

Investigation of the Dragonfly Mission Lander, Backshell, Parachute Dynamics through Subscale Drop Tests

Justin A. Shafner,^{*} N. Giovanni Guecha-Ahumada^{*}, Chris Meek,[†] Brian E. Duvall,[‡]
Matthew N. Gray,[§] Imran A. Khasawneh,[¶] Jody E. Miller^{||}
NASA Langley Research Center, Hampton, Virginia 23681

Brayden L. Chamberlain^{**}
ViGYAN Inc., Hampton, Virginia 23666

The Dragonfly mission will place a nuclear-powered rotorcraft on Titan by 2034. The entry, descent, and landing system of the Dragonfly mission includes a drogue parachute and main parachute. Just prior to Dragonfly lander release, while descending under the main parachute, the heatshield is jettisoned and the system descends under main parachute with the lander exposed to the Titan atmosphere. Subscale drop tests were used to investigate the system dynamics in the stowed and posed configurations. All models were geometrically scaled to 16.67 percent of the full-scale system. Key findings include that the dynamics of the system descending under the main parachute with the Dragonfly lander are bounding and non-growing during steady-state descent. It was found that the overall dynamics of the system in both the stowed and posed configurations are larger than those experienced by the full aeroshell configuration, but are of acceptable amplitudes to the program.

I. Background

NASA selected the Dragonfly mission under the New Frontiers Program. This mission intends to place a nuclear-powered rotorcraft (subsequently denoted as “lander”) on the surface of Titan (Saturn’s largest moon) to study its prebiotic chemistry and habitability. Launch is scheduled for 2028, with arrival at Titan by 2034. The mission is led by the Johns Hopkins University Applied Physics Laboratory (APL). Other partners in this mission include Lockheed Martin Space (LMS), providing the entry aeroshell, NASA, leading the entry, descent, and landing (EDL) system development, and Airborne Systems of North America (ASNA), providing the parachute decelerator subsystem (PDS).

The Dragonfly EDL sequence is unique due to its two-hour duration [1], which is considerably longer than the seven minutes of a typical Mars entry trajectory. The Dragonfly mission uses a Genesis-derived aeroshell, which will descend under parachute for the majority of the trajectory. Just prior to releasing the lander, the heatshield of the aeroshell is ejected, exposing the lander to the Titan atmosphere for the first time (in a stowed configuration). Shortly thereafter, the lander is lowered from the stowed to posed configuration to ensure its rotors clear the backshell. The current Dragonfly EDL concept of operations is shown in Figure 1. During entry, after the aeroheating and deceleration pulses are over, a drogue parachute will deploy by a mortar. This deployment will occur at a nominal Mach number of 1.5. The drogue parachute is a scaled version of the Viking Disk-Gap-Band (DGB) parachute with a nominal diameter of 8.25 m. After descending under the drogue parachute for approximately 104 minutes, at an altitude of approximately 4 km above the surface, the drogue parachute then acts as a pilot parachute to deploy the main parachute. The main parachute is of the 20 geometric porosity Conical Ringslot type and has a nominal diameter of 16.7 m. The main parachute has several purposes: 1) to provide sufficient ballistic coefficient difference for the heatshield and lander separation events, 2) to reduce the dynamic motions of the aeroshell, and 3) to deliver the lander to the desired separation vertical velocity of 2.9 m/s at an altitude above the surface of approximately 0.8 km. The time from main parachute deployment to lander separation is approximately 2 minutes. Powered flight starts after lander separation, followed by the first landing.

^{*}Research Aerospace Engineer, Atmospheric Flight and Entry Systems Branch, AIAA Member, Mail Stop 489.

[†]Mechanical Engineer, Aeronautics Systems Engineering Branch, Mail Stop 238.

[‡]Robotics and Automation Engineer, Aeronautics Systems Engineering Branch, Mail Stop 238.

[§]Electrical Engineer, Aeronautics Systems Engineering Branch, Mail Stop 238, AIAA Member.

[¶]Robotics and Automation Engineer, Aeronautics Systems Engineering Branch, Mail Stop 238.

^{||}Electronics Technician, Aeronautics Systems Engineering Branch, Mail Stop 238.

^{**}Research Engineer, 30 Research Drive.

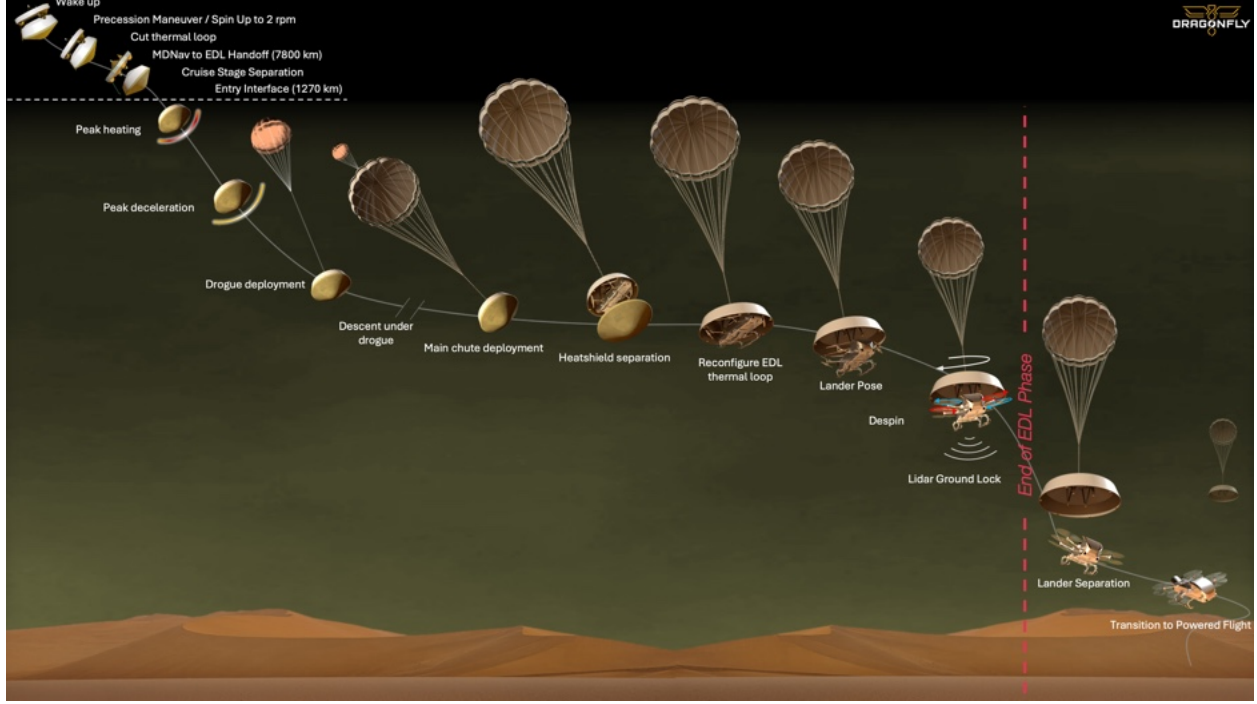


Fig. 1 Dragonfly EDL concept of operations [1]

One of the key concerns related to the EDL phase is the dynamic behavior of the system after heatshield jettison during Preparation for Powered Flight (PPF). Just after heatshield release, the lander is in the "stowed" configuration. Prior to lander release, it is lowered into the "posed" configuration to enable powered flight. During both of these phases, the open backshell is a dynamically unstable geometry, with little previous test data to characterize how oscillatory the angles and rates of the system will be during this critical phase of flight. To better understand the dynamics of the system during the posed and stowed configurations, a series of subscale drop tests were performed. The test objective was to acquire physically meaningful data about the dynamics of both the stowed and posed backshell/lander configuration while under the main parachute. These drop tests were the third phase of tests with Phases I and II previously summarized in Cruz et al. [2]. This paper summarizes the scaling and development of the drop tests, analysis of the dynamics of the system, and implications of the results in the context of the Dragonfly mission to Titan.

II. Subscale Test Setup

A. Dynamic Scaling

The Phase III test was sized using Froude scaling [3] such that a model vehicle with 1/6-geometric scale, and appropriately-sized mass properties, would have similar dynamics at sea-level on Earth to those expected at flight environments on Titan. Froude scaling is a method for scaling a test article which preserves the ratio of inertial and fluidic forces. The Froude scaling parameters are summarized in Table I. In this table N is a dimensionless scaling factor, defined as the ratio of the model value to the full-scale value. The subscript of N specifies the quantity being scaled. The subscripts M and F are used to specify model-scale or full-scale respectively.

The typical workflow for determining the dynamic scaling of a Froude-scaled test is to start with a geometric length-scaling factor. In the case of the Dragonfly Drone Drop Test Phases I, II, & III, this factor is 16.67%. Then, the environmental factor ratios are determined using estimations of both the environment the model will be tested in and the expected conditions that the full-scale system will experience during flight. The outcome of performing dimensional analysis using just the geometric and environmental scale factors are the mass, time, and fluid dynamics factors at the bottom of Table I. The mass and inertia values are the required scale factors necessary to derive the model mass properties to ensure dynamic scaling. One of the consequences of Froude scaling is a time scale factor such that the

temporal evolution of dynamics is not one-to-one. Any dynamics observed during the testing of the model will be N_t times slower at full-scale in the flight environment.

Table 1 Froude scaling parameters

Scale Factor Parameter	Parameter Type	Symbol	Derivation	Value
Length	Geometric	N_L	L_M/L_F	0.167
Density	Environment	N_ρ	ρ_M/ρ_F	0.0234
Gravity	Environment	N_g	g_M/g_F	7.26E
Coeff. of Viscosity	Environment	N_μ	μ_M/μ_F	3.06
Mass	Mass	N_m	$N_\rho N_L^3$	1.08E-03
Inertia	Mass	N_I	$N_\rho N_L^5$	3.01E-05
Time	Time	N_t	$\sqrt{N_L/N_g}$	0.151
Rotation Rate	Time	N_ω	$\sqrt{N_g/N_L}$	6.60
Reynolds	Fluid Dynamics	N_{Re}	$N_\rho/N_\mu \sqrt{N_g N_L^3}$	1.40E-02

The Phase III tests were designed to correspond to a full-scale Titan altitude of roughly 0.8 km, just prior to lander release. In this configuration, the lander is exposed to the flow, and must deploy from a stowed configuration to allow its rotors to spin and enable it to successfully perform its first landing. To account for this, the Phase III test was split into two distinct subphases: stowed and posed. A slice of the CAD of the subscale models used is shown in Figure 2.

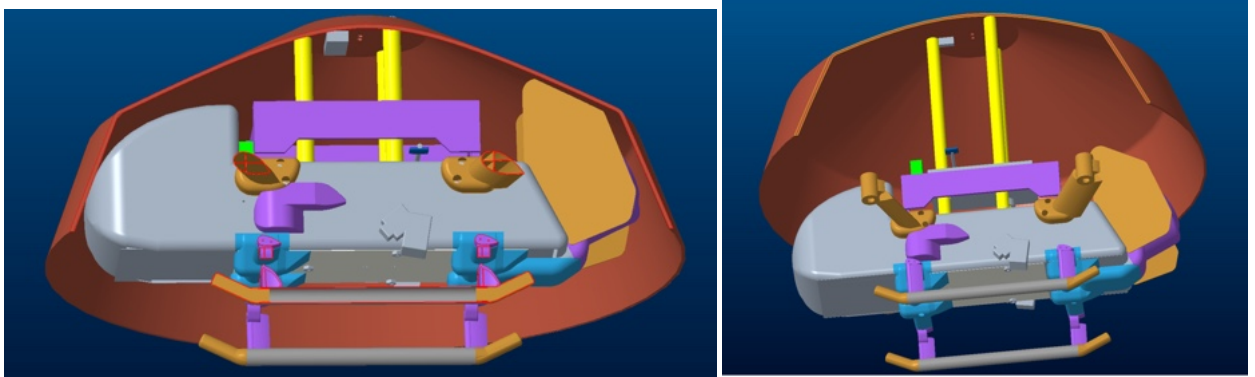


Fig. 2 CAD assembly of the backshell and lander models mated by carbon fiber spars. The stowed model (left) is tucked into the aeroshell, while the posed model (right) exposes the entire lander to the freestream flow.

B. Aeroshell Model

The full-scale aeroshell diameter is 4.50 m. Given that $N_L = 0.1667$, the model aeroshell was 0.75 m. The geometry of the model aeroshell is that of the 2004 Genesis spacecraft's aeroshell [4] with dimensions specified in Figure 3. This geometry was the starting point for the Dragonfly aeroshell geometry. Differences between the Dragonfly and Genesis aeroshell geometries are mainly at the shoulder where the forebody and aftbody meet. Since this model has no forebody, these small differences are not a factor.

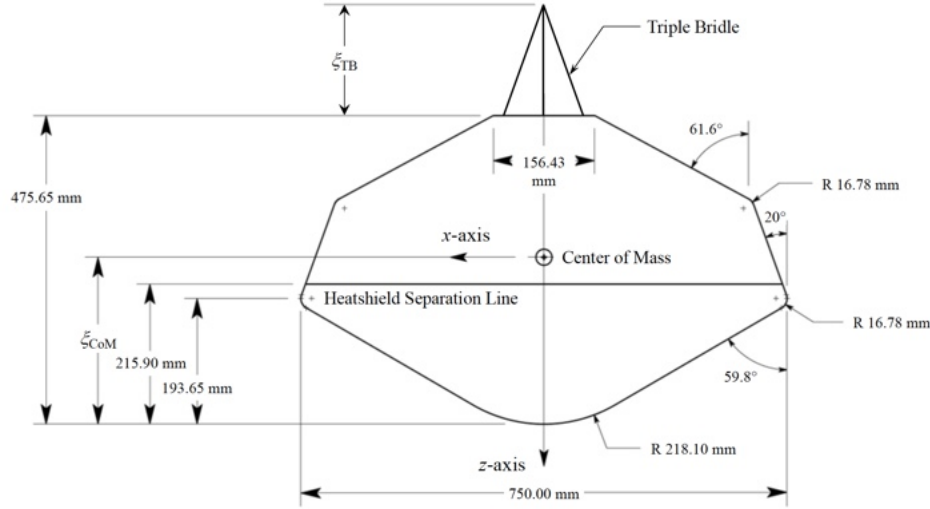


Fig. 3 Dimensioned schematic of the Genesis aeroshell geometrically scaled to 16.67% ($D = 0.75$ m) of the Dragonfly capsule ($D = 4.5$ m).

For the Phase III drop tests, only the backshell of the aeroshell is used since the test investigates dynamics that occur after heatshield separation. The backshell was fabricated from epoxy-impregnated Kevlar fabric laid up in purpose-built female molds. Additional components of the backshell were fabricated from carbon-epoxy, plastic printed parts, and steel ballast to meet the desired mass properties.

C. Lander Model

Both the stowed and posed models made use of a singular plastic-printed 16.67% scale Dragonfly lander. Not every exterior detail of the lander was printed, but a significant amount of features to provide representative aerodynamic characteristics were added including the lander body, landing legs, pose mechanism, fins, and rotor arms. Figure 2 shows the CAD model integrated into the backshell for the stowed (left) and posed (right) configurations.

Individually fabricated components are shown as different colors in Figure 2. The only hardware difference between the stowed and posed landers are the lengths of the carbon fiber spars, shown as yellow cylinders in the CAD. These spars are used to attach the printed lander model to the backshell. Energy absorbers were required in order to mitigate damage to the model upon ground impact. The legs of the lander were attached to the main body using toothpicks such that the landing skids would shear from the body upon impact. This resulted in minimal energy transfer to the fragile plastic-printed lander body and thus minimal repairs to the lander model between drops.

The overall mass target of the backshell and lander system was 2.21 kg to achieve the desired dynamic scaling. The as-built mass properties were 2.14 kg for the posed configuration and 1.95 kg for the stowed configuration.

D. Parachute Model

Phase III was conducted using the same main parachute and triple bridle attachment geometry as Phase II [2]. A schematic of the parachute and how it attaches to the backshell is shown in Figure 4.

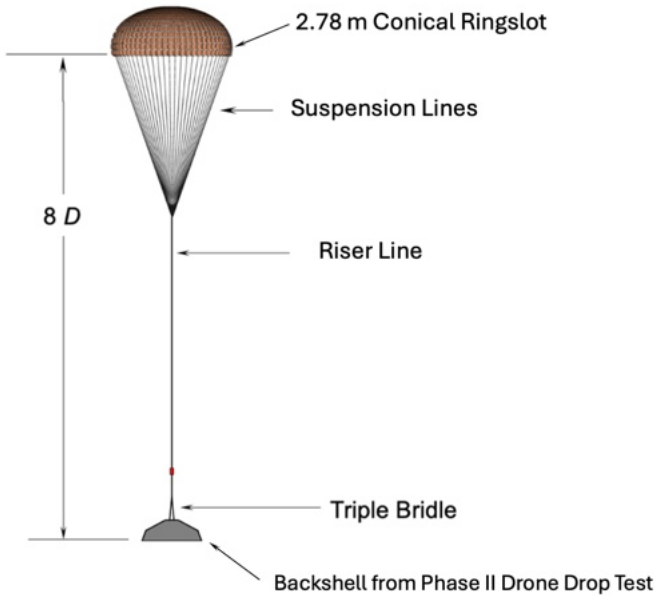


Fig. 4 Schematic of the Conical Ringslot canopy attached to the backshell via a triple bridle and riser.

As a summary, the full-scale nominal diameter of the main parachute is 16.7 m. Thus, given that $N_L = 0.1667$, the model main parachute nominal diameter was 2.78 m. Both full-scale and model main parachutes are of the 20 geometric porosity Conical Ringslot type. The model main parachutes were fabricated using the same low-permeability parachute fabric that is being used for the full-scale main parachutes. The model main parachutes had a mass of approximately 274 g. It was not possible to perfectly scale the model parachutes. Following are some of the compromises that had to be made:

- 1) The model parachutes had a different number of suspension lines.
- 2) The mass of the model parachutes was higher than their desired dynamically scaled values.
- 3) The fabric permeability for the drogue parachute was not correctly scaled. For the main parachute the effect of fabric permeability is minimal – both the full-scale and model main parachutes use low-permeability fabric.

These compromises were considered to be acceptable and insufficient to significantly affect the results.

III. Test Operations

Test operations were conducted at a private, near sea-level, airport close to the NASA Langley Research Center. The test procedure was similar to that of Phase I and II [2]:

- 1) The drone was flown to an altitude of 200-250 m above the ground.
- 2) The backshell was released.
- 3) As the backshell dropped, it pulled and deployed the riser, suspension lines, and parachute (Figure 6).
- 4) The parachute inflated.
- 5) The backshell and lander descended under parachute for approximately 60 s.
- 6) The model landed and was retrieved. The on-board data was downloaded.
- 7) The model was reset for another drop.

For this set of tests, the backshell and lander were mounted upright under the Alta-X drone, as shown in Figure 5. The backshell attaches to the drone via a remotely operated servo release mechanism. The carbon fiber landing legs of the Alta-X drone were extended to ensure that there was ground clearance in both the stowed and posed configurations. The parachutes were packed into plastic containers seen mounted to the right-most leg of the Alta-X in Figure 5. Similar to Phase I and II, the apex of the canopy is held in place within the packing container using a rubber band. The suspension lines are cross-folded over the container opening to prevent the canopy from deploying early. The remainder

of the riser line is coiled around a spool such that only a few inches of slack of the triple bridle is permitted while mounted to the drone.



Fig. 5 Subscale drop test article mounted to an Alta X carrier drone in the stowed configuration (left) and in the posed configuration (right).

Once at the predetermined drop location, the drone pilot manually commanded the servo release mechanism open, allowing the backshell and lander to separate from the Alta-X. The drop sequence is pictorially represented in Figure 6. Upon servo actuation, the backshell with lander enters a free-fall. The parachute riser and suspension lines are unfurled from their respective tape and rubber band attachment points under the weight of the drop test model. Upon line stretch, the main parachute is pulled from the pack container and the apex is snatched from its rubber band attachment point. During free-fall, the backshell with lander configuration is highly unstable leading to large initial attitude states. As the canopy inflates, and thus a restoring moment is enacted on the backshell, the system stabilizes until a quasi-steady state descent is established. It should be noted, that while the quasi-steady state descent represents scaled dynamics of the Dragonfly system in either the posed or stowed configurations, the parachute deployment, inflation, and transient attitude states are not flight-like. During the Dragonfly EDL sequence, the full aeroshell, with the heatshield on, will be descending under a drogue parachute prior to main parachute deployment and inflation. In this drop test, the backshell with exposed lander is released from the carrier drone with no canopy. Therefore, the initial few moments of descent are free fall and are not equivalent to any portion of the Dragonfly EDL sequence.

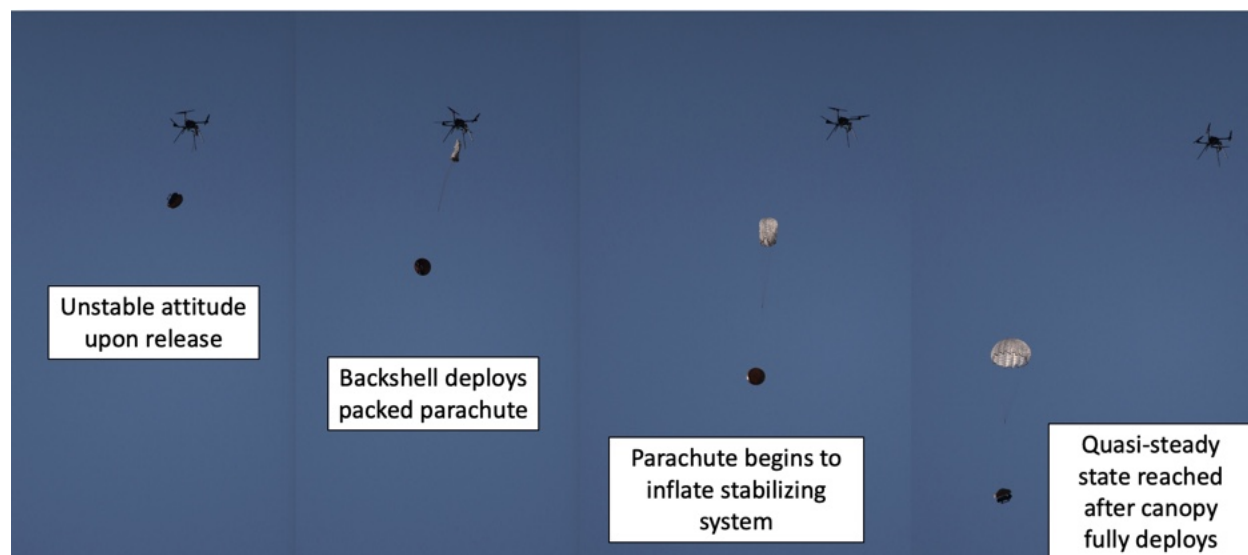


Fig. 6 Subscale main parachute canopy deployment sequence as seen from the ground.

Range containment of the descending backshell was important to mitigate potential injury and damage to property

on the ground. To ensure the backshell would land in the field, prior to each drop, a latitude and longitude drop point was calculated. The drop point was calculated knowing the information in Table 2.

Table 2 Data Sources Required for Determining Release Location

Parameter	Source
Landing Location Coordinates	Ground Control Targeted
Drift Distance from Landing Location	Discretization Over Flight Envelope
Current Horizontal Winds	Zefphir 411 LiDAR Ground Station
Fixed Position Attitude of Drone	Alta-X Onboard IMU/GPS

A MATLAB application was built by the drone operations team that infused the parameters found in Table 2 to find an optimal drop location such that the desired landing location is reached. The real-time winds were read from the ground-based Zefphir 411 LiDAR station that reports a horizontal wind magnitude at user-defined altitude bands. By commanding the Alta-X drone to hold a fixed altitude and coordinate location, the orientation information of the drone can be used to calculate the prevailing wind direction. Using the approximated terminal descent rate of the backshell under the main parachute of about 3 m/s and the drift distance from the landing location, the application determined where within the bounding box of the range the Alta-X should release the payload. The optimal waypoint solution was calculated and uploaded to the airborne Alta-X just minutes prior to payload release.

IV. Available Datasets

A. Available Data

Phase III testing was conducted during February and March of 2025 over four days. Twelve drop tests were conducted with the posed model and another twelve with the stowed model. A total of 28.4 minutes of quasi-steady state descent data was acquired (approximately 14 minutes in the stowed and 14 minutes in the posed configurations). Thus, given the time-scale factor of $N_t = 0.151$, roughly 90 minutes of Titan-equivalent dynamics data were acquired for each configuration.

1. Onboard Instrumentation

The onboard instrumentation consisted of an mRobotics Control Zero F7 data recorder that includes an IMU and magnetometer. Data were stored in a microSD 32 GB card. Power was provided by two 2S 1300 mAh Lithium-Polymer batteries. The IMU was installed at the center of mass of the aeroshell. Temperature calibration of the IMU improved the accuracy of the results. Specifically for Phase III, a Flysight GPS was integrated into the data recorder to enable onboard position and velocity measurements. The data collected are shown in Table 3.

Table 3 Data Sources Required for Determining Release Location

Measurement	Rate
Acceleration, 3-axis	200 Hz
Rotation Rates, 3-axis	200 Hz
Magnetometer, 3-axis	200 Hz
Static Pressure	10 Hz
Euler Angles (calculated)	10 Hz
Position Data	5 Hz
Velocity Data	5 Hz

The GPS was added as a lessons-learned from Phase I and II where using onboard static pressure and ambient temperature sensor data proved too unreliable to be used to reconstruct the trajectory or atmospheric profile of the drop tests.

2. LiDAR Ground Station

A light detection and ranging (LiDAR) wind measurement system was used to estimate the wind velocity above the test range. The system fires a laser into the atmosphere and measures the back-scatter caused by the beam reflecting off of particles in the air. Figure 7 shows the Zephfir 411 LiDAR Ground Station deployed during the Phase III drop test campaign. In total, the system measured horizontal and vertical wind components at 11 different altitude stations at a measurement frequency of 1 Hz. This data was logged continuously throughout the test day to characterize the evolution of the winds over time.



Fig. 7 Zephfir 411 LiDAR ground station in-use during the drop test campaign.

B. Data Segmentation

The on-board instrumentation recorded data from several minutes before drone takeoff to several minutes after landing. These long streams of data from each drop were prepared as MATLAB files for analysis. Each drop was loaded into a viewing script that plotted rotation rates p , q , and r as well as the Euler angles ϕ , θ , and ψ in the coordinate frame defined in Figure 3. A partial record of the rotation rates and Euler angles recorded for a sample Phase III drop from payload release to the time of landing is shown in Figure 8. Because the backshell is released first to statically deploy the parachute, a significant high dynamic period is observed for approximately 12 s. By $t = 12$ s the dynamics have stabilized to a quasi-steady state. The period of interest to quantify the dynamics is labeled “Quasi-steady state descent” in Figure 8. For all drops during Phase III, the backshell with lander reached a quasi-steady descent in less than 15 s. There was no statistical difference observed in time-to-stabilize after payload release between the stowed and posed configurations.

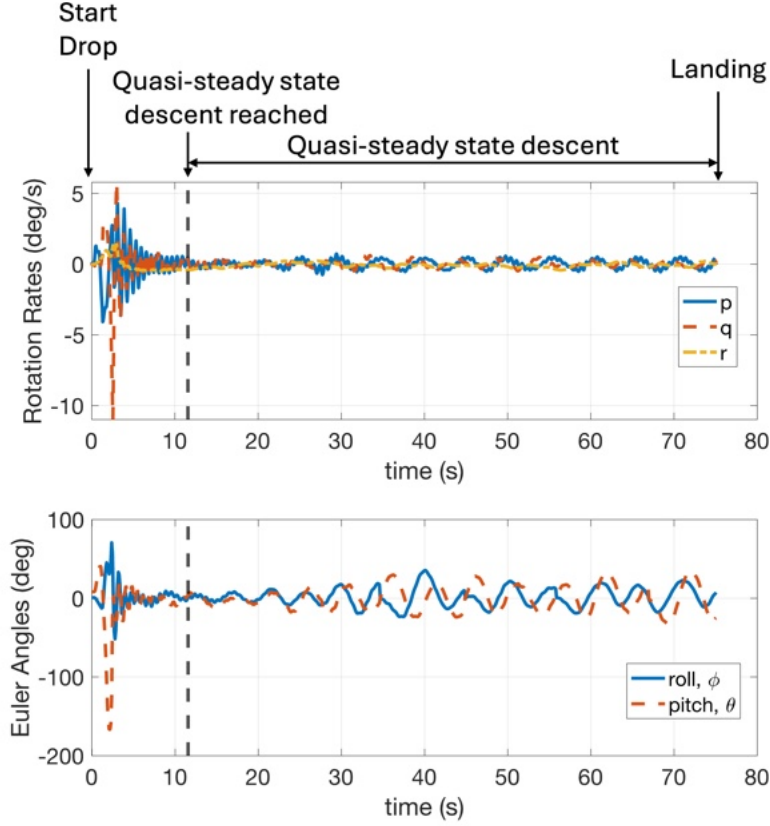


Fig. 8 Sample data stream from onboard IMU.

C. Quantities of Interest

The time history of each individual drop is appended together for each test configuration, similar to the approach developed for Phase I and II presented in Cruz et al. [2]. The appended signal is created by combining the quasi-steady "settled" phase of flight for each drop to create one long datastream. Since individual drop datasets are subjected to variance in environmental factors, analysis to characterize the dynamics of the system is performed on the ensemble of quasi-steady flight data.

1. Nadir Angles

The Euler angles are used to calculate the nadir angle, Θ , defined in Equation 1 specifically for the "z-down" coordinate system used for these drop tests.

$$\Theta = \cos^{-1} [\cos(\theta) \cos(\phi)] \text{ where } 0^\circ \leq \Theta \leq 180^\circ \quad (1)$$

2. Rotation Rates

The rotation rates in the p (x -axis) and q (y -axis) are used to calculate the combined (RMS) rotation rate, Ω , defined in Equation 2 and referred to as the lateral rate of the system.

$$\Omega = \sqrt{q^2 + p^2} \quad (2)$$

3. GPS Data

Altitude, position, and velocity data from the onboard GPS is processed for the appended quasi-steady state of flight to assist in analysis of how the system is affected by winds and to attempt to determine the drag coefficient of the parachute canopy.

4. Wind Data

The LiDAR ground station was capable of logging and storing wind data over the course of the 8-hour test day. In an attempt to correlate wind gusts to observed dynamics of each drop, the wind profile was not generated as an average over the course of the test day. Rather, the wind measurements at each altitude station were extracted during the ± 5 minutes surrounding the payload release time. From this dataset, a mean and standard deviation of the horizontal and vertical wind components were calculated at each discrete altitude station. Using this, a bounding wind profile as a function of altitude could be generated for each drop.

V. Results

A. Appended Data and Percentiles

An example of the appended nadir angle time history is shown in Figure 9 for the stowed configuration and Figure 10 for the posed configuration.

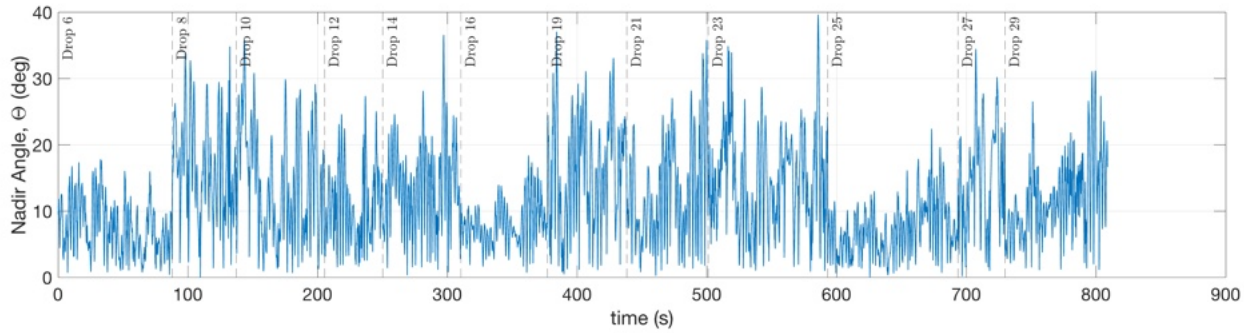


Fig. 9 Stowed configuration: appended nadir angle

The stowed configuration (Figure 9) appears to exhibit a bimodal set of dynamics during the quasi-steady phase of flight. During drops 6 and 16, the nadir angle oscillations remain low (below 18 degrees). However, in the majority of drops, the nadir angle oscillations exhibit a limit cycle often exceeding 30 degrees. Drop 25 starts in a low-amplitude limit cycle that seems to amplify over the duration of the drop. In drops 14, 21, 23, 27, and 29 a large amplitude nadir angle occurs just prior to landing. As observed in Phases I and II, it appears that the system is subjected to low-altitude turbulence as it drops below the treeline that surrounds the test range [2].

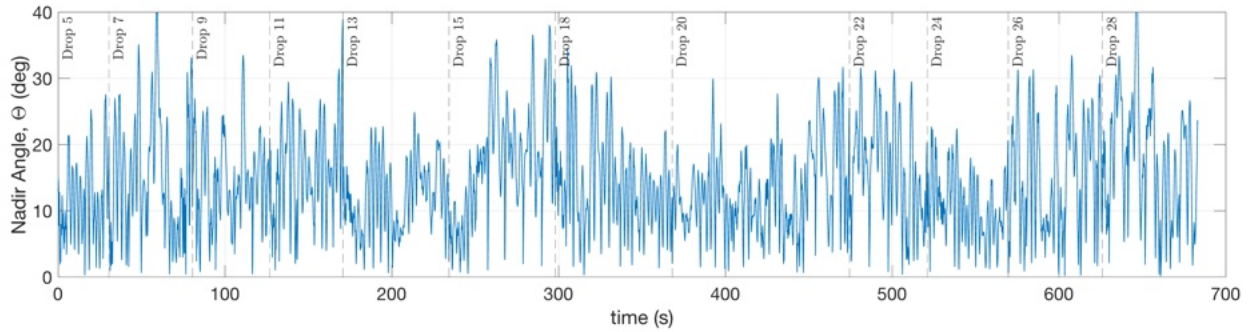


Fig. 10 Posed configuration: appended nadir angle

The posed configuration (Figure 10) experiences similar limit cycle amplitudes as the stowed configuration, with less obvious bimodal behavior. It should be noted that the stowed and posed configurations were alternated sequentially to minimize the impact of day-of environmental factors.

The lateral rates of the stowed and posed configurations, Figure 11 and Figure 12 respectively, exhibit similar

amplitude steady-state values. As seen in the nadir angle data, the lateral rate was also observed to briefly amplify at low altitudes, most likely caused by wind gusts at the treeline.

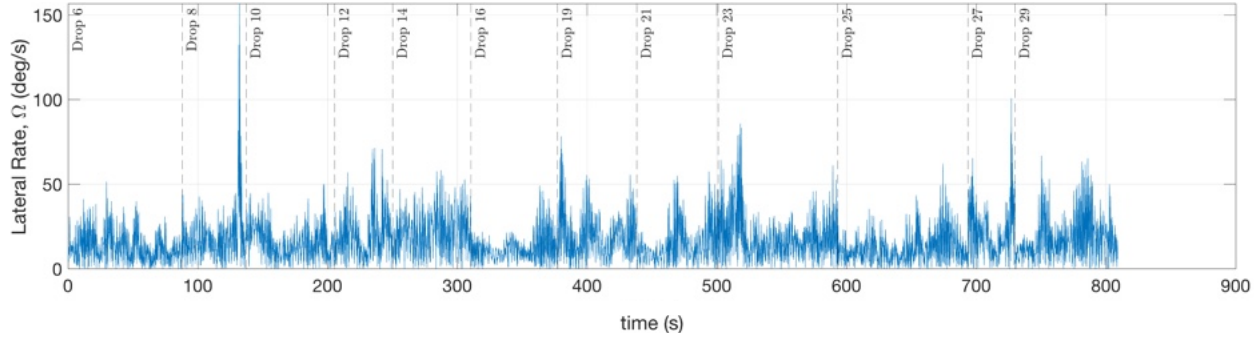


Fig. 11 Stowed configuration: appended rotation rate

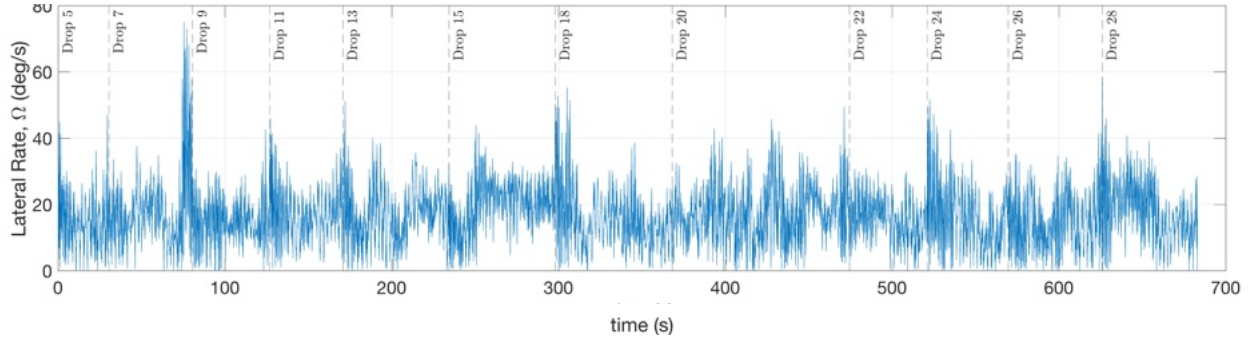


Fig. 12 Posed configuration: appended rotation rate

Statistical analysis is performed on the appended data signals to extract the percentiles of the system dynamics of interest. Note that for the Euler angles roll, ϕ , and pitch, θ as well as rotation rates of p and q , the absolute value of the quantity is used. A summary of the statistics of the stowed and posed datasets are provided in Tables 4 (angles) and 5 (rates). The percentiles from Phase II [2], which was the same parachute, but used a full aeroshell, are included for comparison.

Table 4 Configuration comparison statistics: attitude angles

Config	Roll Euler Angle $ \phi $ (deg)			Pitch Euler Angle $ \theta $ (deg)			Nadir Angle Θ (deg)		
	Aeroshell [2]	Stowed	Posed	Aeroshell [2]	Stowed	Posed	Aeroshell [2]	Stowed	Posed
50%-tile	2.86	5.83	9.56	3.26	6.23	6.04	5.47	10.43	13.55
90%-tile	7.99	16.32	19.28	7.73	16.40	15.90	10.58	22.09	24.91
95%-tile	9.66	19.88	25.80	9.50	20.29	19.28	12.14	25.29	28.14
99%-tile	13.11	26.58	31.38	12.71	26.75	25.23	15.42	31.22	33.66

Table 5 Configuration comparison statistics: rotational rates (in full-scale time)

Config	Roll Rate $ p $ (deg/s)			Pitch Rate $ q $ (deg/s)			Rotation Rate Ω (deg/s)		
	Aeroshell [2]	Stowed	Posed	Aeroshell [2]	Stowed	Posed	Aeroshell [2]	Stowed	Posed
50%-tile	0.73	1.16	1.60	0.78	1.31	1.27	1.32	2.15	2.46
90%-tile	1.92	3.30	3.44	1.93	3.67	2.96	2.55	4.75	4.11
95%-tile	2.36	4.15	4.00	2.32	4.63	3.54	3.00	5.81	4.65
99%-tile	3.39	6.22	5.56	3.40	6.93	4.60	4.19	8.12	6.20

From the results shown in Tables 4 and 5, the following observations, focusing on the 95%-tile and 99%-tile values, can be made.

- 1) The differences between the pitch and roll rates and angles (i.e., $|\theta|$ and $|\phi|$, and $|q|$ and $|p|$) were small for Phase II and the stowed configuration. In contrast, the posed configuration exhibits larger dynamics along the x-axis ($|\phi|$ and $|p|$). This could be caused by differences in the moments of inertia between the x-direction and y-direction.
- 2) Both the stowed and posed configurations, with the heatshield off and lander exposed to the freestream, are more dynamic than the system with a full aeroshell in Phase II. The 95%-tile nadir angle for the stowed and posed configurations are over twice that observed while descending under the same main parachute without the lander exposed to the flow.
- 3) In general, the stowed and posed configurations had similar levels of dynamics. The stowed had slightly higher lateral rates, while the posed had slightly higher nadir angle percentiles. In general, these results indicate that there would not be a large change in dynamics when the Dragonfly system changes from the stowed to posed configuration.
- 4) For all configurations, the values of $|q|$, $|p|$, and Ω were low when considered in the full-scale, Titan time of 6.604 times slower than observed in test.

B. Spectral Content

The appended datasets contain roughly 14 minutes of steady-state flight for both the stowed and posed configurations. The IMU data was downsampled to 10 Hz for post-processing, which implies a Nyquist cutoff frequency of 5 Hz. A power spectral density (PSD) was taken of the Euler angles and nadir angle to characterize the dynamics of the stowed and posed configurations during the ensemble of quasi-steady state data. Figure 13 shows the amplitude versus frequency for the stowed (left) and posed (right) configurations in Titan, full-scale rates. The spectra reported from the Phase II, full aeroshell descending under main parachute [2] is also provided at the top of Figure 13. Since the Froude-scaling resulted in $N_\omega = 6.60$, a 6.60 Hz mode observed in the model would correspond to 1 Hz at full-scale, Titan conditions.

For both the stowed and posed configurations, a low frequency Euler angle mode of 0.035 Hz is observed, followed by a 0.07 Hz nadir angle mode. This corresponds to a pendulum mode, a swinging motion passing through the axis of symmetry about the center of mass of the system, that is solely dependent on the overall mass of the system. The roll

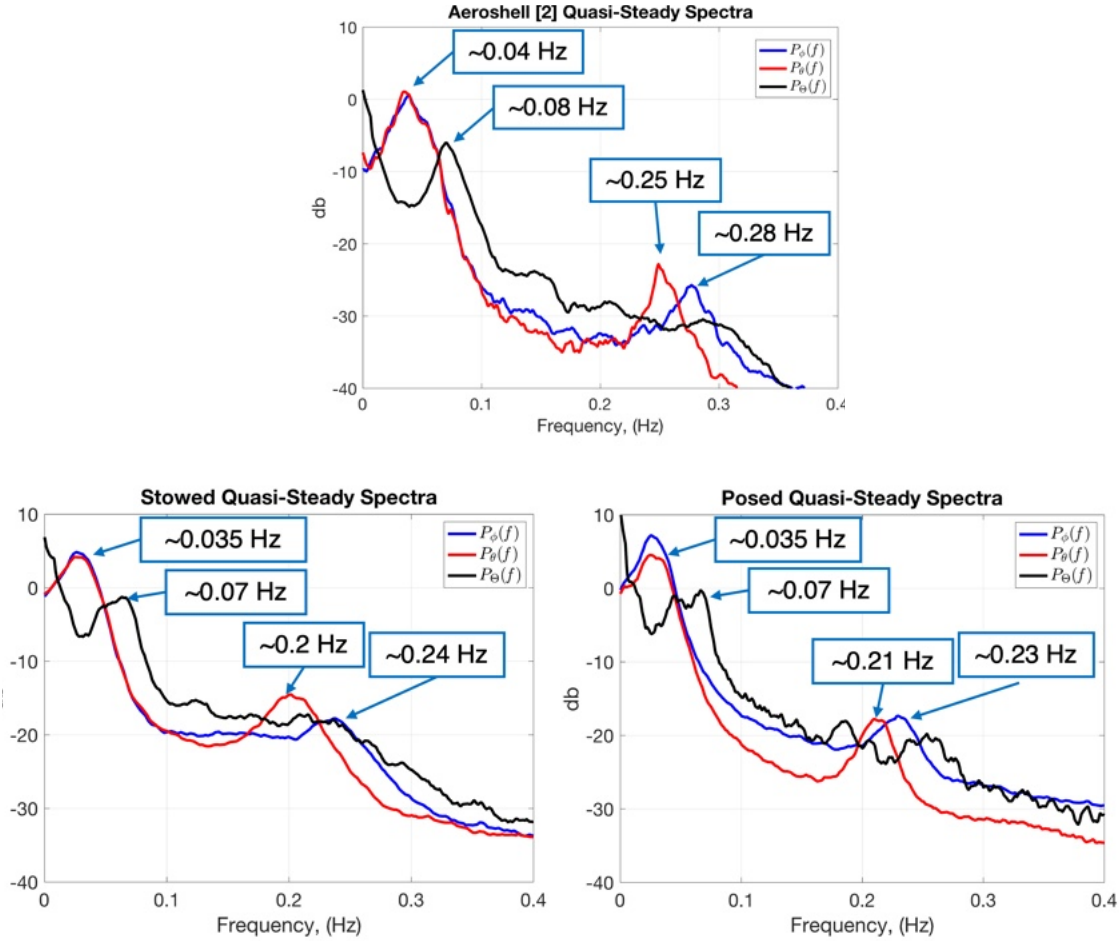


Fig. 13 Power Spectra of the Euler and nadir angles for the full aeroshell (top), stowed (right) and posed (left) configurations. Spectra of roll (red), pitch (blue), and nadir angle (black) showing normalized amplitude versus full-scale, Titan frequency.

and pitch angles show this mode at the same frequency since it is independent of moments of inertia. Since the nadir angle (in one-dimension) is effectively the absolute value of the Euler angle, it is expected to have frequency content twice as fast as each individual Euler angle.

The higher frequency content mode is expressed between 0.2-0.25 Hz for both the stowed and posed configurations in Figure 13. However, unlike the symmetric characteristic of the presumed pendulum mode, this mode is shifted such that, for all three configurations, the roll mode occurs at a higher frequency than the pitch mode. This is presumed to be the wrist mode, an angular oscillation about the triple bridle confluence point. Since its motion resembles a deviation about a fulcrum point, it would be expected that the specific frequency response of a particular Euler angle would be dependent on its moment of inertia. Since the roll and pitch axes do not have the same moments of inertia, the wrist mode appears at offset frequencies for each. This offset results in a relative phase shift in the context of the nadir angle and therefore the mode is not as pronounced in the nadir angle spectra for either configuration.

In general, the frequency content of the stowed and posed configurations contain similar dominant modes and trends as the system with the full aeroshell from Phase II.

C. GPS and Wind

The altitude (top) and descent velocity (bottom) data for the posed configuration is shown as an example in Figure 14. The height signal from the GPS appears to be accurate, however there is significant noise in the prediction of descent velocity. It was neither expected, nor observed, that the descent velocity of the two configurations tested would have

high-frequency fluctuations as the descent velocity signal in Figure 14 suggests. In general, the descent velocity under the main parachute matches the predicted 3 m/s descent rate estimated prior to testing.

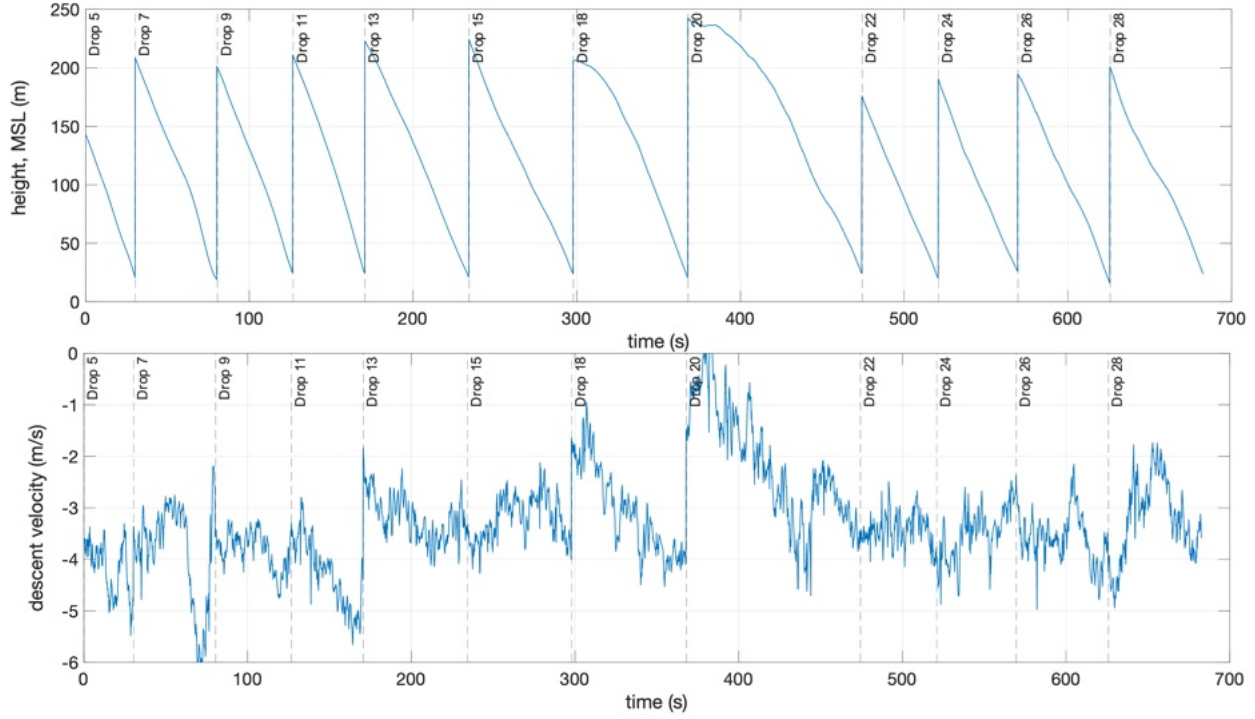


Fig. 14 Posed configuration: appended GPS data

Figure 15 shows the resultant wind profiles using this extraction process for drop 14. The extracted horizontal wind profile indicates the formation of the expected surface boundary layer. Disturbances in the wind profile are observed between 35 and 65 meters thought to be explained by low-altitude turbulence induced by the treeline surrounding the test range. It should be noted that the LiDAR also measured the wind direction such that the horizontal wind could be further decomposed into North-South and East-West components. Ultimately, this capability was not needed in assessing and comparing the dynamics of the test to the Monte Carlo reconstruction efforts in Williams et al. [5].

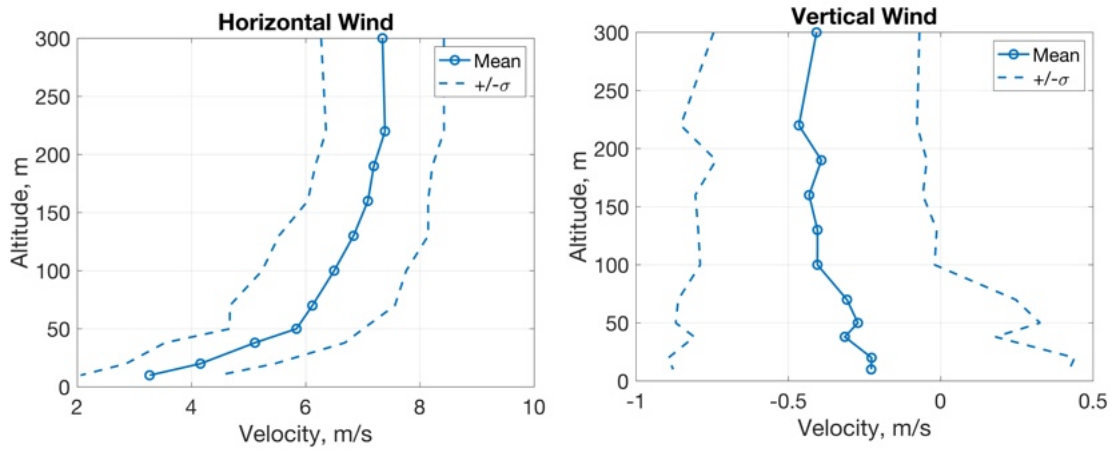


Fig. 15 Example wind data extracted from the LiDAR data sampled within ± 5 minutes of a drop.

VI. Conclusion

The Dragonfly mission will have a long duration suspended under parachutes during EDL. A series of subscale drop tests were performed to assess the dynamics of a Froude-scaled aeroshell and lander in three separate phases of flight, which correspond to prior to the drogue-to-main deploy event, immediately after the drogue-to-main deploy event, and prior to the release of the lander. Comparisons between the results of Phase II, full aeroshell, and Phase III indicate that the exposed lander, in both the stowed and posed configurations, is susceptible to higher nadir angles and lateral rates.

While the dynamics in the stowed and posed configurations are larger than the dynamics of the full aeroshell under main parachute, the lateral rates remain relatively low. Generally, the lander is more sensitive to lateral rates than nadir angle. There are expected to be differences between the dynamics observed during a subscale drop test at Earth compared to the actual Dragonfly system flying at Titan. Namely, the length scale of the turbulence is off by multiple orders of magnitude and the mass properties of the parachute system cannot be dynamically scaled. Therefore, the values observed in test should not be used to extrapolate the dynamics at Titan during lander release.. Instead, a Monte Carlo reconstruction of the drop tests, published by Williams et al. [5], is used to verify relevant models to build trust in the full-scale simulation at Titan conditions.

Acknowledgments

This test campaign was conceptualized, developed and started by Juan R. Cruz, Langley Research Associate. The contributions of the following individuals from the NASA Langley Research Center are gratefully acknowledged. Richard E. Martin and Donald S. Smith, Manufacturing Applications Branch. Matthew W. Coldsnow, Jennifer W. Fowler, Mark W. Frye, Skyler J. Hudson, Jontae Park, and Amanda D. Neff, UAS Operations Office. Caleb Thompson, Aeronautics System Engineering Branch. Caleb Robb, Jimmy Williams, Anthony Palazzo, Atmospheric Flight and Entry Systems Branch. Sean Laughter, Engineering Integration Branch and Chad Stimson, Science Directorate. The models of the main parachutes were designed and fabricated by staff at ASNA.

References

- [1] Pensado, A. R., Winski, R. G., Williams, J. W., and Robb, C., “Dragonfly Mission Entry and Descent Modeling and Simulation Overview,” *AIAA SCITECH 2025 Forum*, 2025. <https://doi.org/10.2514/6.2025-2237>
- [2] Cruz, J., Shafner, J., Duvall, B., Gray, M., Khasawneh, I., Meek, C., Miller, J., and Chamberlain, B., “An Investigation of the Dragonfly Mission Aeroshell/Parachute Dynamics Through Subscale Drop Tests,” *AIAA AVIATION FORUM AND ASCEND 2024*, 2024. <https://doi.org/10.2514/6.2024-4329> URL <https://arc.aiaa.org/doi/abs/10.2514/6.2024-4329>
- [3] Wolowicz, C. H., James S. Bownman, J., and Gilbert, W. P., “Similitude Requirements and Scaling Relationships as Applied to Model Testing,” Tech. Rep. NASA Technical Paper 1435, National Aeronautics and Space Administration, 1979. URL <https://ntrs.nasa.gov/api/citations/19790022005/downloads/19790022005.pdf>
- [4] Desai, P. N., and Cheatwood, F. M., “Entry dispersion analysis for the genesis sample return capsule,” *Journal of Spacecraft and Rockets*, Vol. 38, No. 3, 2001, pp. 345–350.
- [5] Williams, J., Pensado, A. R., Winski, R., Robb, C. S., Manwell, M., Guecha-Ahumada, N. G., and Shafner, J., “Simulation of the Dragonfly Subscale Drop Tests,” *AIAA SCITECH 2026 Forum*, 2026, p. 1957.