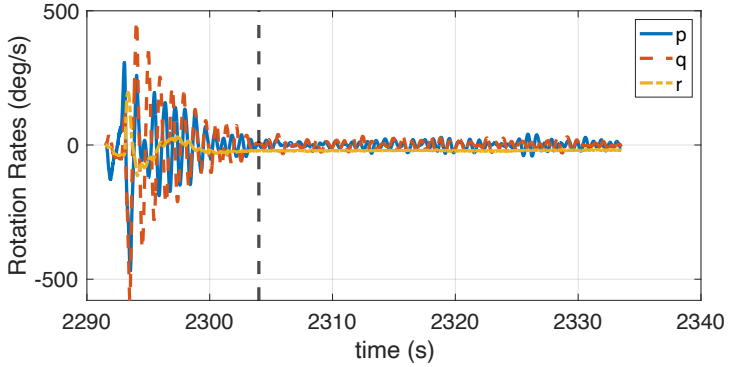


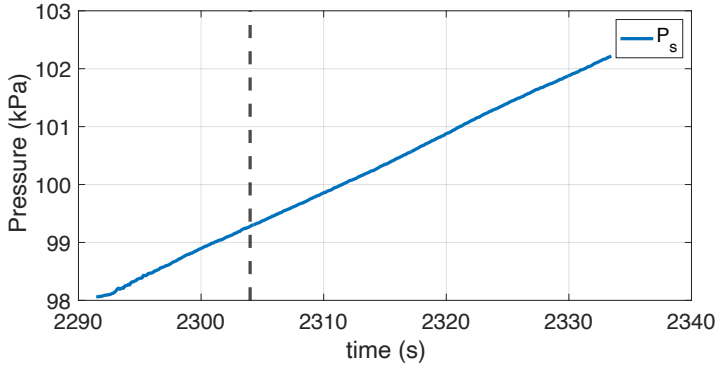


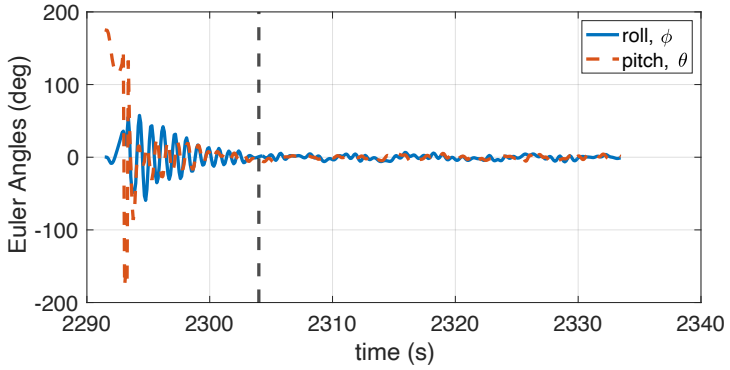
Backup Chart: Drop 2 Data Streams

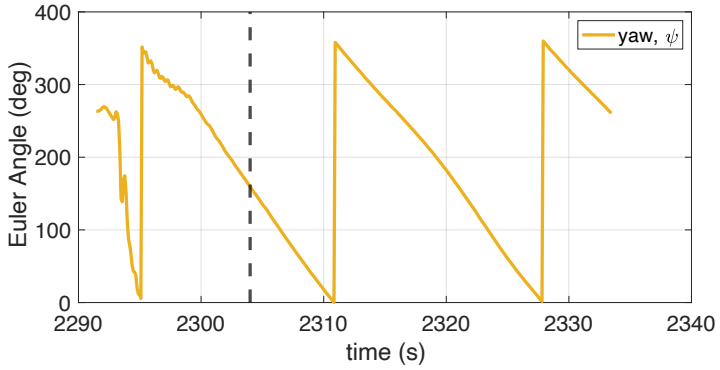




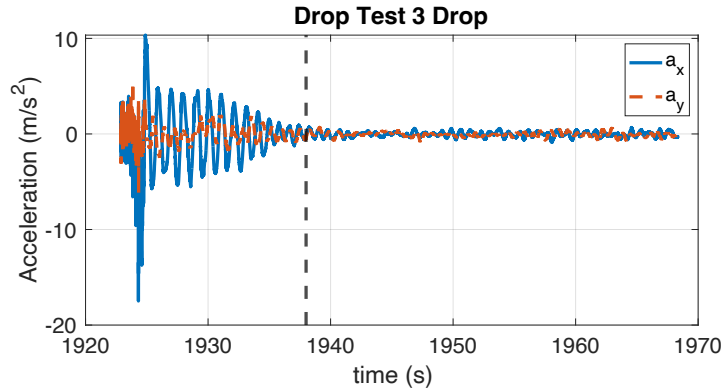


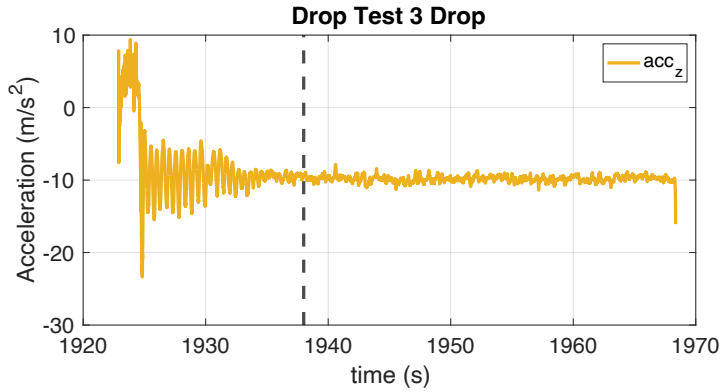


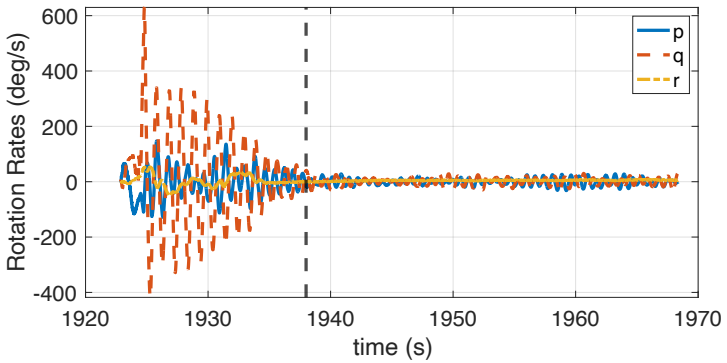


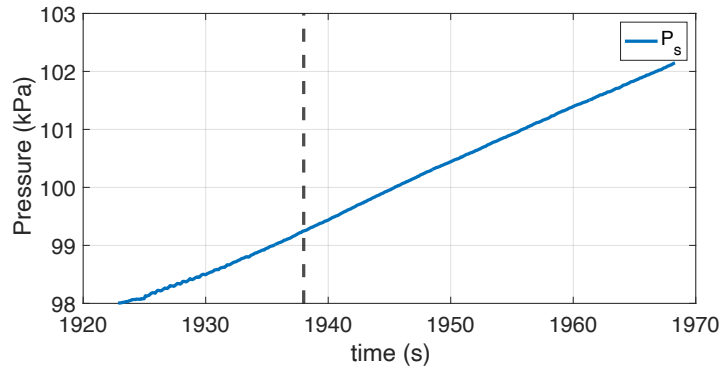


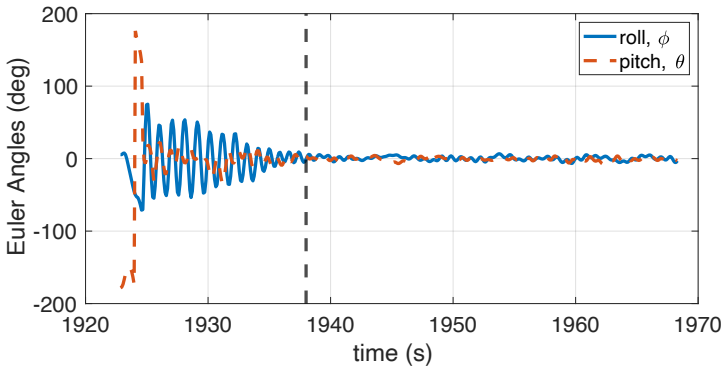
Backup Chart: Drop 3 Data Streams

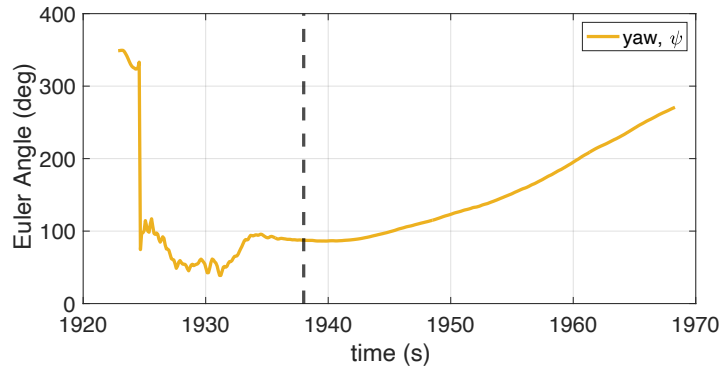




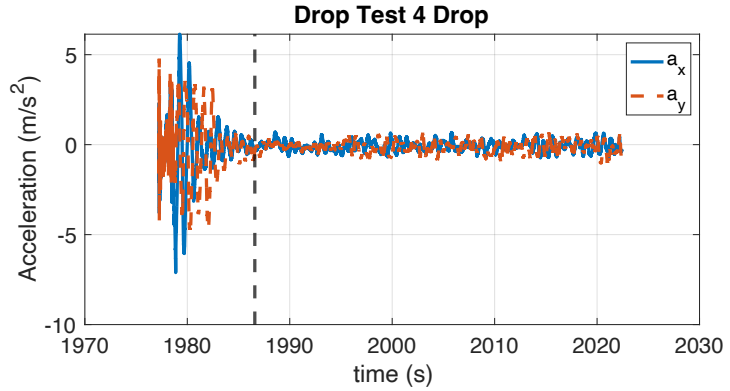


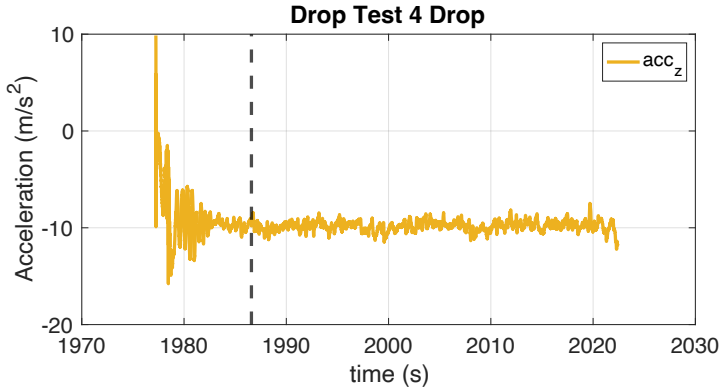


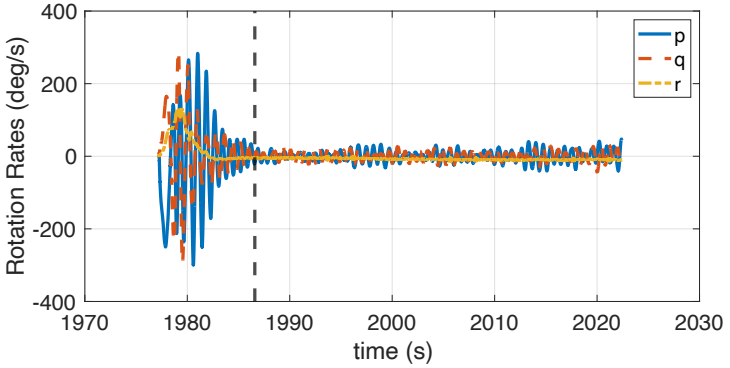


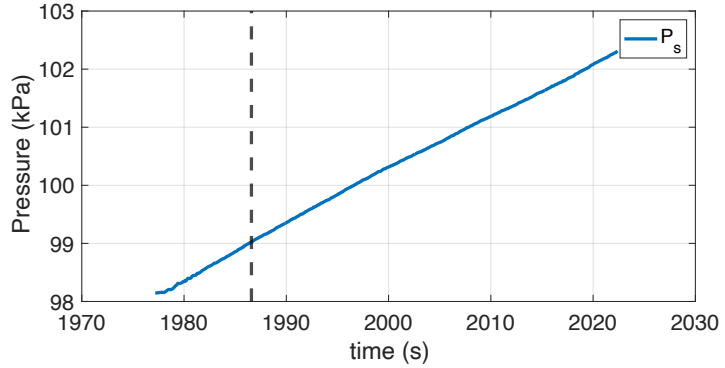


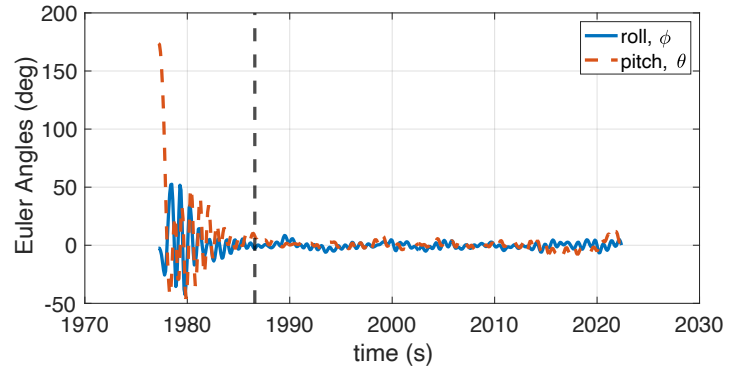
Backup Chart: Drop 4 Data Streams

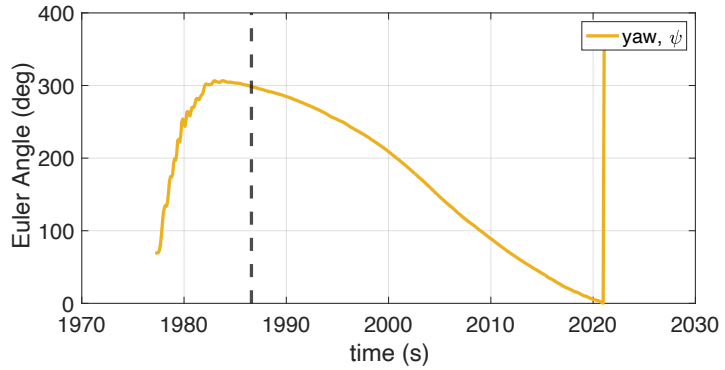




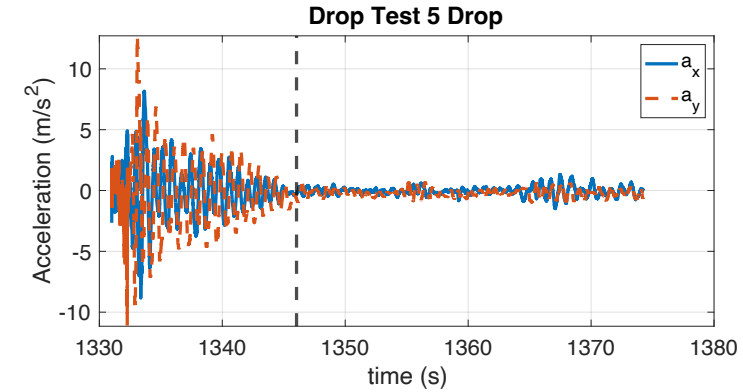


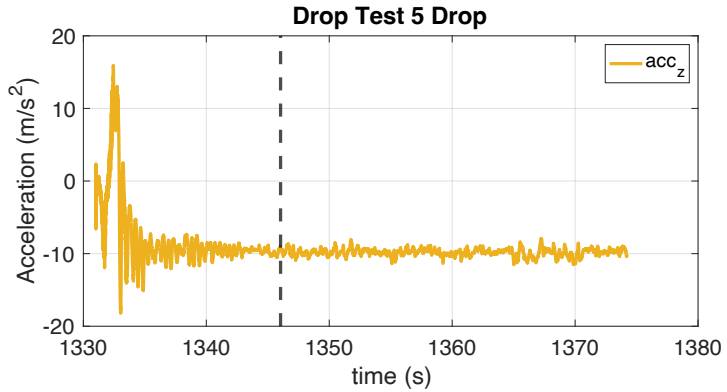


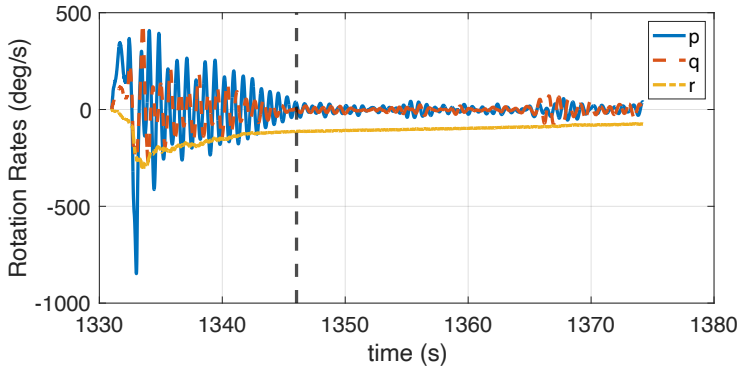


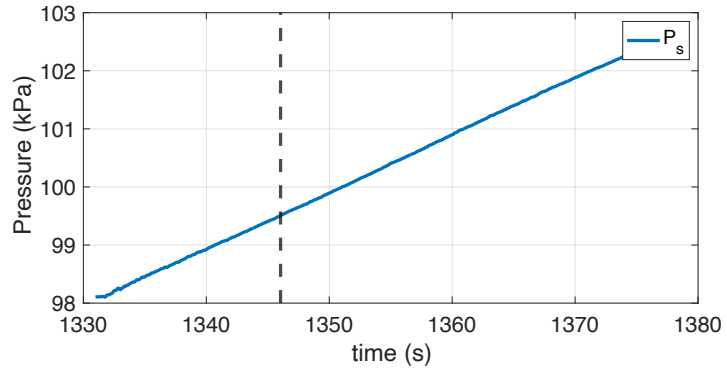


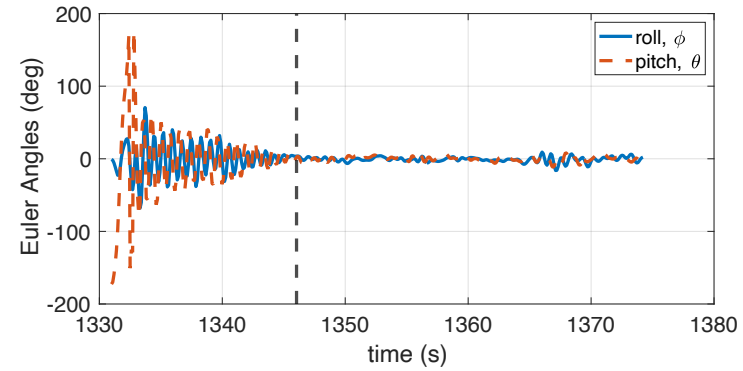
Backup Chart: Drop 5 Data Streams

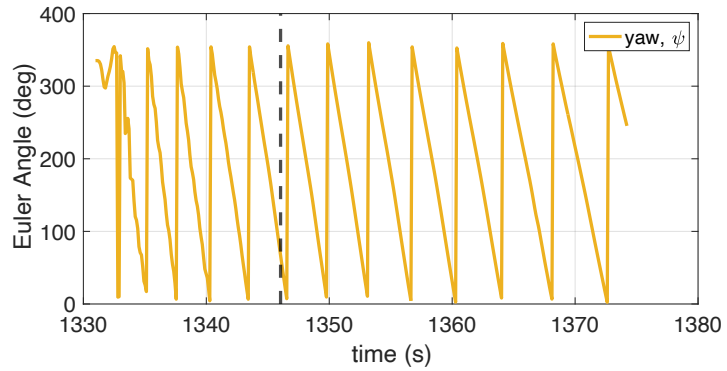




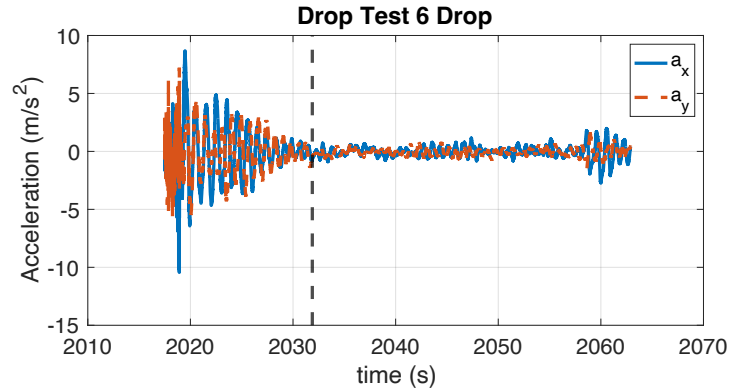


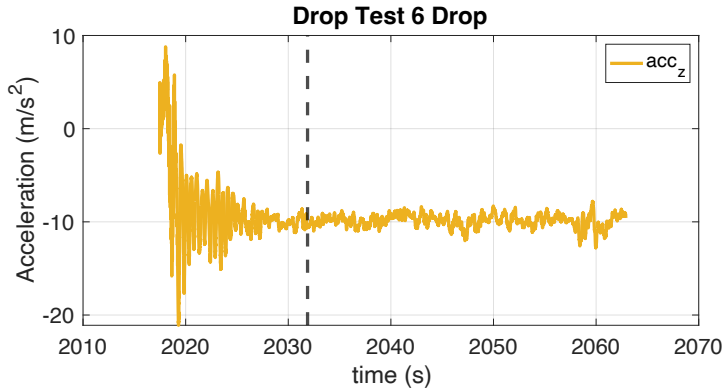


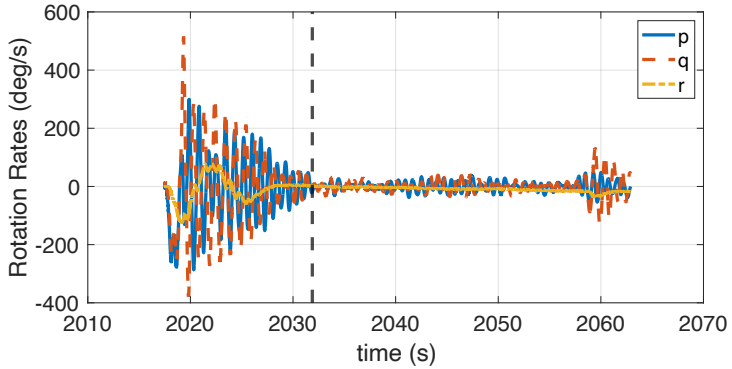


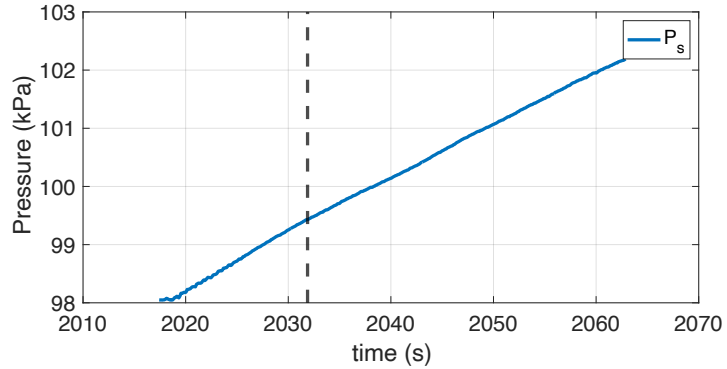


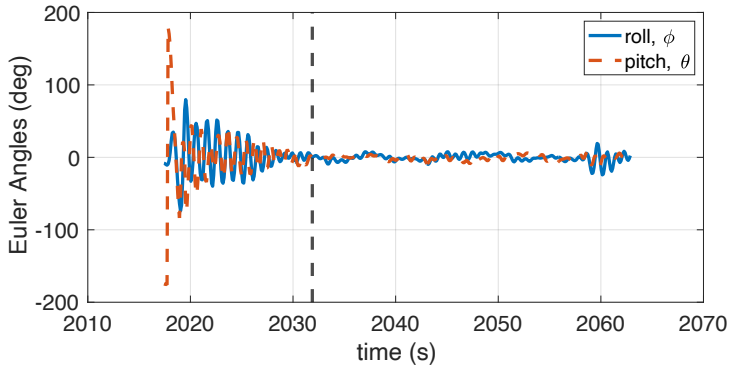
Backup Chart: Drop 6 Data Streams

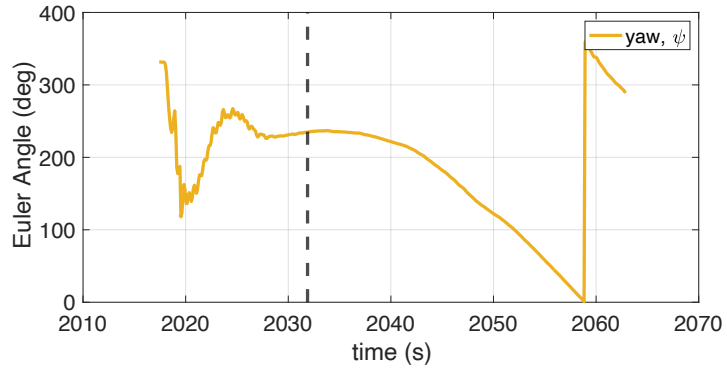




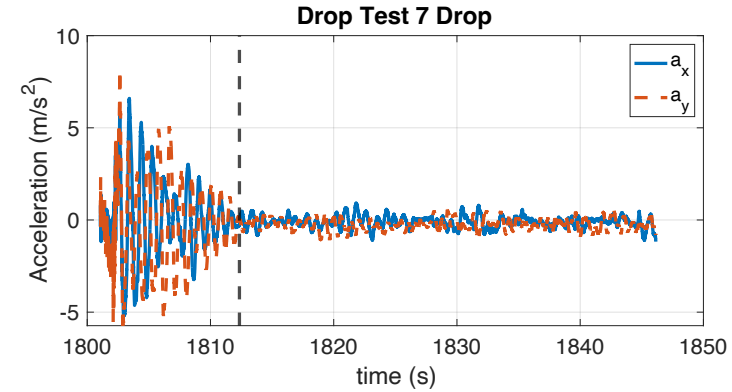


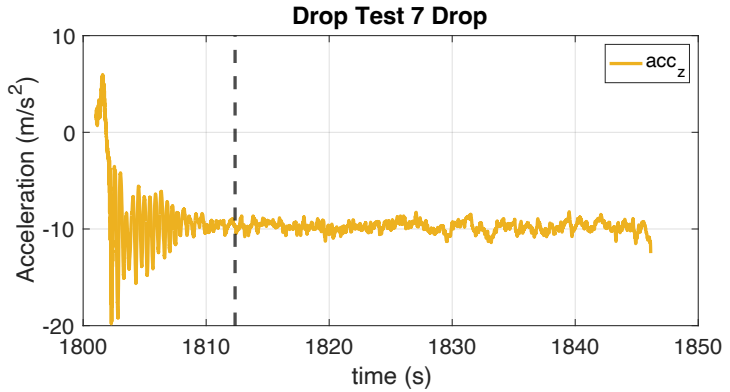


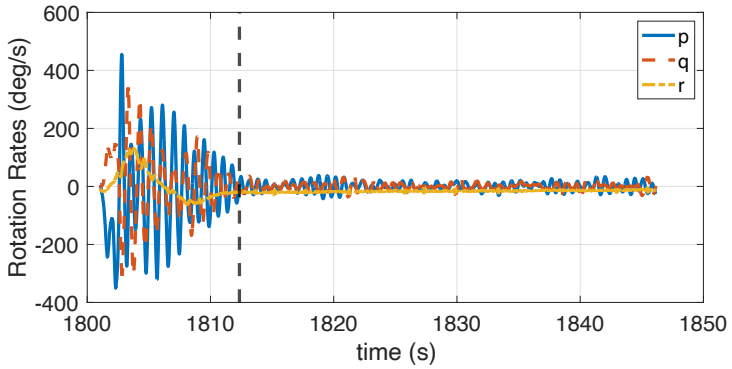


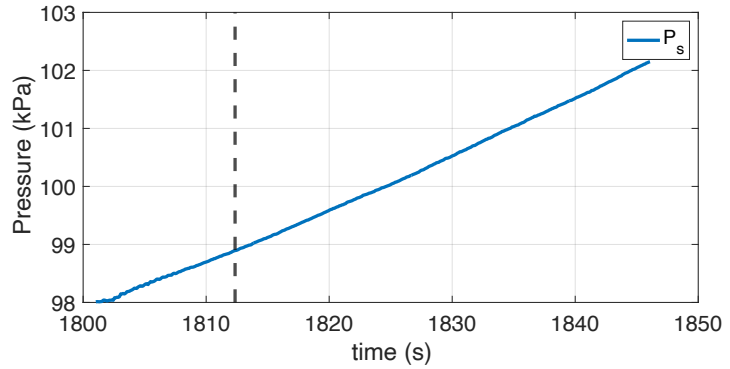


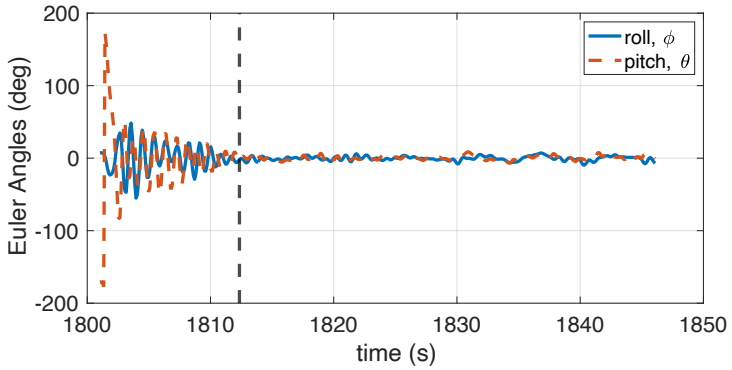
Backup Chart: Drop 7 Data Streams

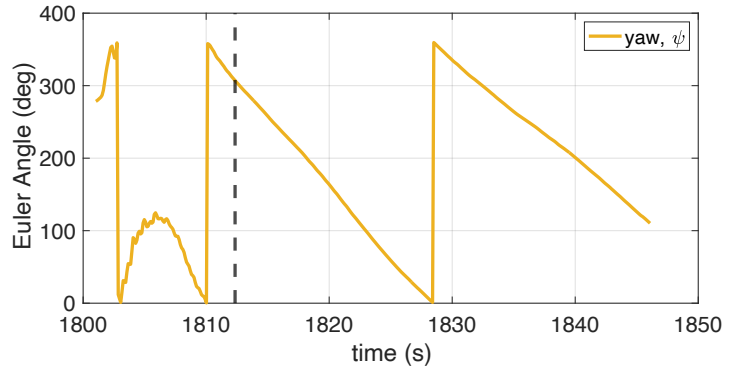




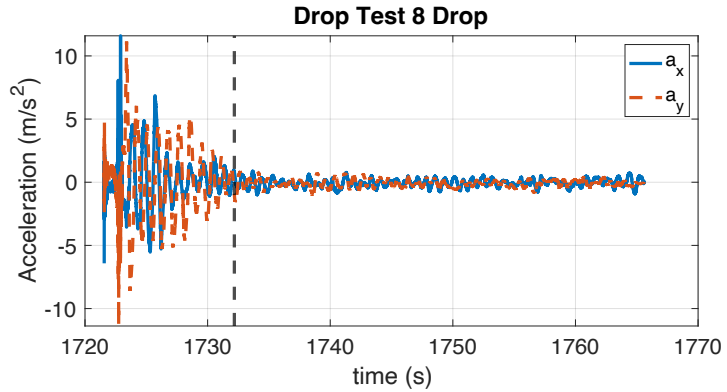


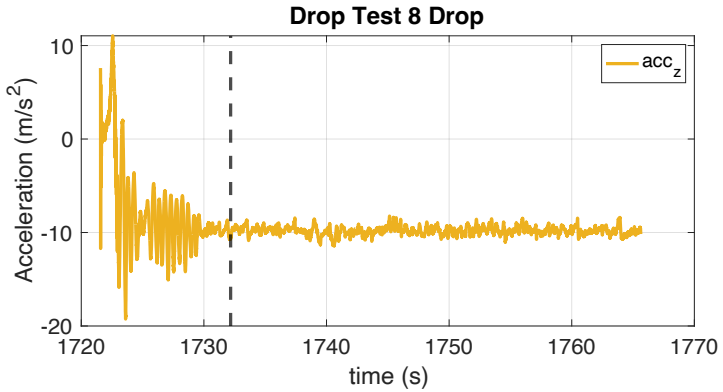


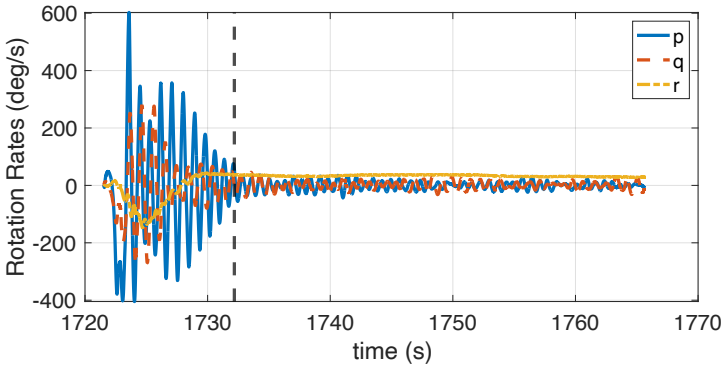


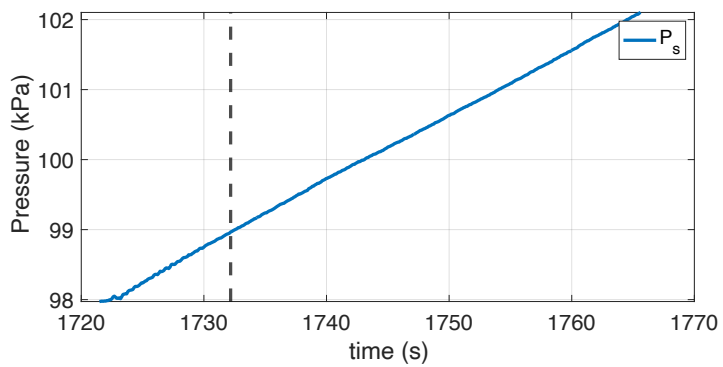


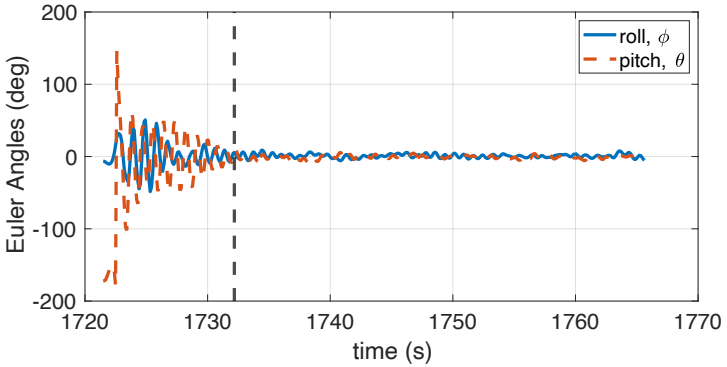
Backup Chart: Drop 8 Data Streams

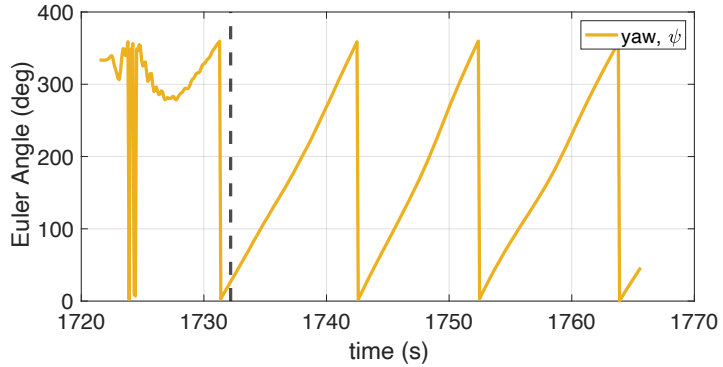




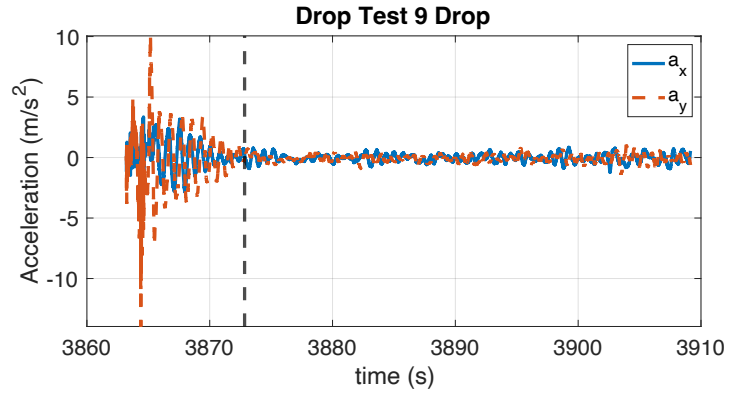


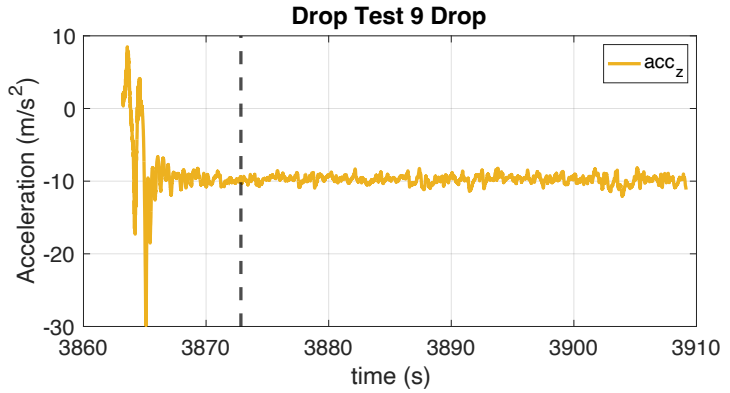


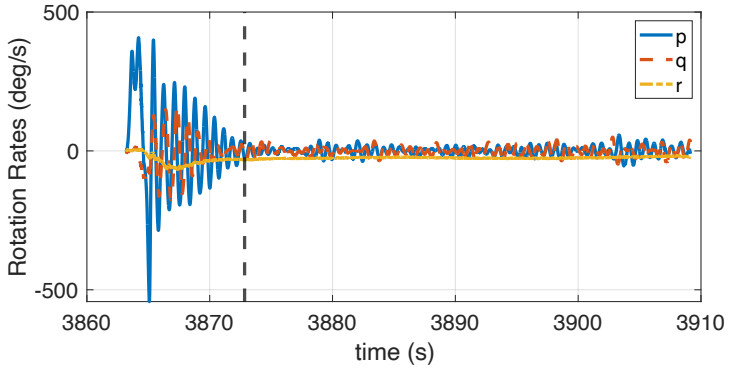


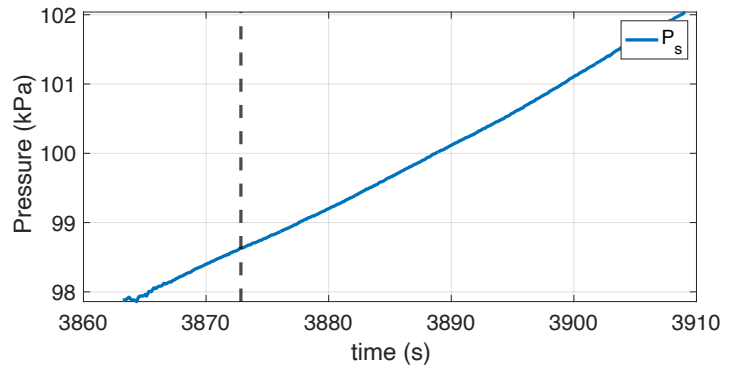


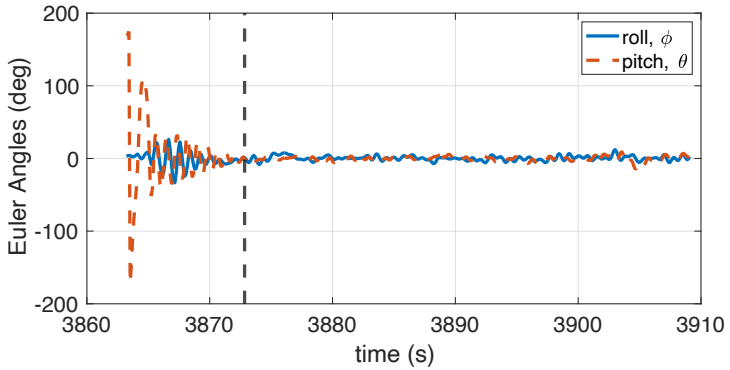
Backup Chart: Drop 9 Data Streams

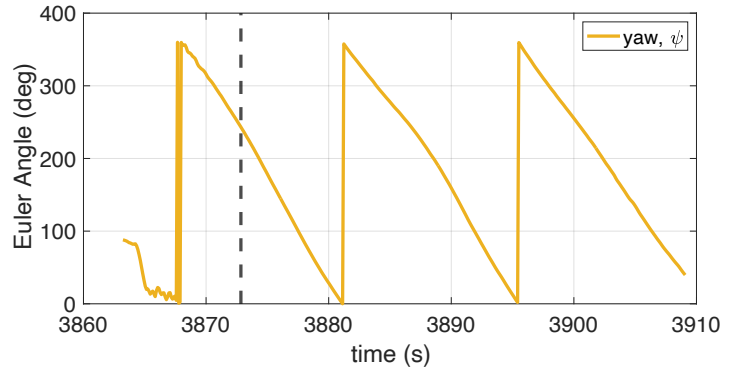




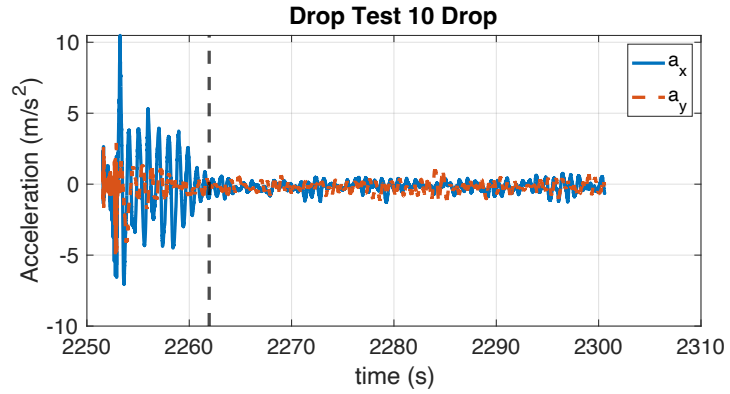


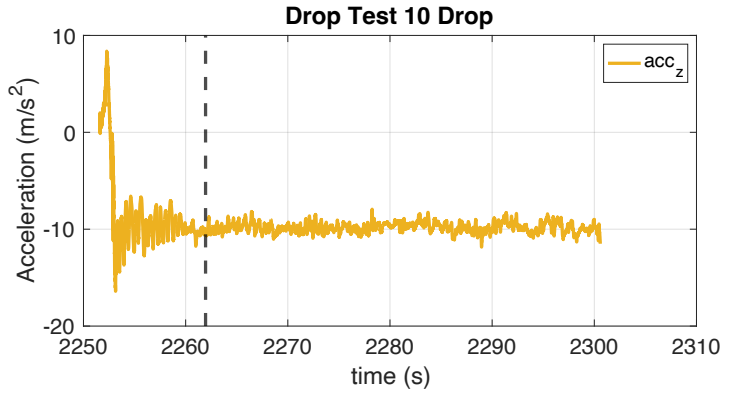


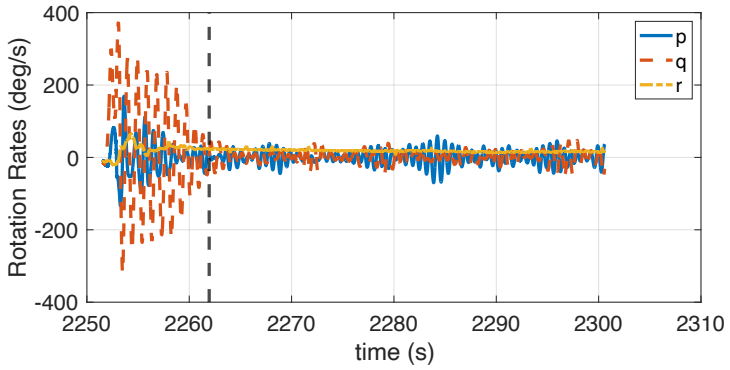


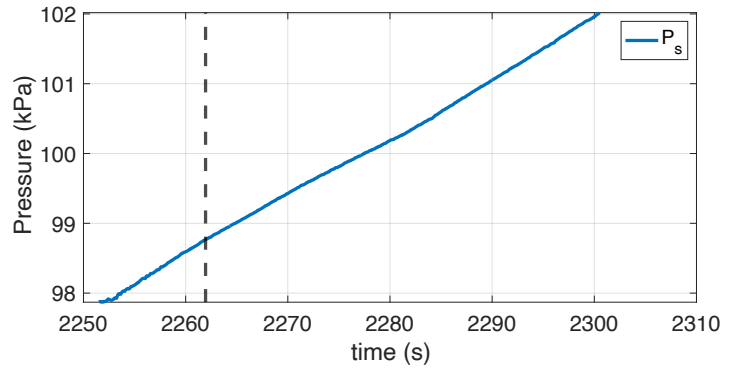


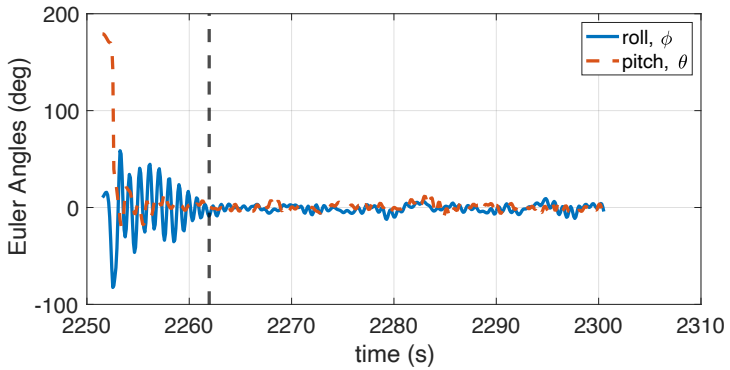
Backup Chart: Drop 10 Data Streams

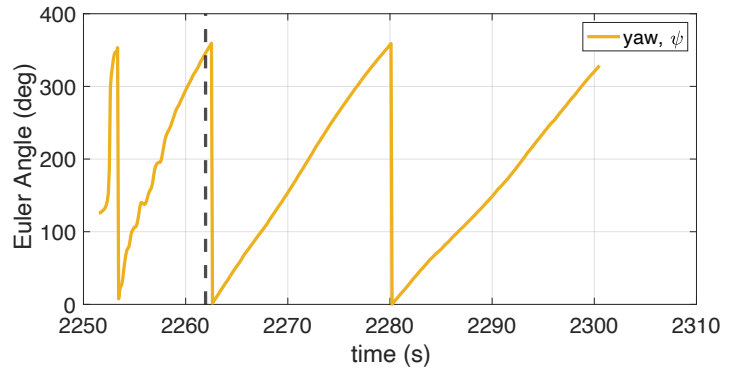




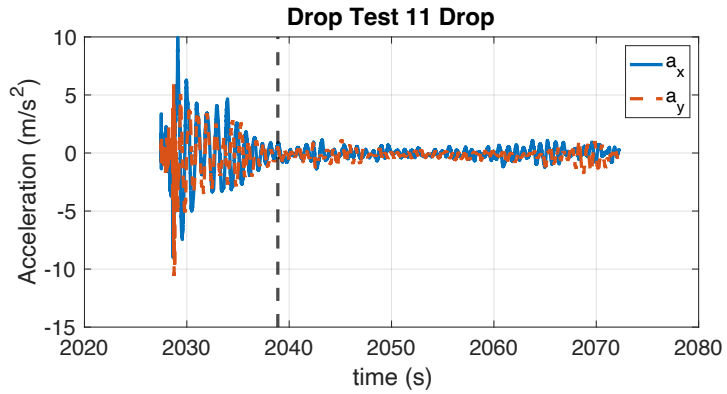


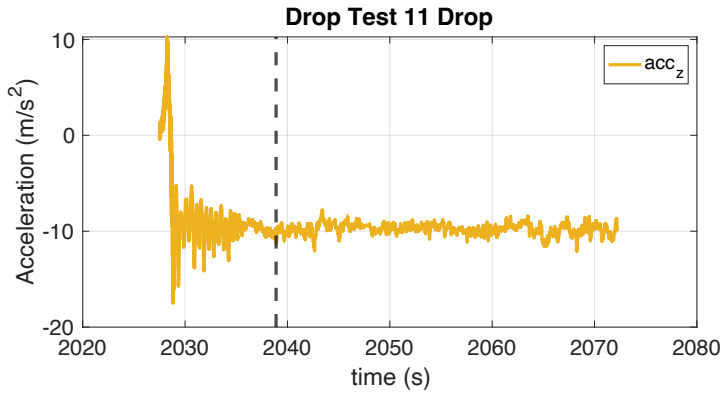


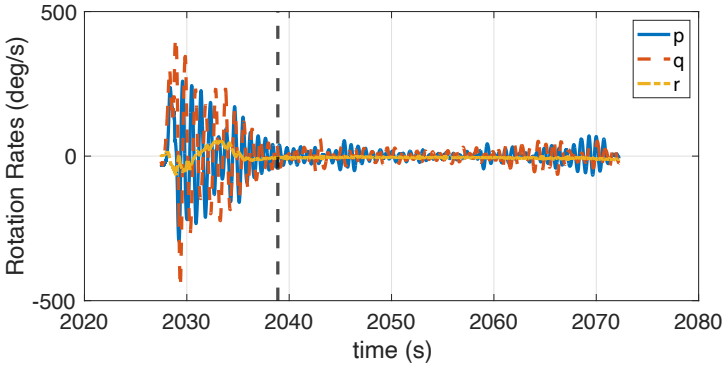


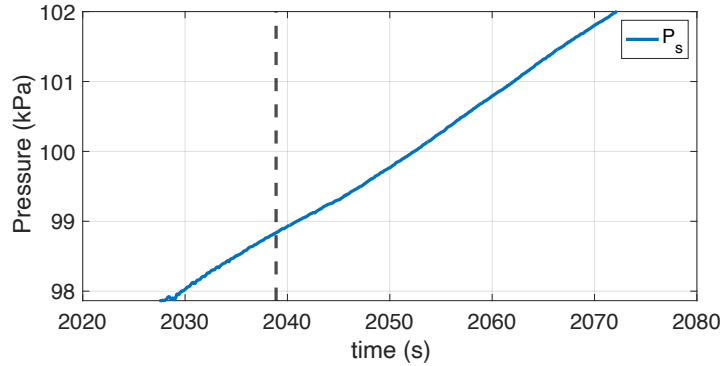


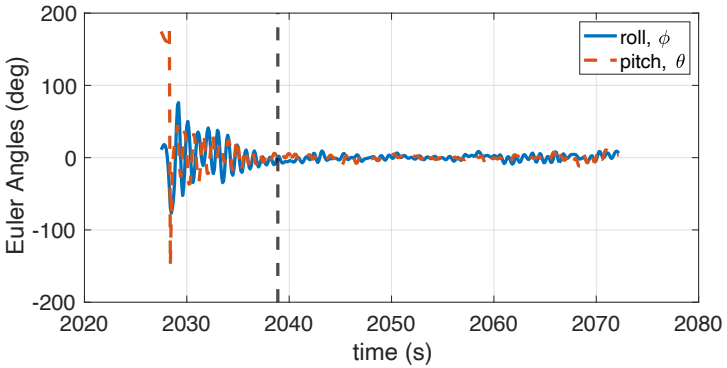
Backup Chart: Drop 11 Data Streams

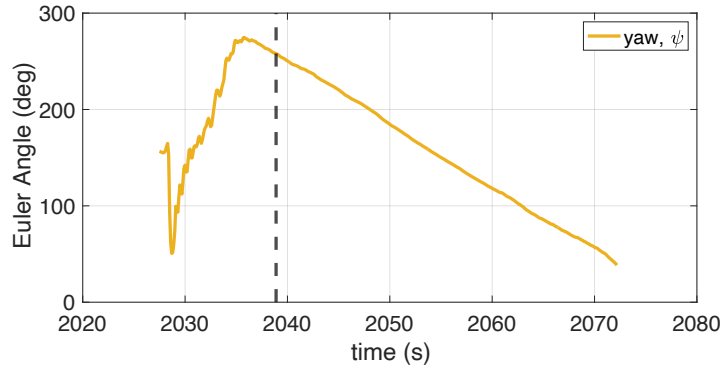












Backup Chart: Drop 12 Data Streams