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Dragonfly Preparation for Powered Flight: Lander Separation State Control to Ensure Successful Landing

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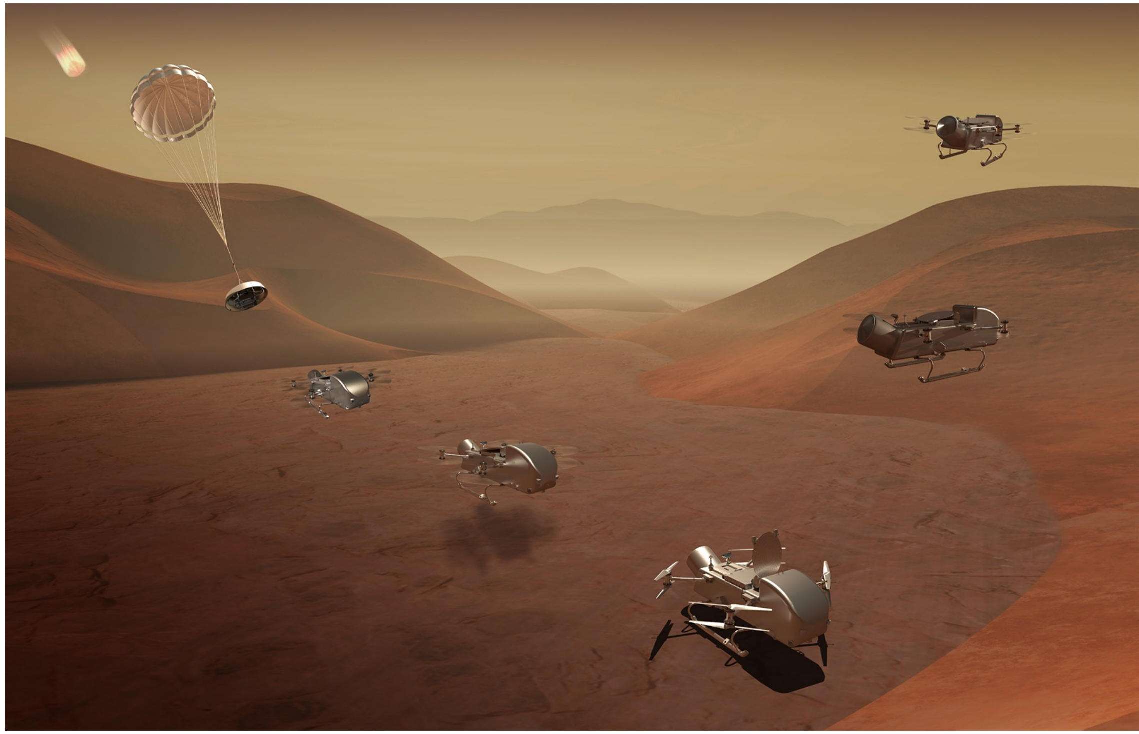
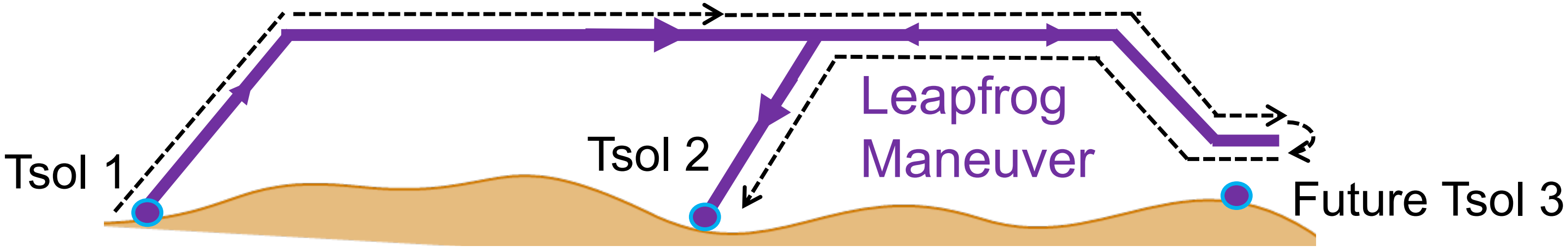
Dragonfly Mission Summary

- NASA's Dragonfly mission will send a relocatable octocopter lander to the surface of Saturn's moon Titan with the goal of:
  - Investigating the prebiotic chemistry on the surface
  - Measuring atmospheric and environmental conditions
  - Relocating to / investigating deposits associated with Selk Crater
- The preliminary landing site is a field of sand dunes that the lander must traverse to reach Selk Crater
- The lander will then spend 1 Titan day (Tsol), about 2 weeks in each location before moving to the next.



Credit: Johns Hopkins APL



This slide adapted from Becca Foust, 2023 AAS/AIAA Astrodynamics Specialists Conference

But First, the EDL Sequence

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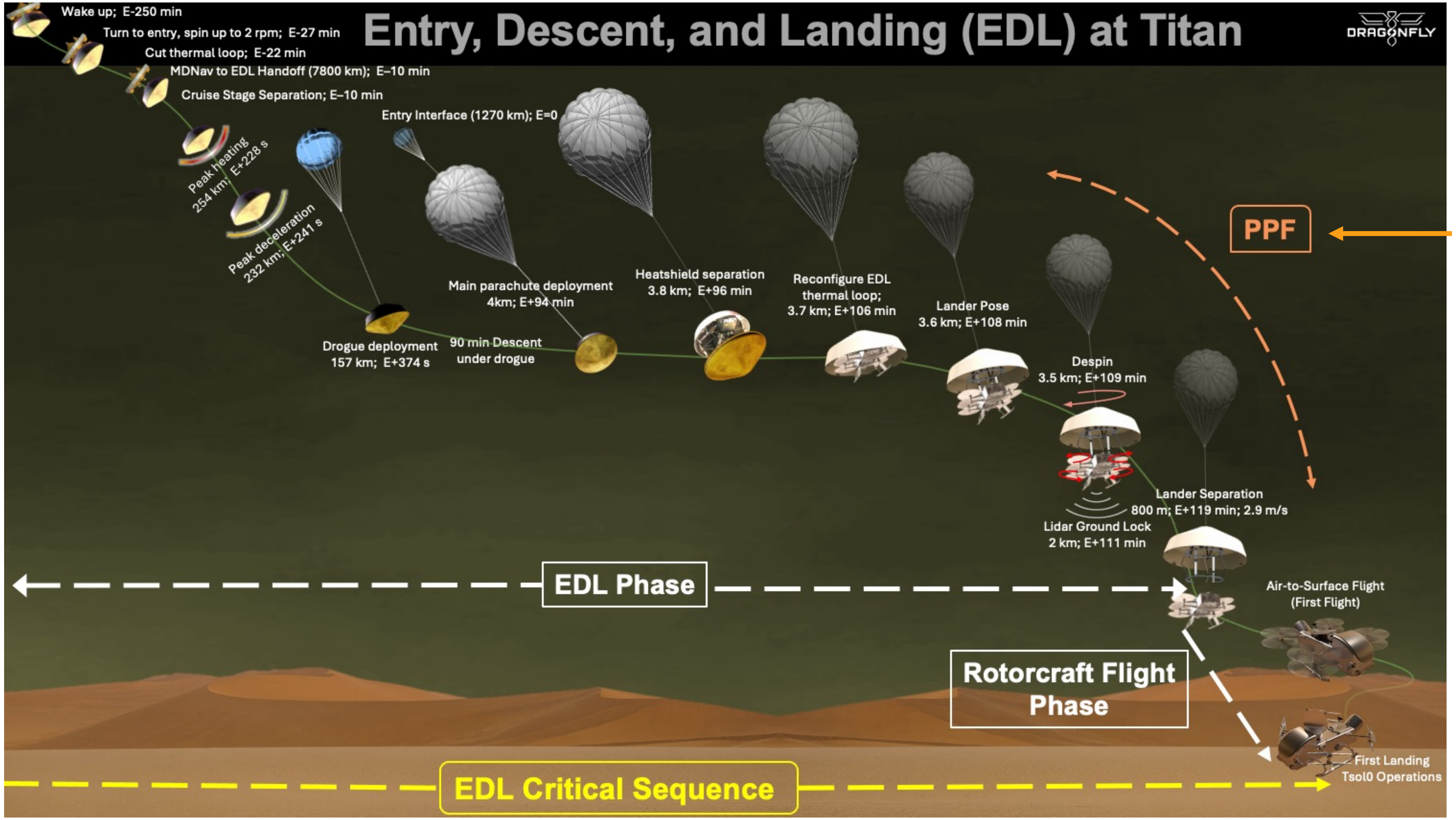
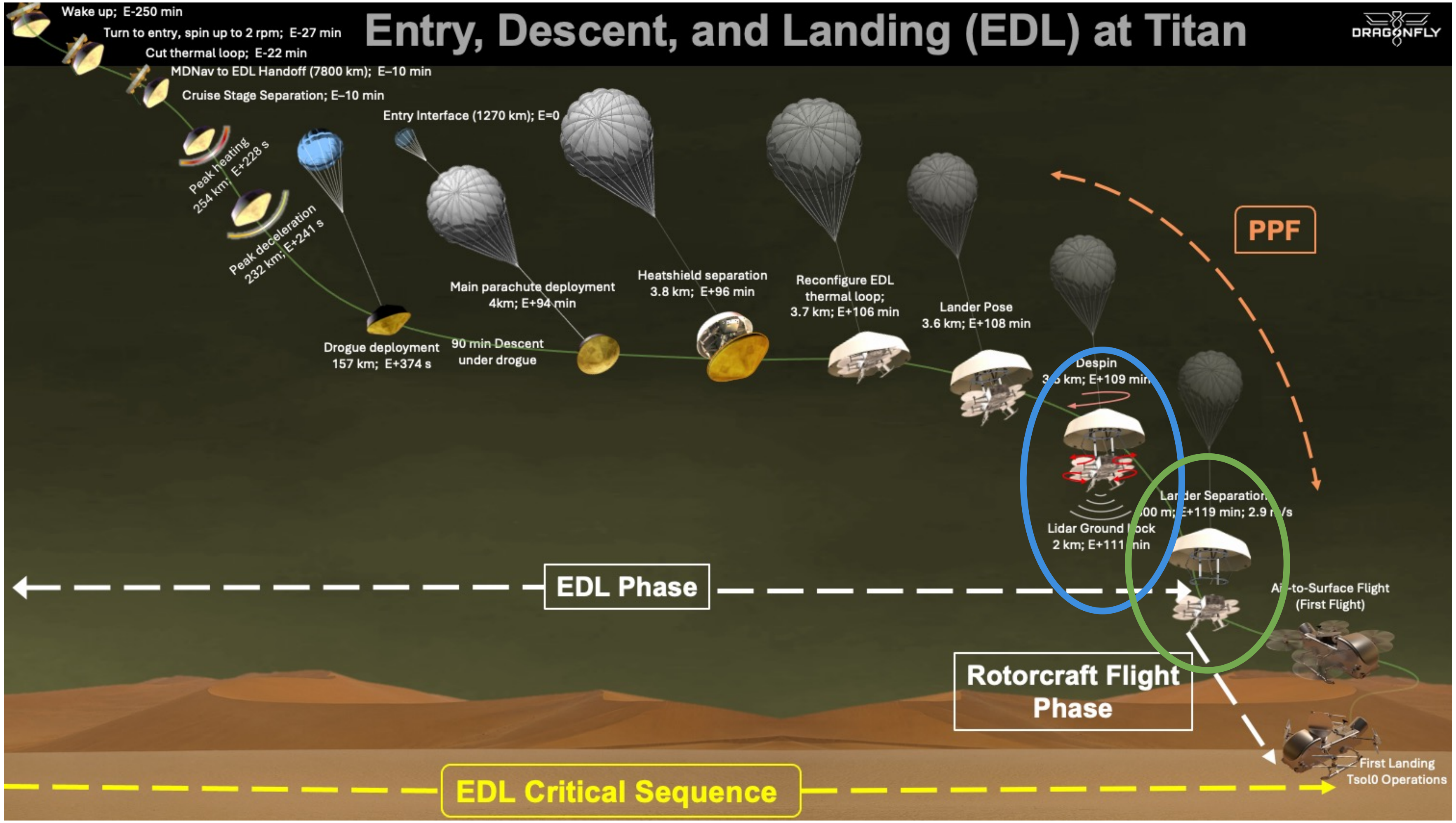


Preparation for Powered Flight (PPF)

- Begins with the lander lowering into the 'posed' configuration
- Ends with lander release & Transition to Powered Flight (TPF)

EDL Sequence: PPF



PPF: Preparation for Powered Flight

This talk discusses the two main components of PPF, both used to put the lander in a desirable state for release from the backshell & parachute.

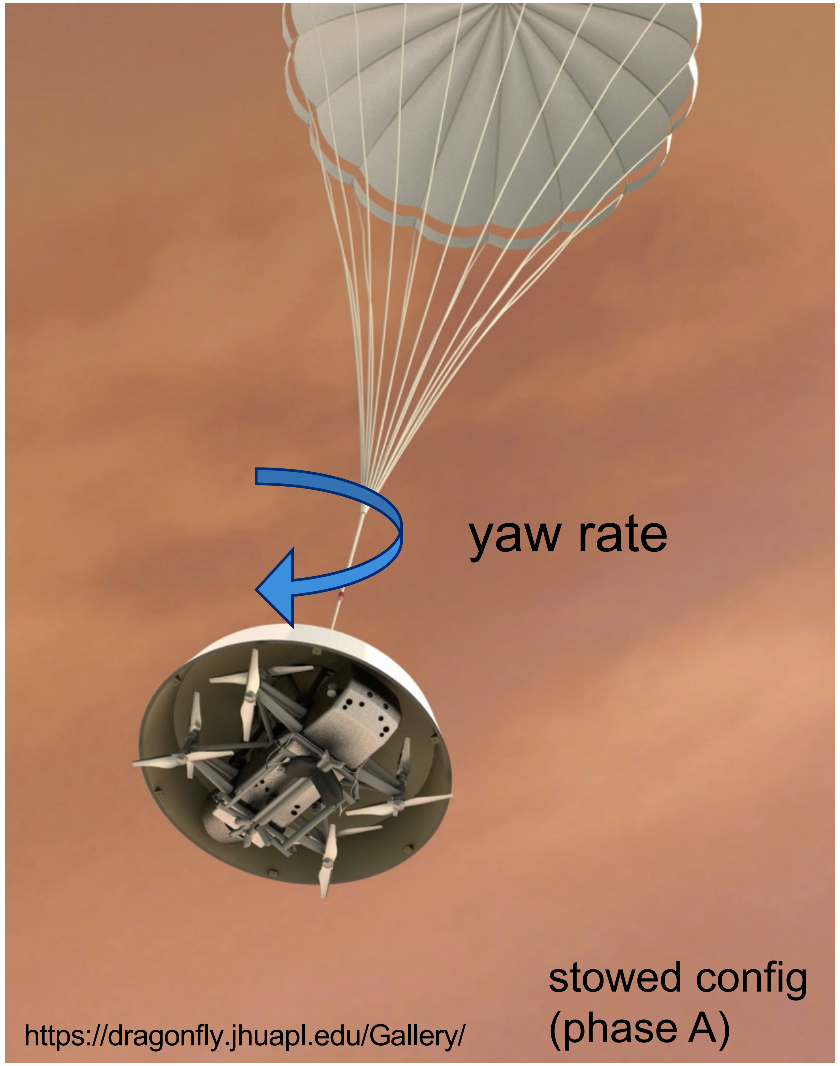
Yaw Despin

The lander spin rate is first reduced

Lander Separation

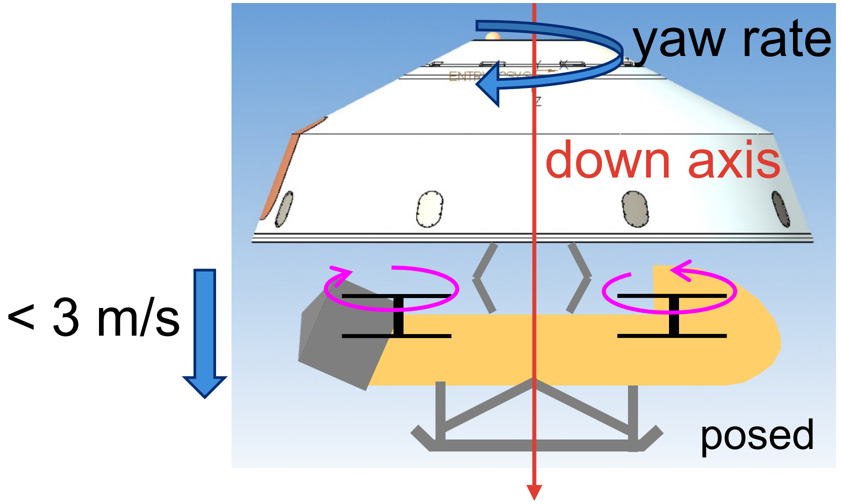
Then a passive trigger is used to release the lander with a desired pitch rate

Yaw Despin Motivation



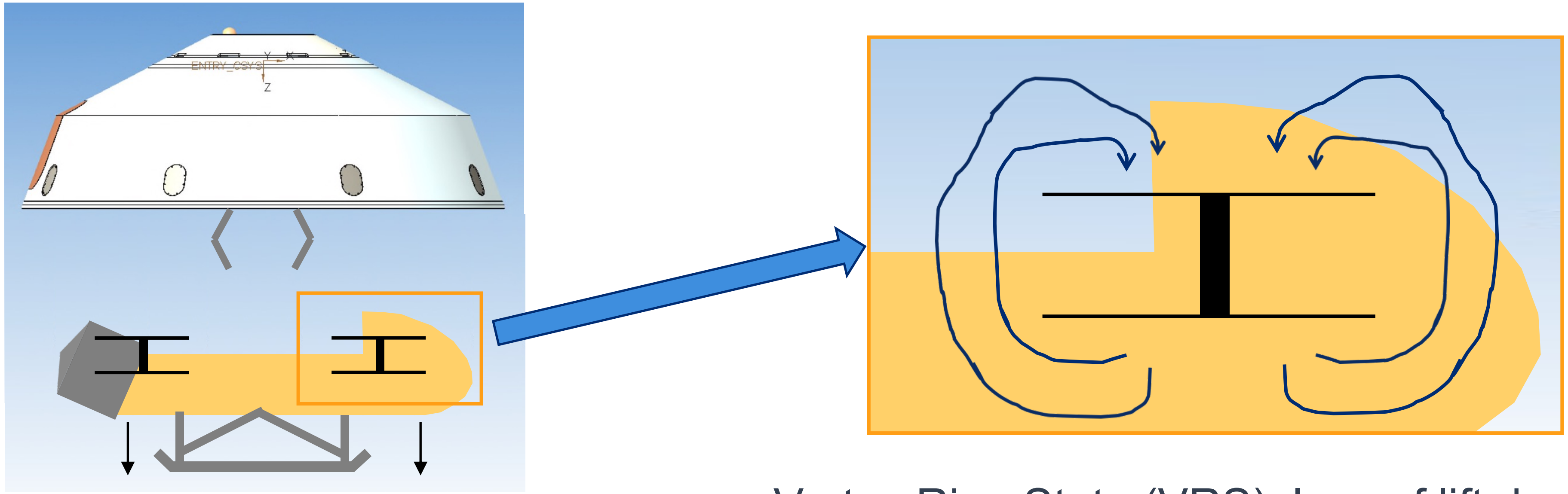
The lander-backshell assembly on the parachute may be spinning too fast (up to **31 deg/s**) for release, navigation filter initialization, and optical measurements.

- Despin the yaw rate using the rotors before release



Release Trigger Motivation: VRS

After release, the lander's rotors will pass through the Vortex Ring State (VRS)



Lander release + Δt

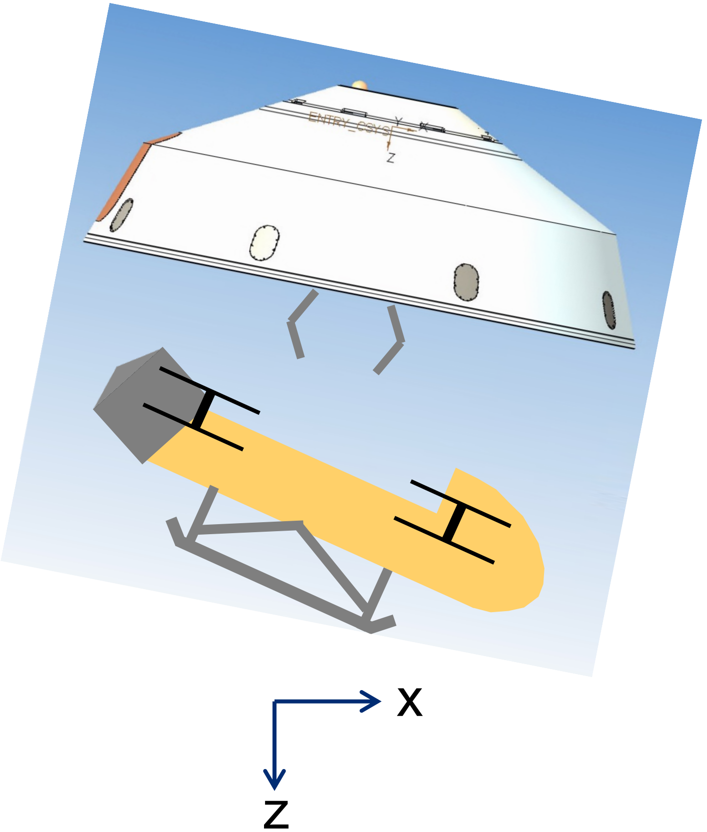
Vortex Ring State (VRS): loss of lift due to reduced net momentum transfer to the atmosphere

VRS

- Reduces lift
- Lowers model fidelity

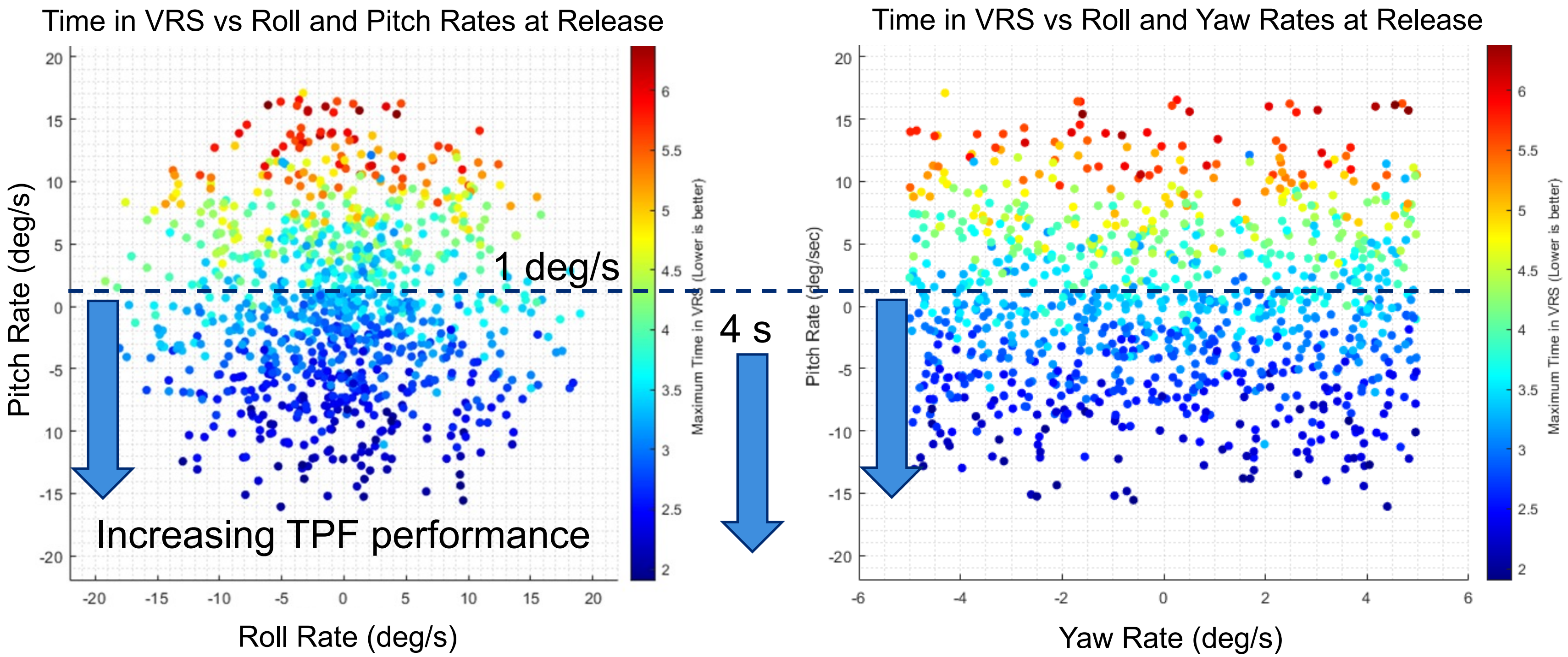
Goal: Release in a state that reduces the transition time through VRS

Time within VRS



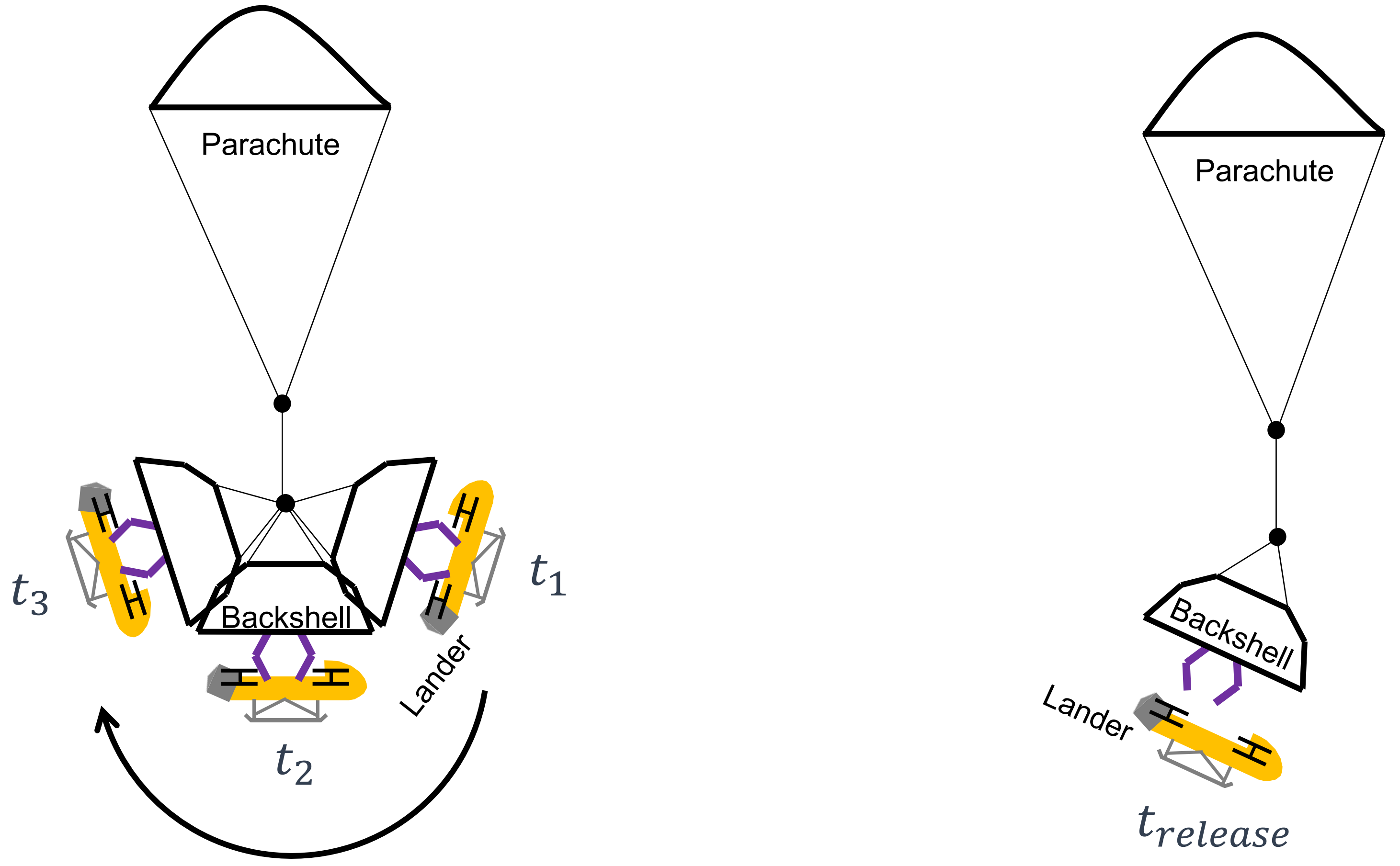
negative pitch rate = nose moving down

Time in the undesirable vortex ring state (VRS) after release decreases if released with more negative pitch rates. Not sensitive to roll or yaw rate, or any angles.



Release Trigger Timing

Time within the Vortex Ring State (VRS) decreases with negative pitch rates at release



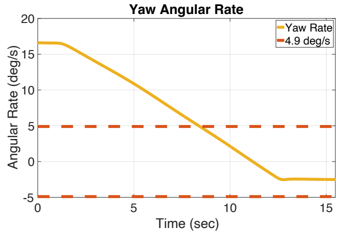
Negative pitch rate swing

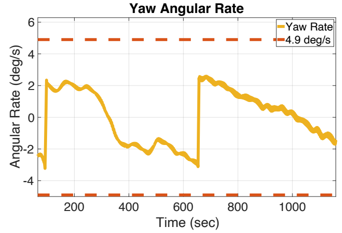
$t_1 < t_{release} < t_3$

2 swinging modes:

- ≈ 4 sec
- ≈ 25 sec

PPF Requirements and Goals





1) Requirement: Despin within sufficient time
   - despin to within ±4.9 deg/s within 3 min from arriving in the posed configuration

2) Requirement: Maintain a despun state until release (station keeping)
   - stay within ±4.9 deg/s from 2 km above ground until release

3) Requirement: No despin action for at least 2 sec prior to release
   - all rotors commanded to the minimum 100 RPM for ≥ 2 sec prior to release; accounts for rotor dynamics

4) Requirement: Lander release shall occur between 1000 m and 800 m above the ground

5) Soft Constraint: Reduce time within VRS immediately after release by releasing with negative pitch rates

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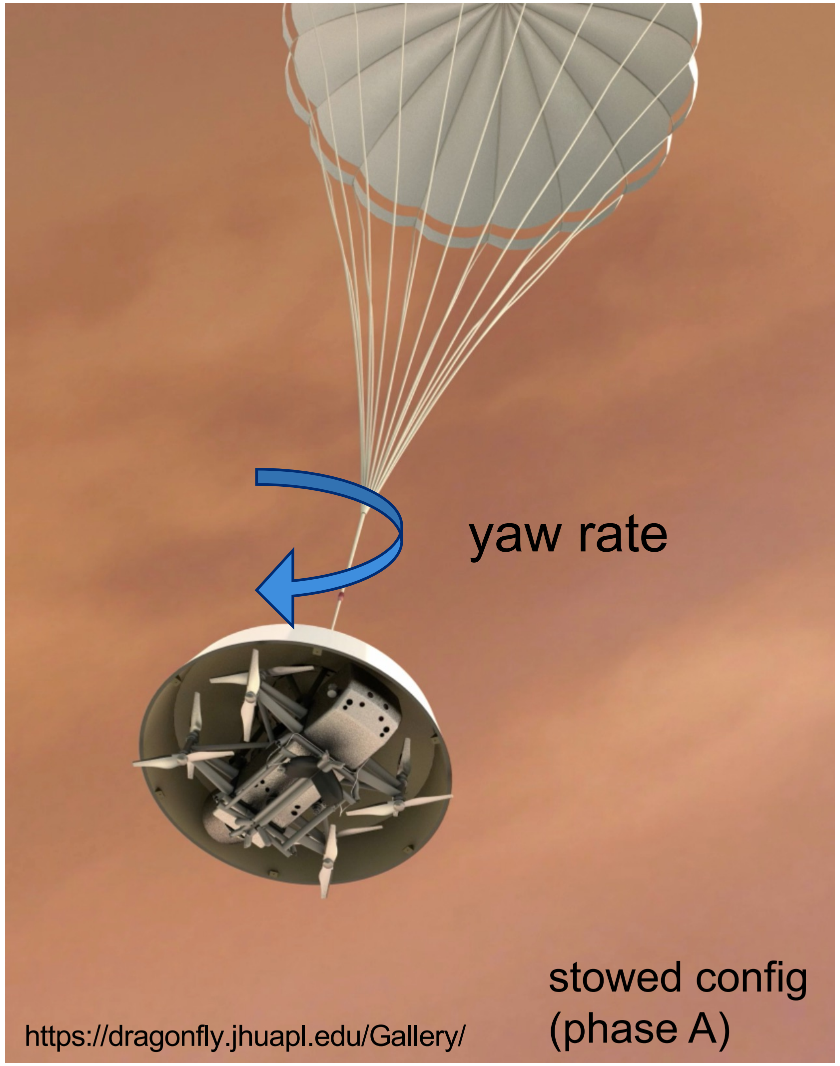
Despin

Simulations in MATLAB/Simulink at APL and POST2 at NASA LRC



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Despin Actuation

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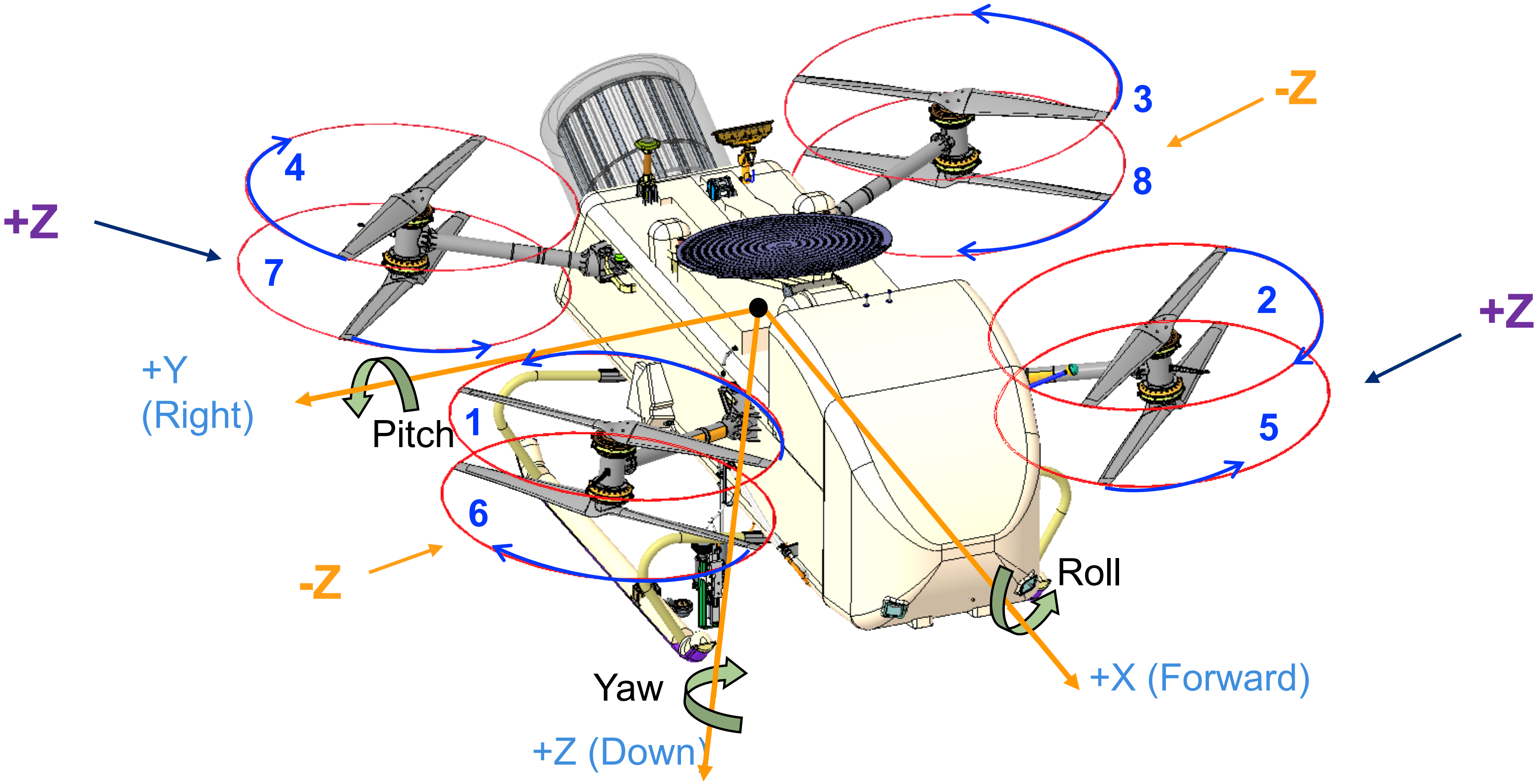
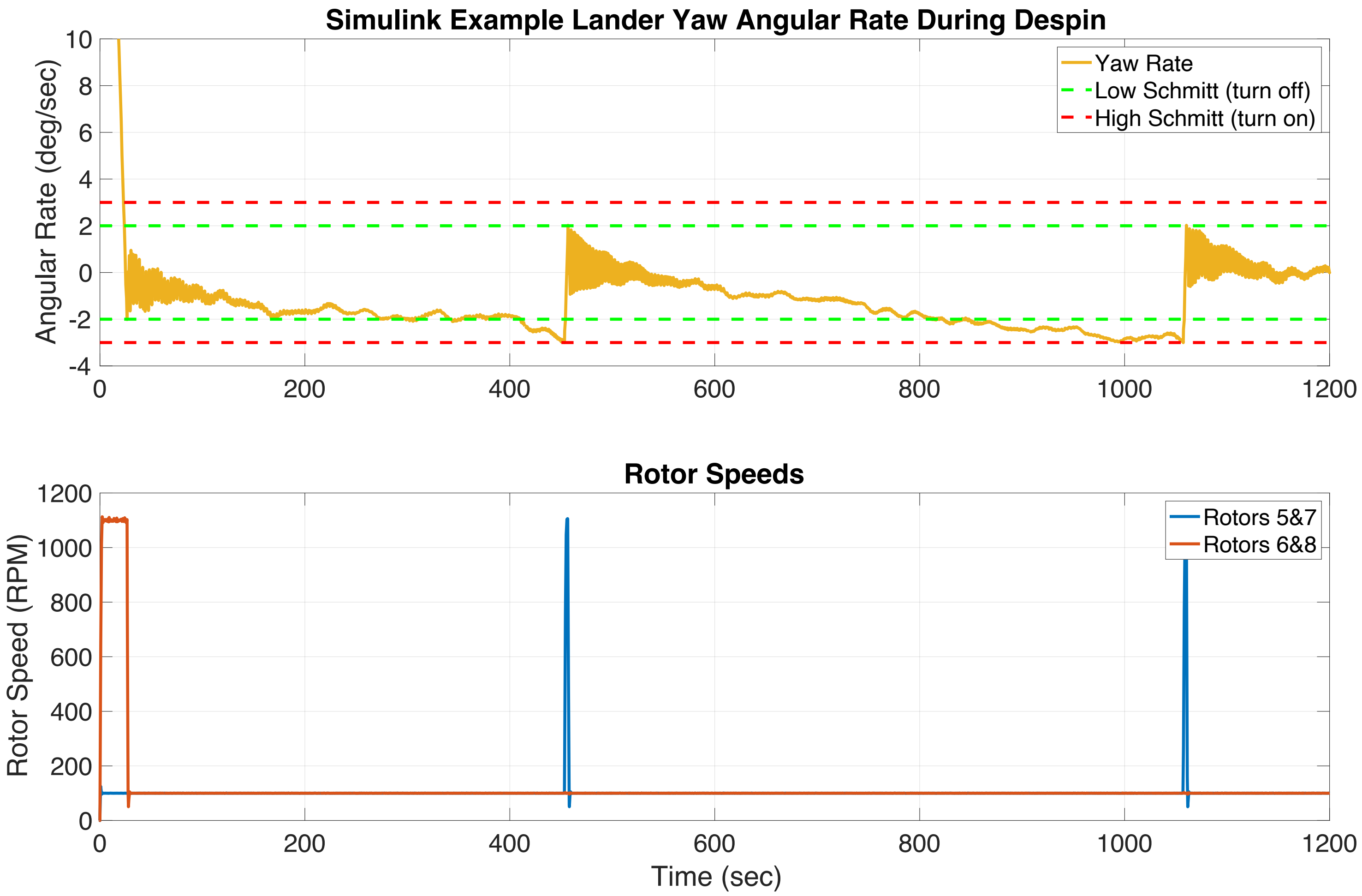
Yaw despin actuated with lower rotors

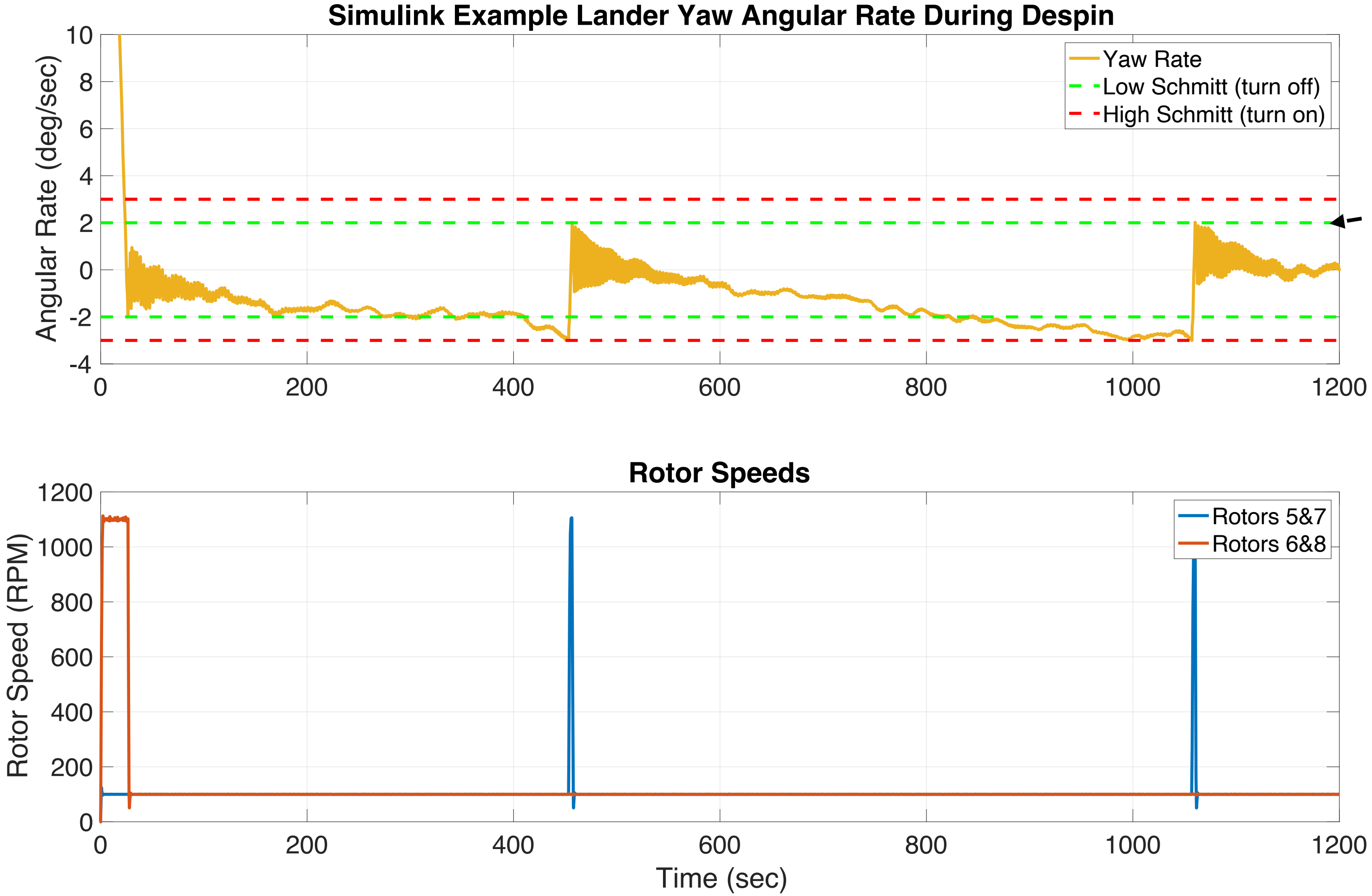
- +Down torque applied with rotors 5 & 7
- -Down torque applied with rotors 6 & 8



Despin Control Design - Bang Bang

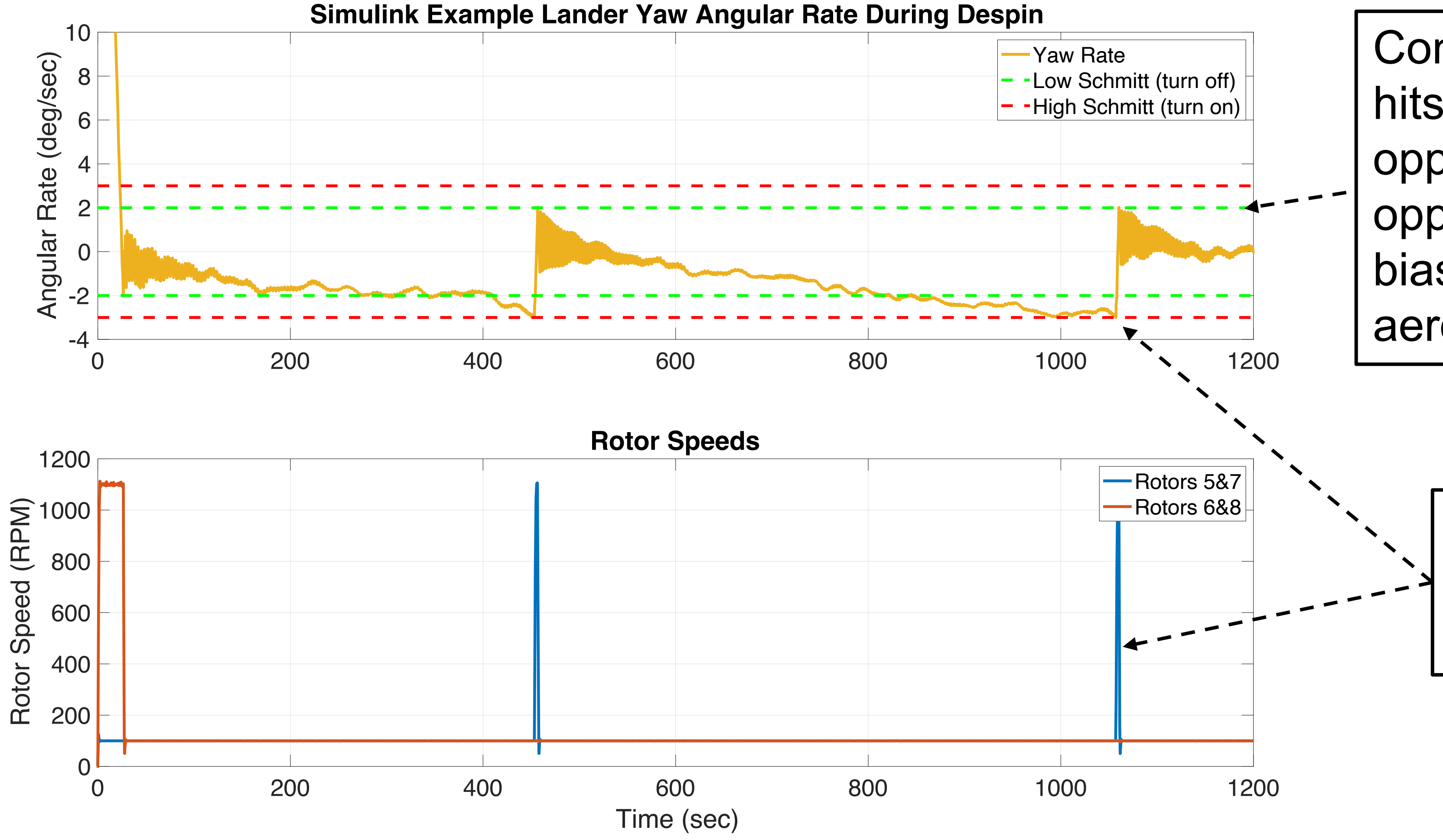


Despin Control Design - Bang Bang



Control turns off when yaw rate hits inner **2 deg/s** limit with opposite sign. Using the opposite sign accounts for any bias torques in the aerodynamics.

Despin Control Design - Bang Bang



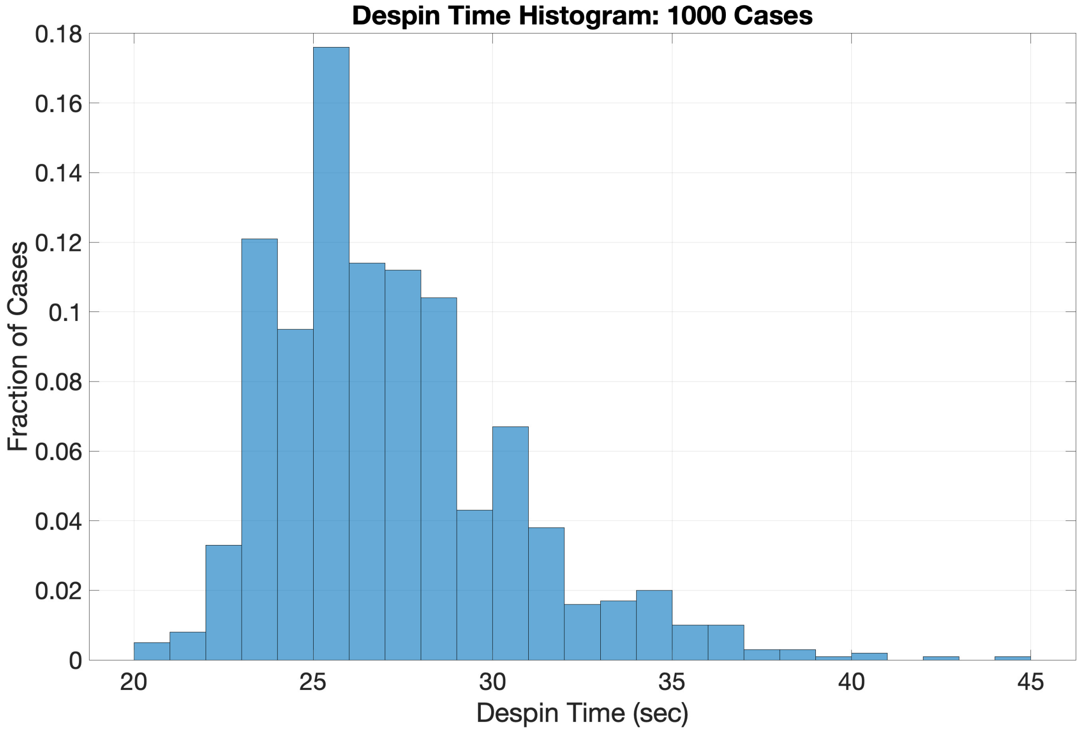
Control turns off when yaw rate hits inner 2 deg/s limit with opposite sign. Using the opposite sign accounts for any bias torques in the aerodynamics.

Control turns on with appropriate rotors when yaw rate > the outer 3 deg/s limits

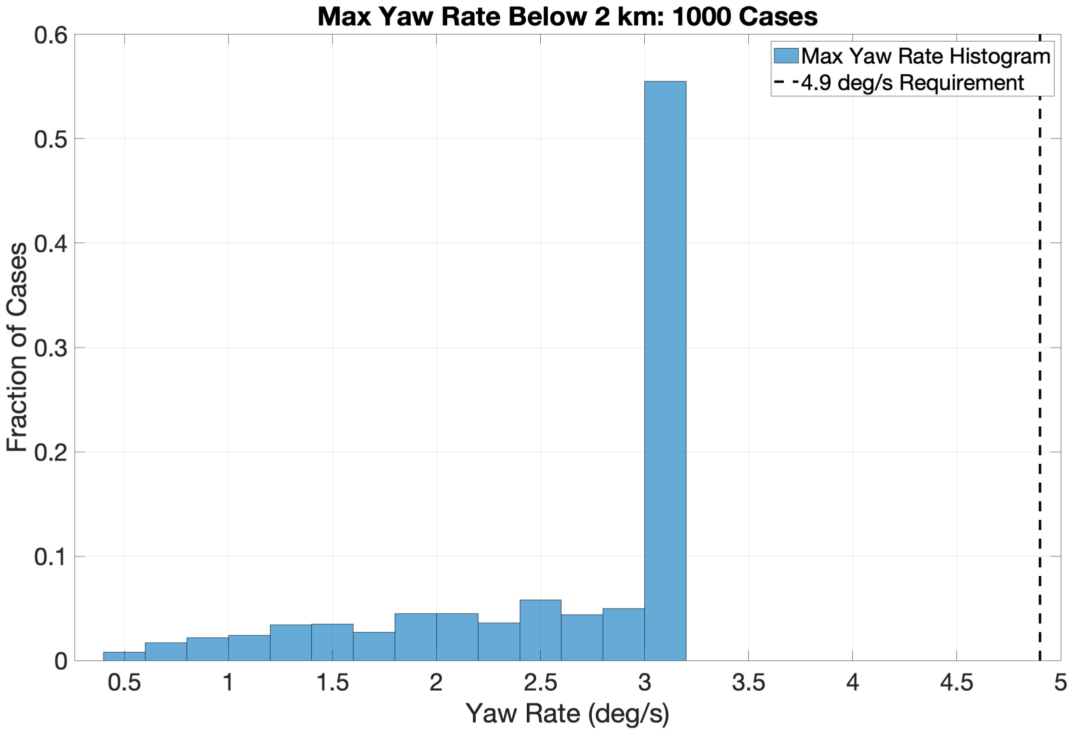
Monte Carlo Simulation Sampling

- Initial rates
  - Roll and Pitch: ±22 deg/s. This rate allows 10% margin over the 20 deg/s from the Langley EDL team
  - Yaw: ±34.1 deg/s. Constant magnitude, random sign. 10% margin over the max 31 deg/s from the ERD.
- Initial angles
  - Roll and Pitch: ≈ ±14.5 deg based on analysis in following slides, which provides 37% margin over the 10.6 deg from the Langley EDL team
  - Yaw: ±180 deg uniform sampling
- Wind
  - 'Titan' wind with gusting up to ≈ ±2 m/s
- Aero tables. From discussions from UCF:
  - 20% uncertainty on each force & moment element in all aero tables: rotors, backshell, lander body
  - Apply a min force/moment variation to table elements that are < 1% max of similar elements. E.g., max body X force in table is 100 N. An element with a nominal 0 N body X force will be varied by +-1 N rather than 0 N.

Monte Carlo Results

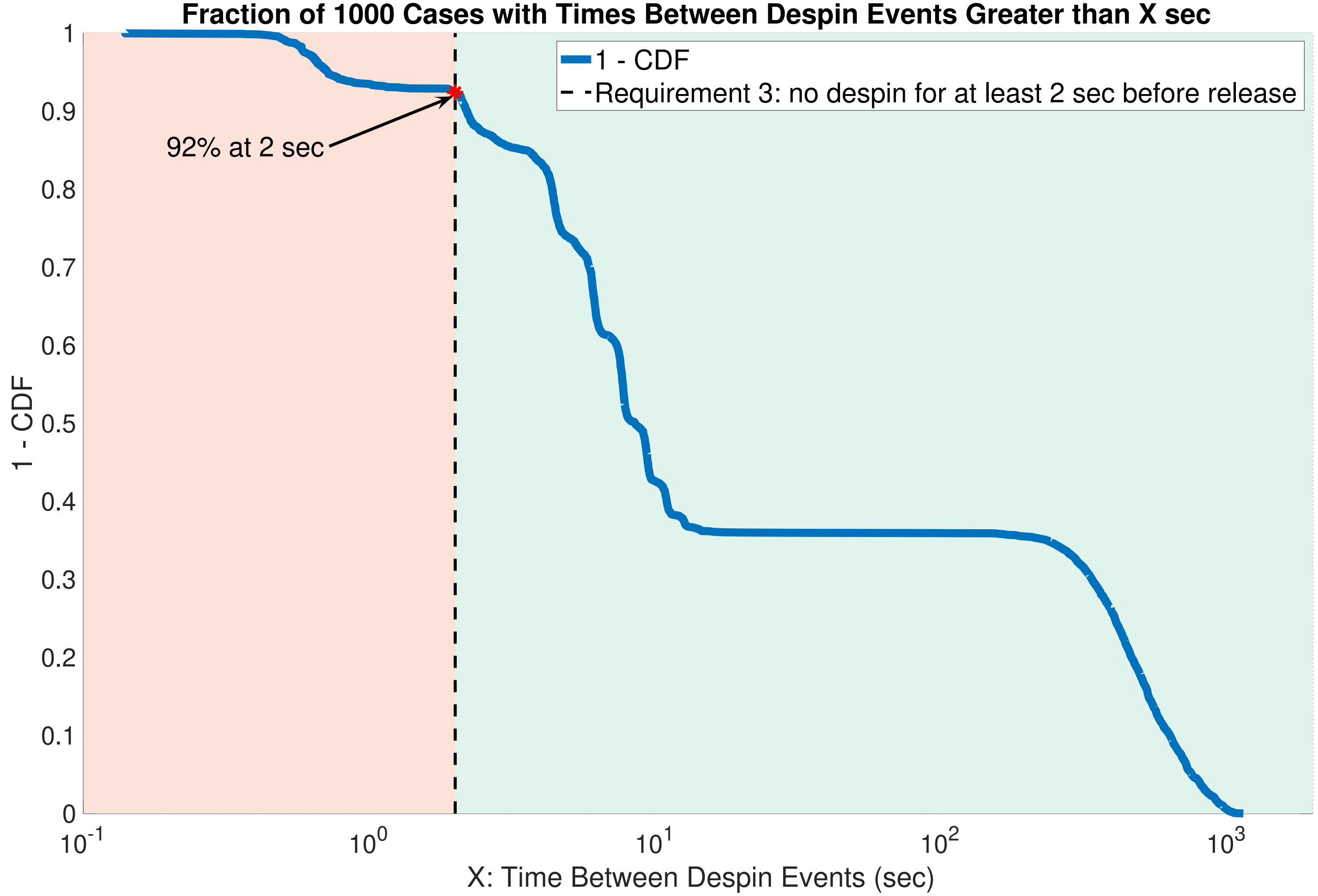


Meets requirement 1: despin < 180 s



Meets requirement 2: station keeping < 4.9 deg/s

Monte Carlo Results



92% of despin events separated by ≥ 2 s -> Addresses Requirement 3: no despin for ≥ 2 s prior to release

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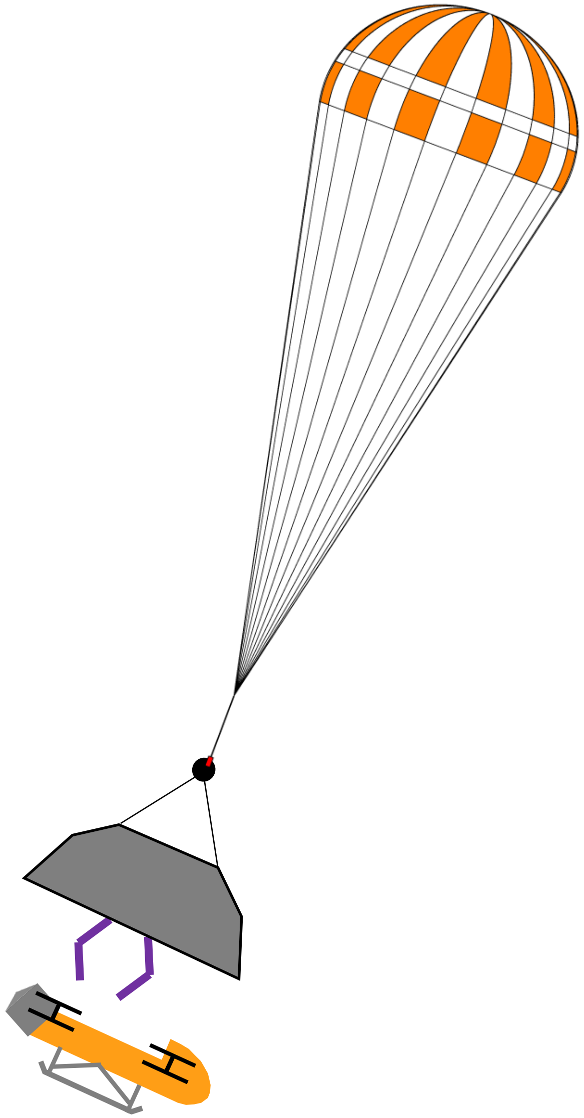
Lander Release Trigger

Simulations in MATLAB/Simulink at APL and POST2 at NASA LRC



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Release Trigger Logic

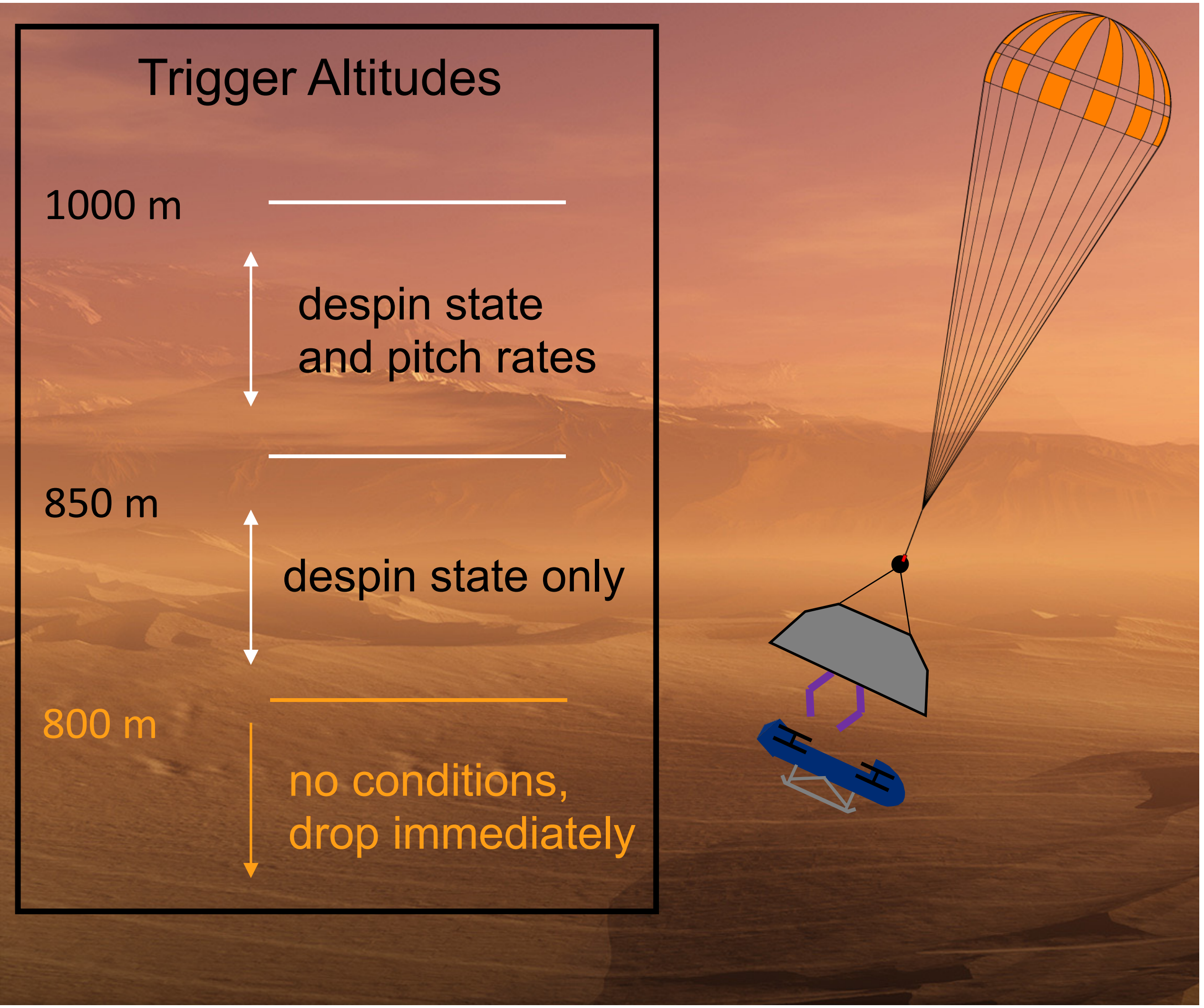

Image Background Credit: Johns Hopkins APL

Altitude	Drop Logic
1000 m to 850 m	no despin ≥ 2 sec AND pitch rate < threshold
850 m to 800 m	no despin ≥ 2 sec
< 800 m	Disable despin, drop once inactive ≥ 2 sec

Trigger Delays: Guiderails & Electronics

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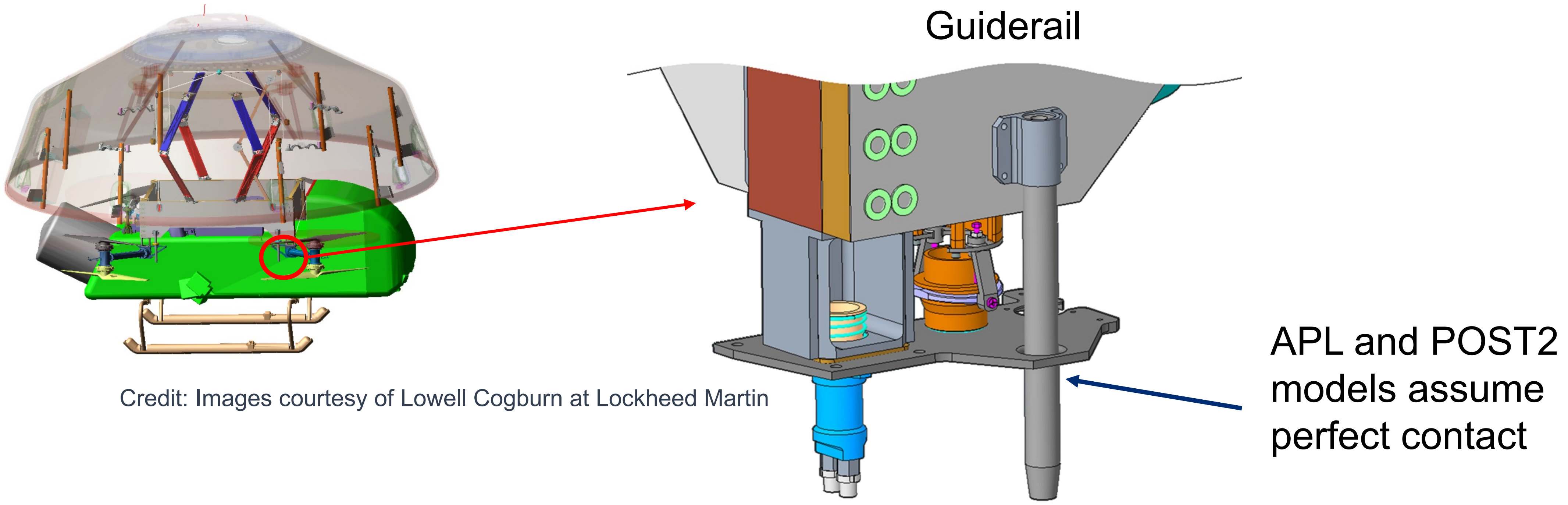
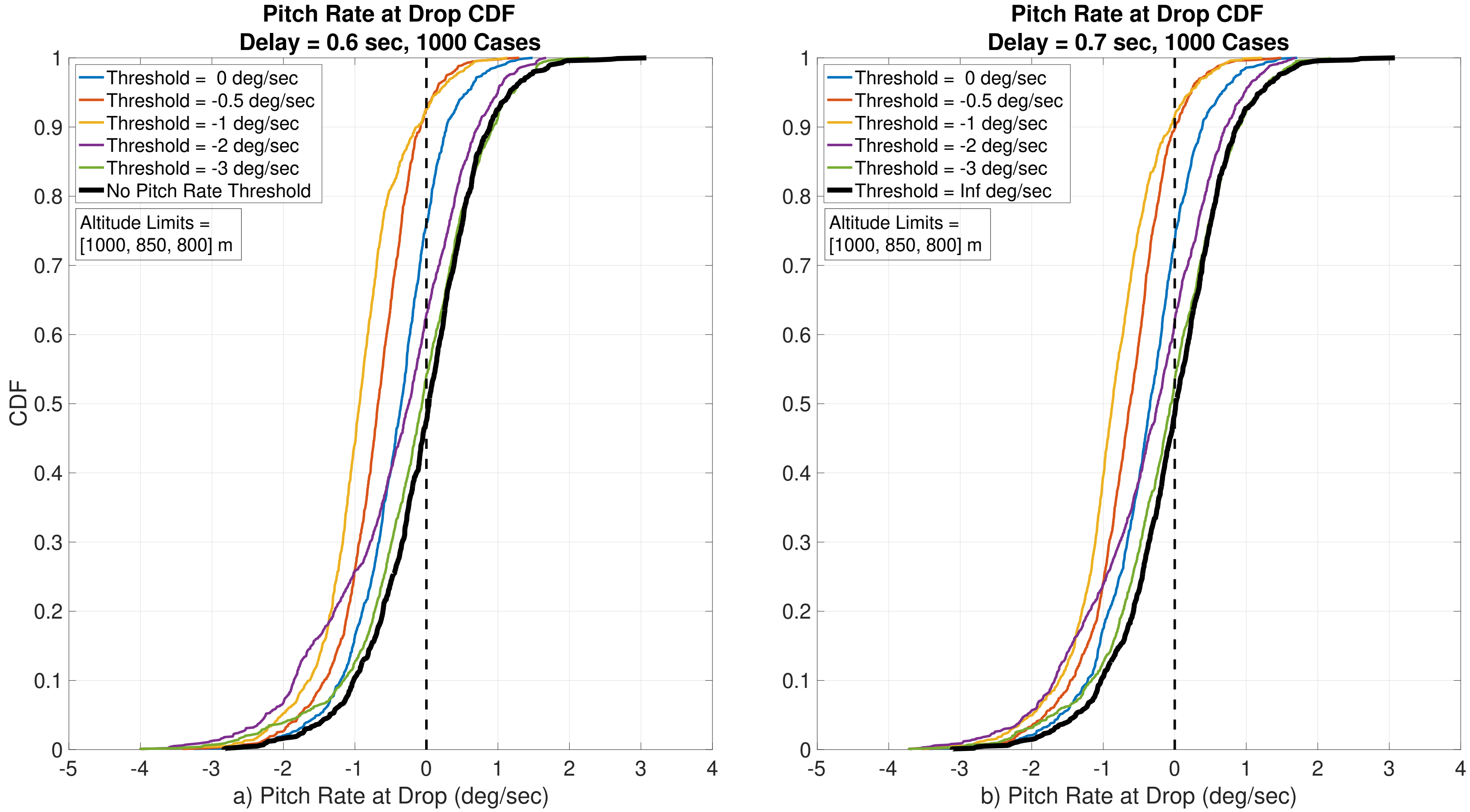


Credit: Images courtesy of Lowell Cogburn at Lockheed Martin

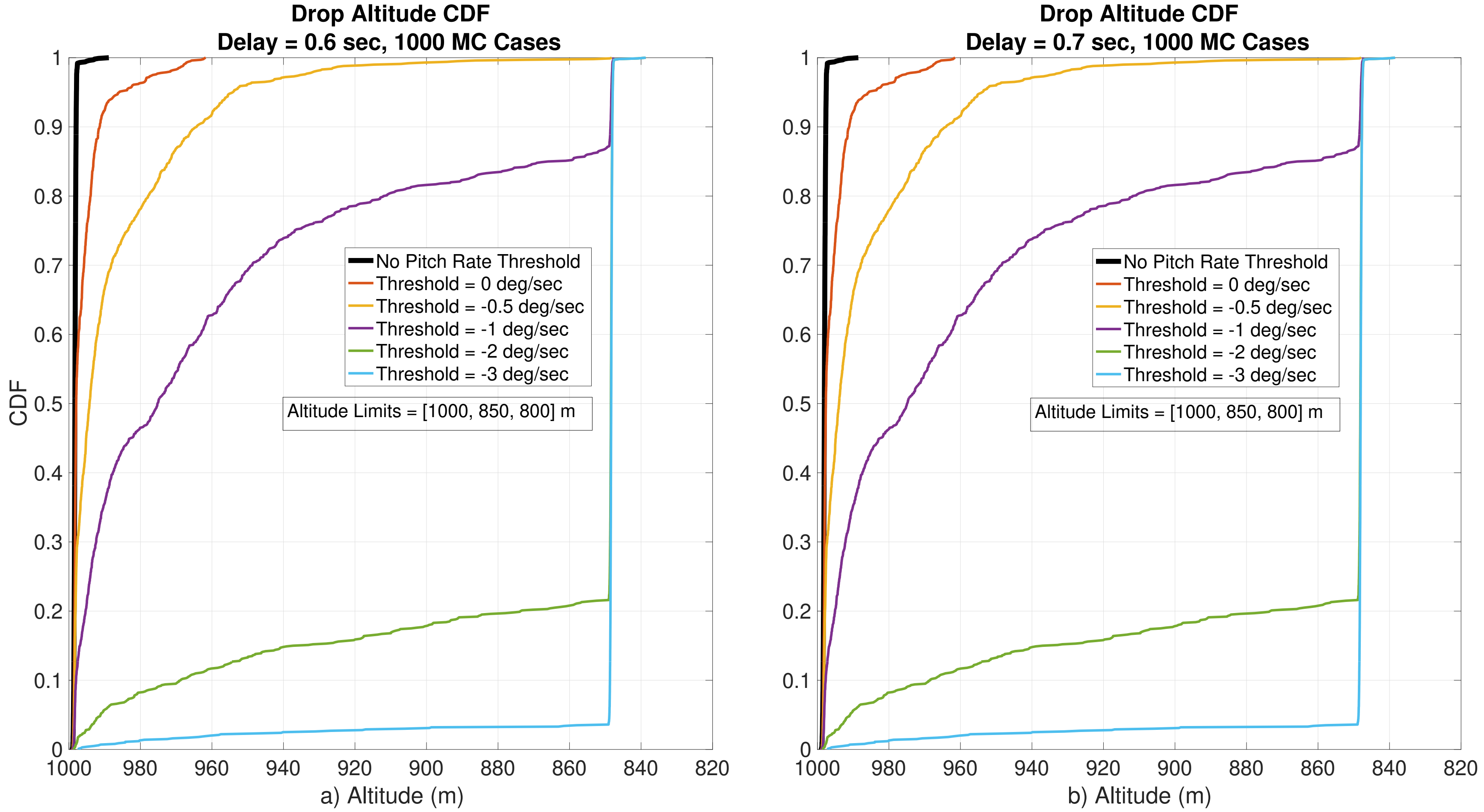
- Descent off guiderails takes 0.5 sec CBE based off ADAMs sims
- Total delay is 0.5 sec descent + 0.1 sec or 0.2 sec trigger delay
  - = 0.6 sec or 0.7 sec -> still relatively short compared to 4 sec oscillation period

Pitch Rates at Release



This addresses the soft constraint to release with negative pitch rates

Release Altitude



Requirement 4: all cases release by 800 m altitude

Conclusions and Work to Go

Conclusions

- Despin control meets all the 4.9 deg/s requirements according to simulations
- Release trigger meets the altitude requirements according to simulations
- Release trigger selects more negative pitch rates, though does not guarantee all negative rates
  - VRS times limited to 4 sec according to simulation
- Poor selection of the Release Trigger threshold does not make pitch rates worse

Work to Go

- Consider non-flat terrain
- Consider fault cases
- Refinement of models

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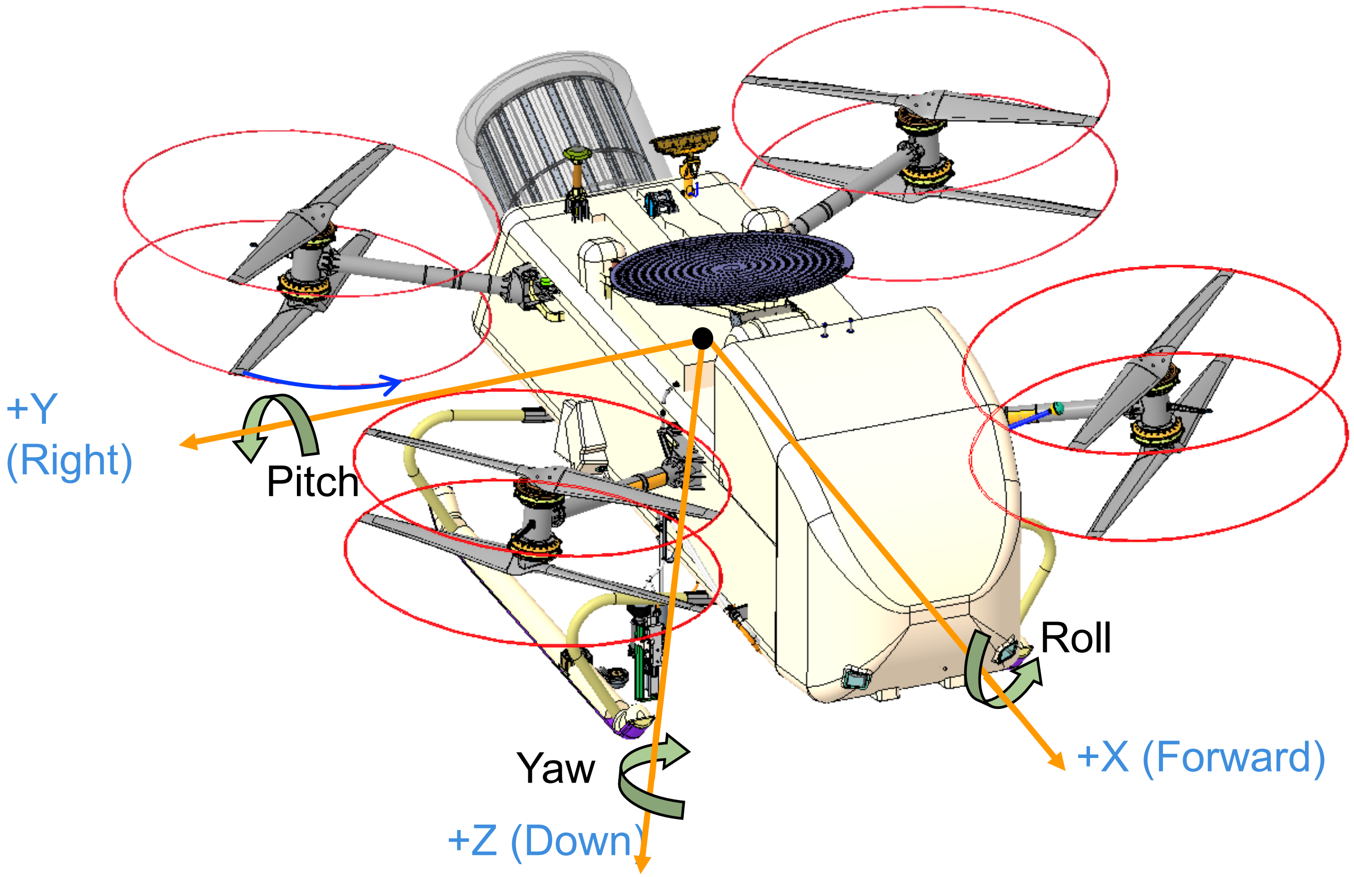
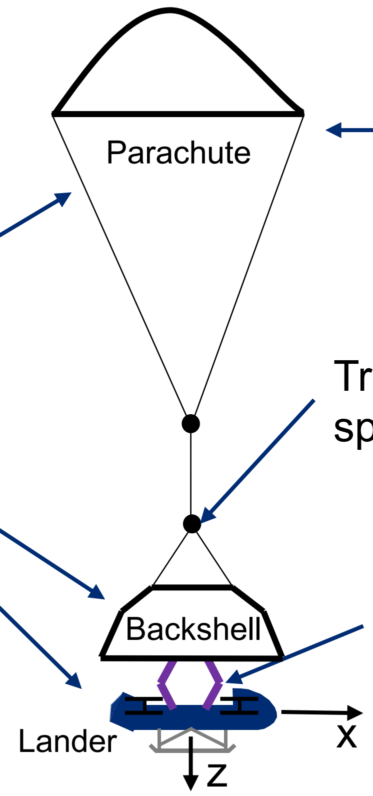
The Dragonfly Lander

Non exhaustive engineering payload list

- **Octocopter, 4 pairs of coaxial rotors**
- **Dual redundant IMUs**
- **LIDAR**
- Pressure sensors
- Navigation cameras
- 2 degree of freedom gimbaled HGA
- 1 degree of freedom MGA
- LGA
- MMRTG



PPF Model



3 rigid bodies

Parachute mass includes entrapped air

Triple bridle: 3-degree-of-freedom spherical joint

Pose mechanism: 3-degree-of-freedom revolute joint

Pitch Resonant Modes
- 25 sec: whole assembly together
- 4 sec: lander + backshell swinging under parachute
- 1.2 sec: pose mechanism flexing

CLS and POST2 Monte Carlo Differences

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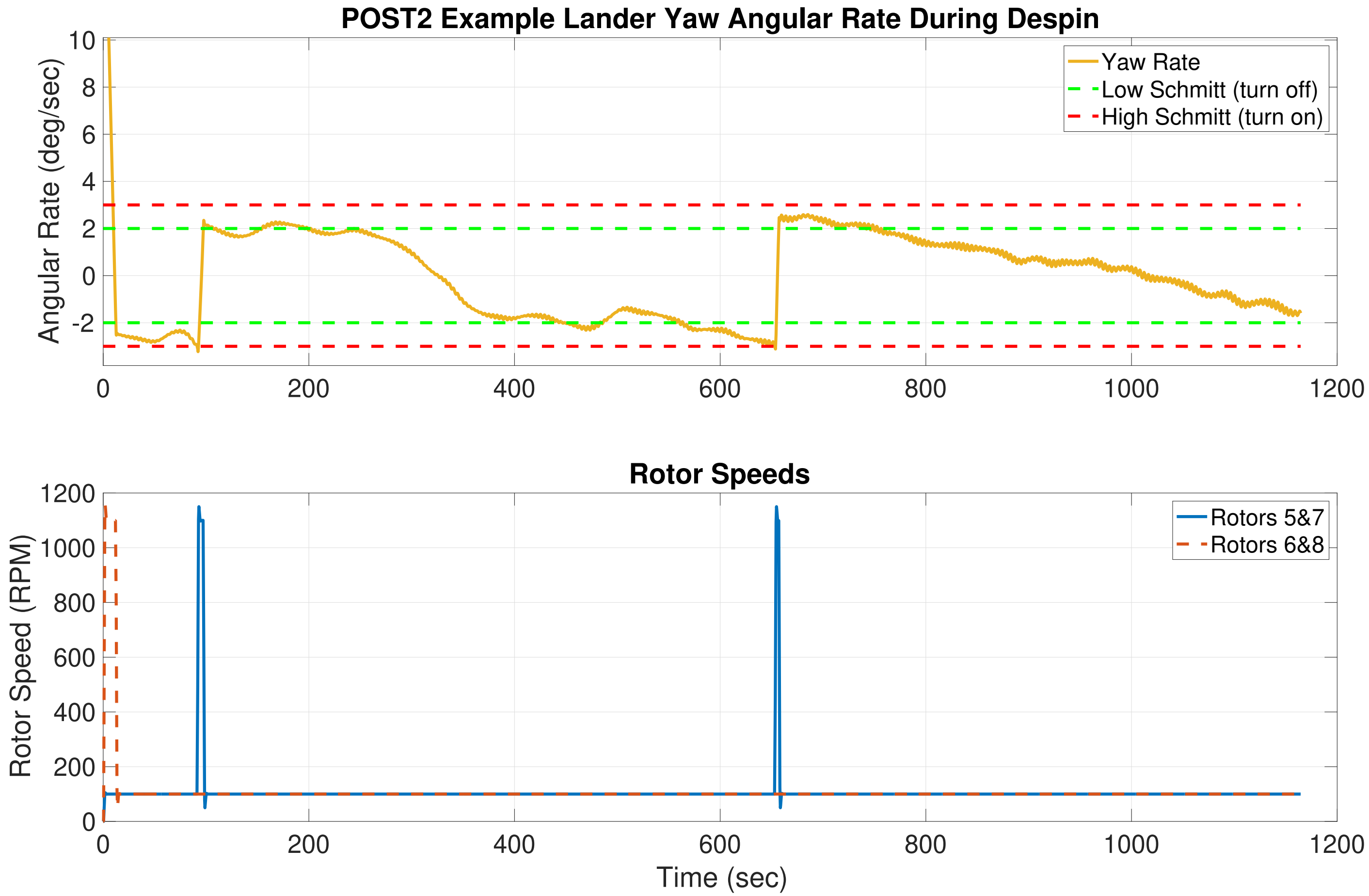
CLS

- Yaw rate at pose: assumes worst case of ±34.1 deg/s for every case
- LIDAR errors included: no
- Guiderail descent delay: assumed exactly 0.5 sec, i.e. the CLS has no guiderail model
- Trigger delay accounting: Monte Carlos plots list 0.5 s + 0.1 s or 0.2 s = 0.6 s or 0.7 s
- 3 degree of freedom pose mechanism

POST2

- Yaw rate at pose: distribution of rates depending on prior descent history
- LIDAR errors included: yes, 100 m uniform variation
- Guiderail descent delay: modeled explicitly, i.e. POST2 includes a model of the guiderails
- Trigger delay accounting: Monte Carlos plots list 0.1 s or 0.2 s because the 0.5 s is already accounted for in guiderail descent.
- Rigid pose mechanism

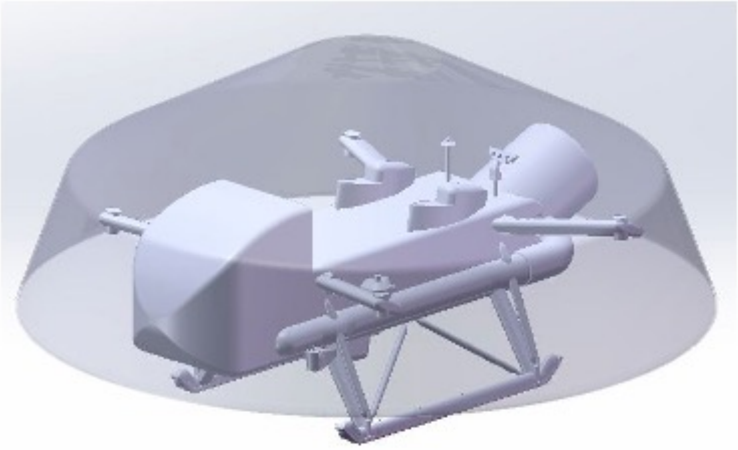
POST2 Yaw Despin Example

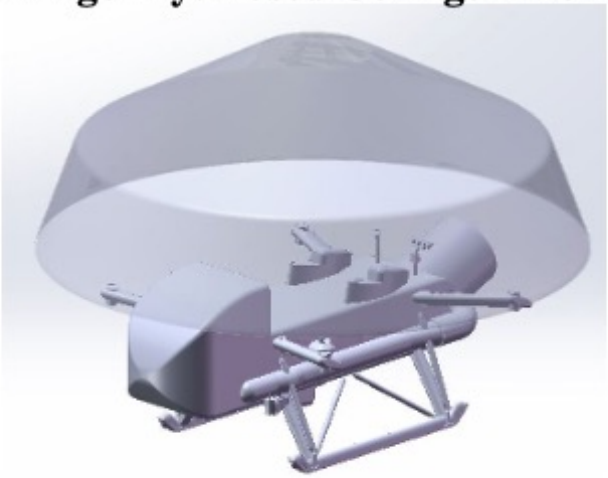


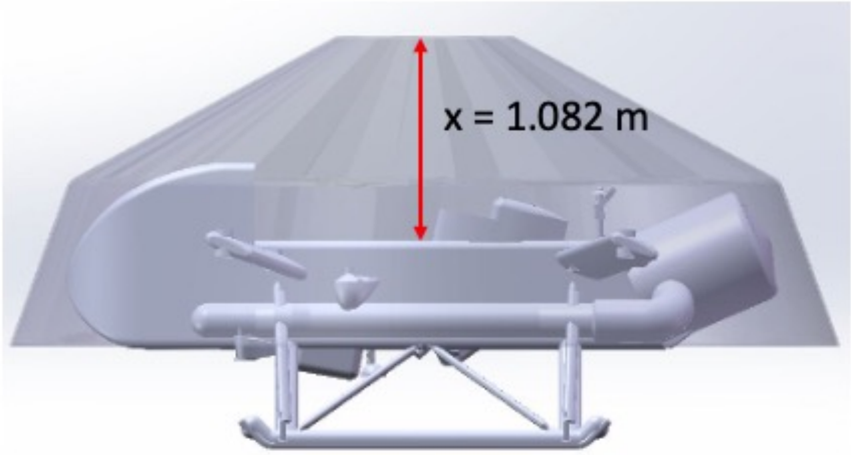
Configurations

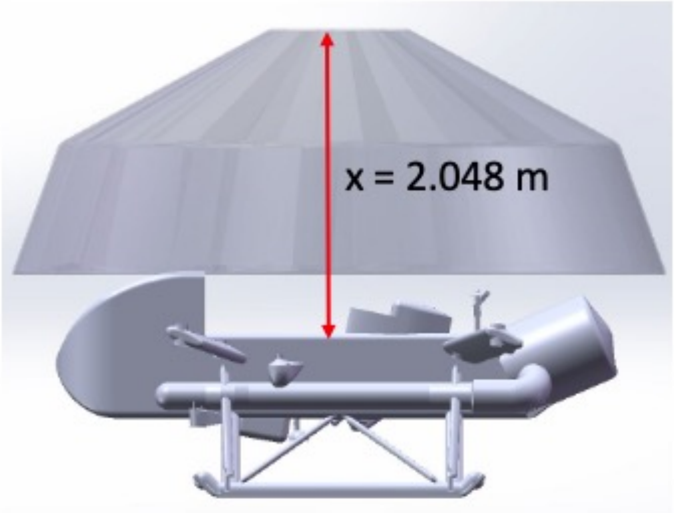
Dragonfly: Stowed Configuration

Dragonfly: Posed Configuration



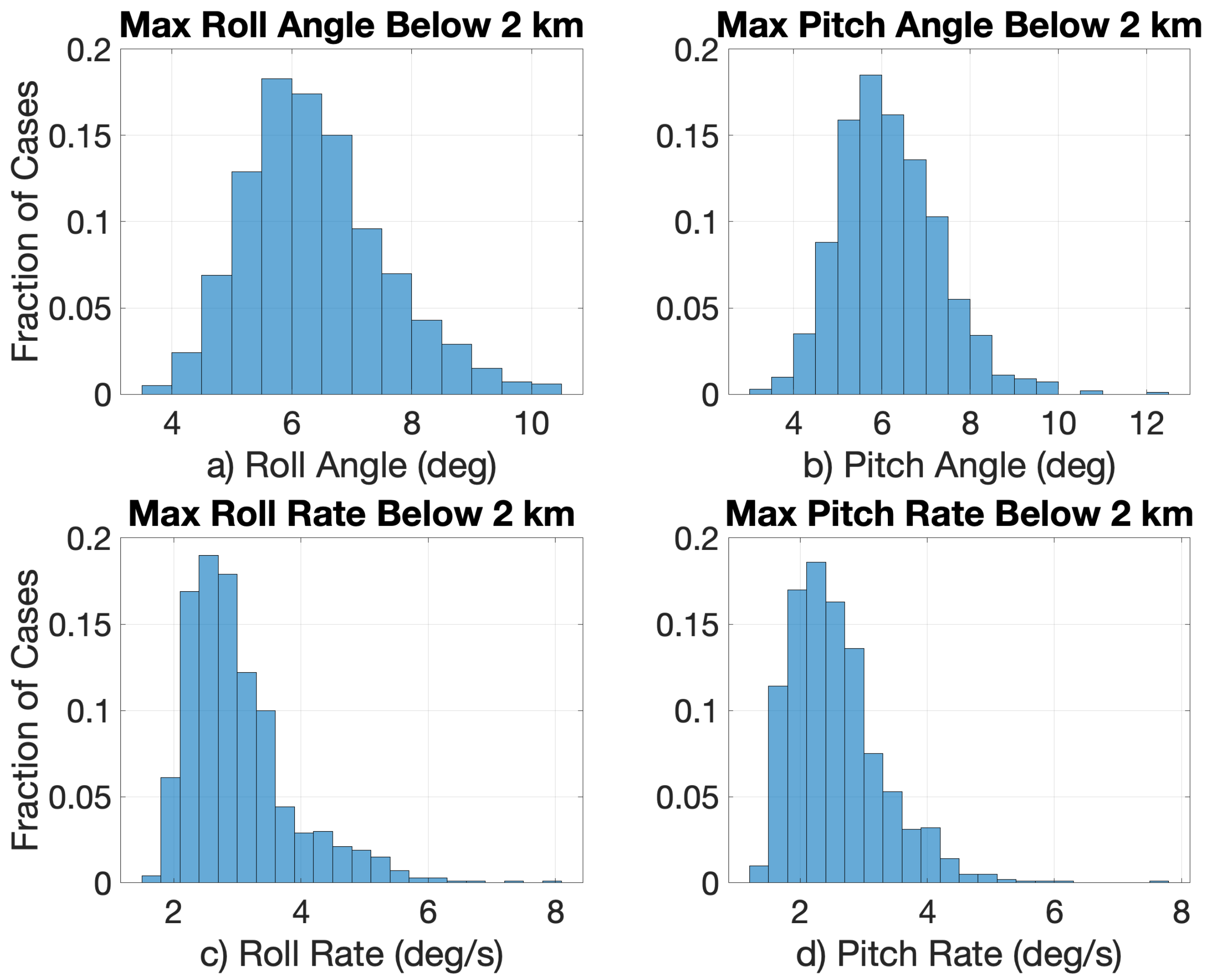




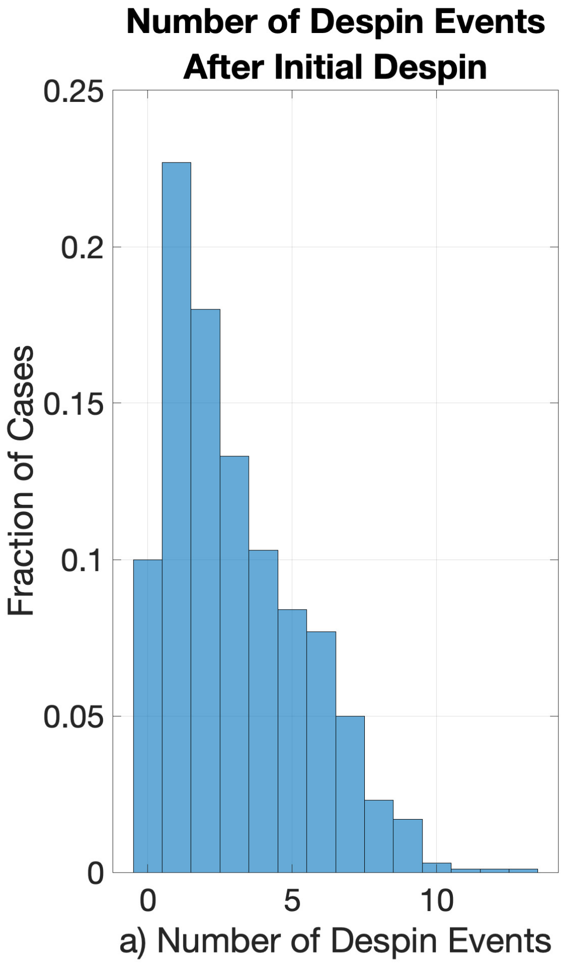


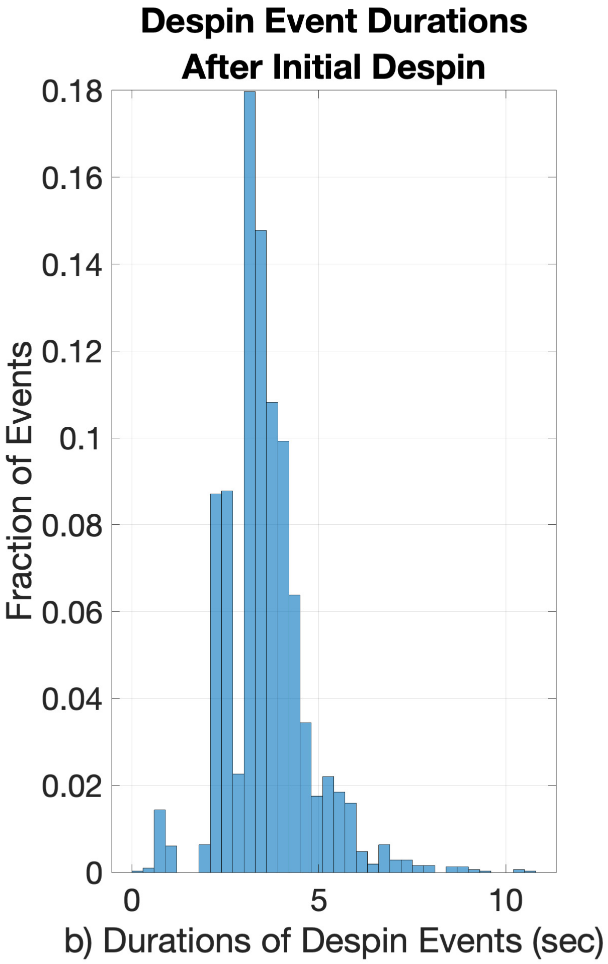
Images courtesy of Mike Kinzel's group at UCF

Despin Monte Carlo Results

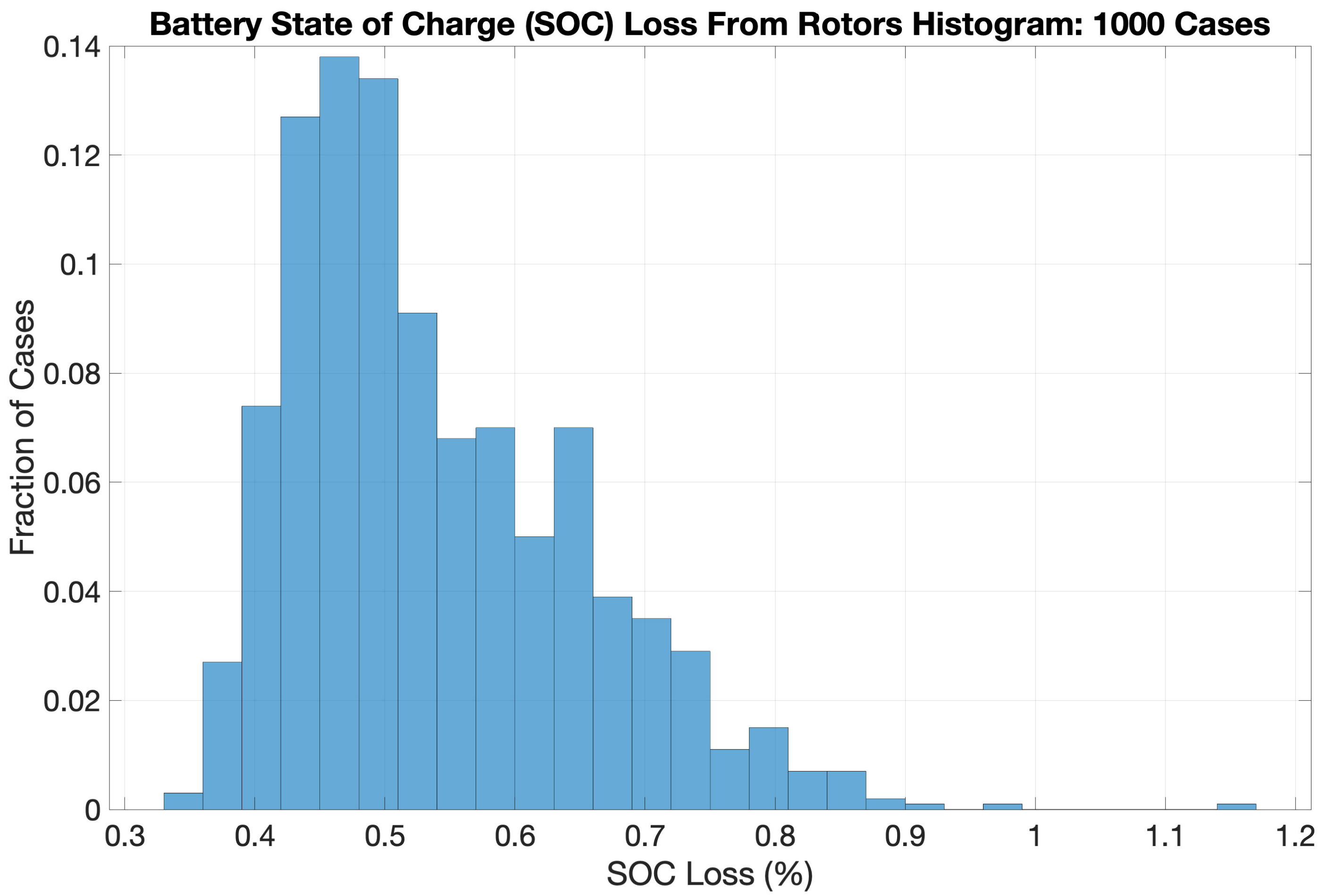


Despin Monte Carlo Results

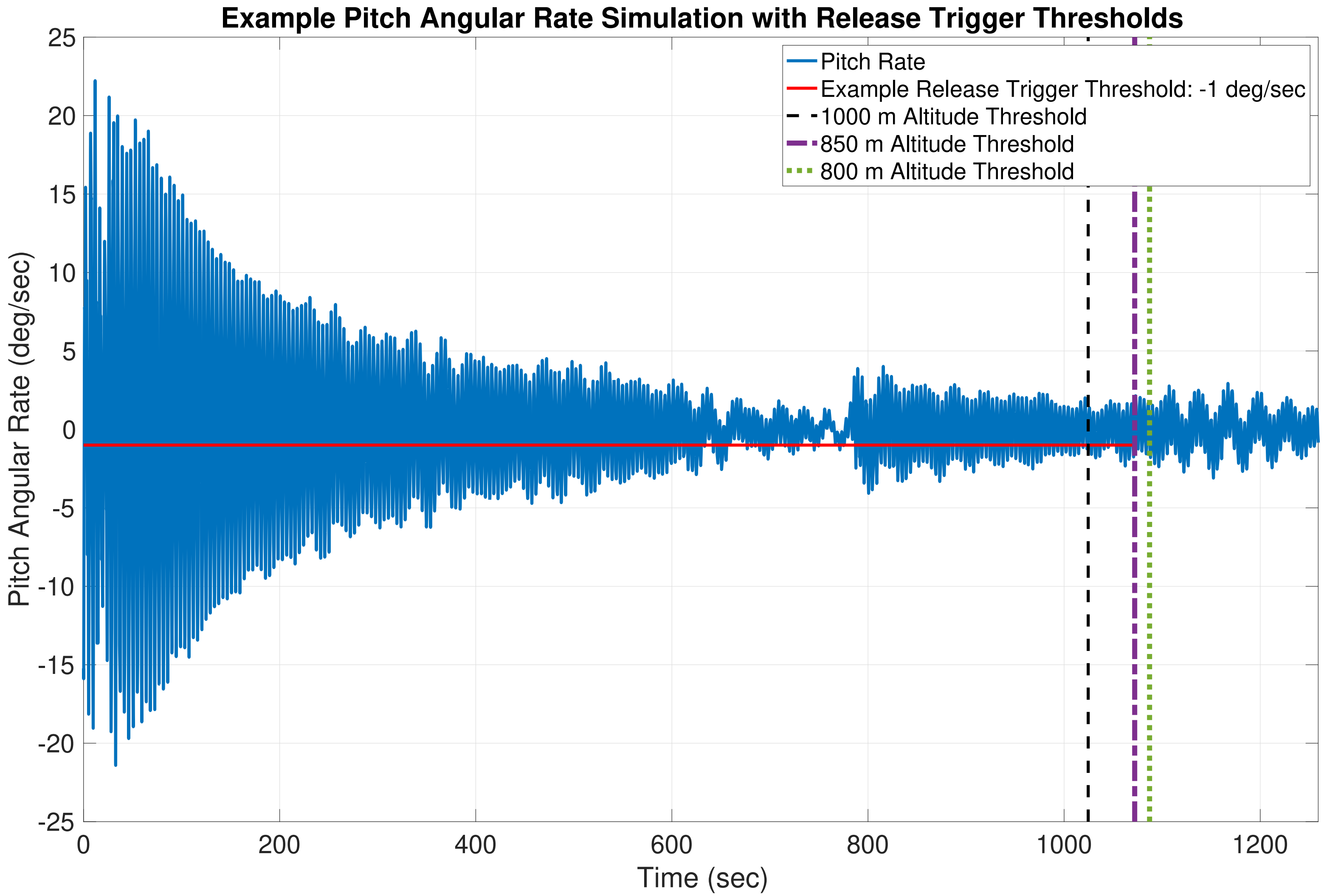




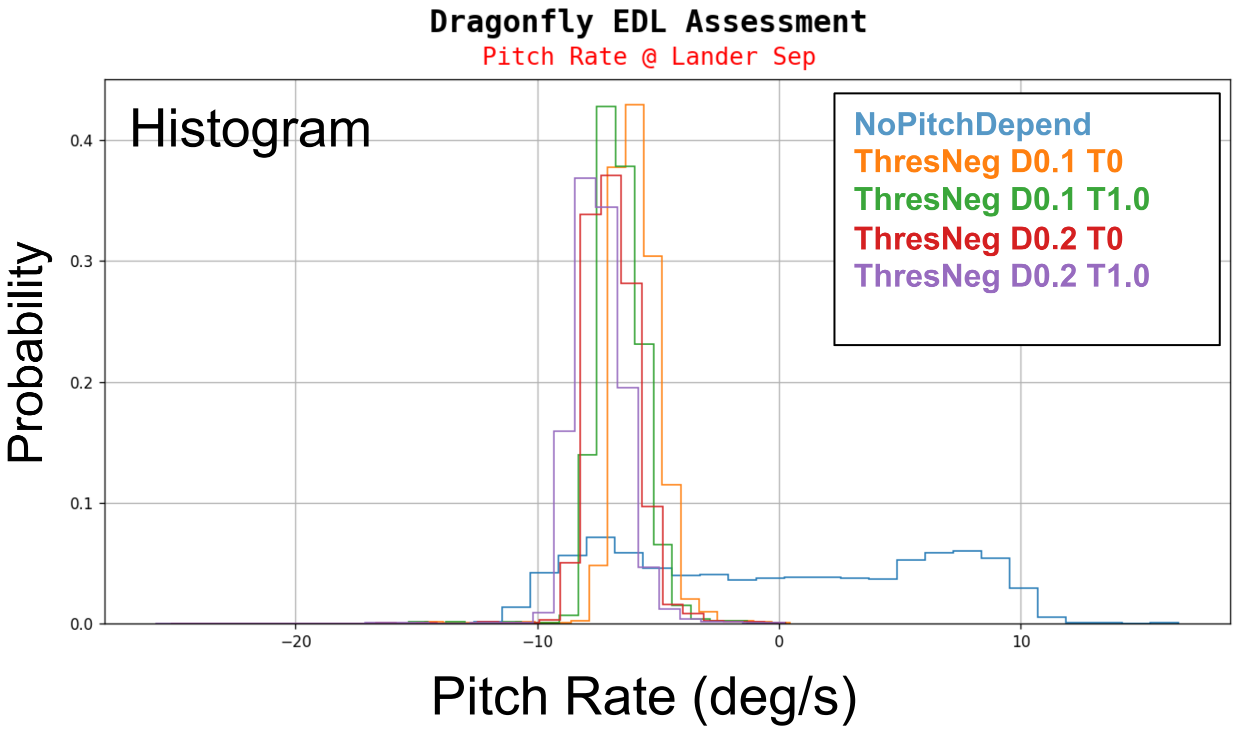
Despin Monte Carlo Results

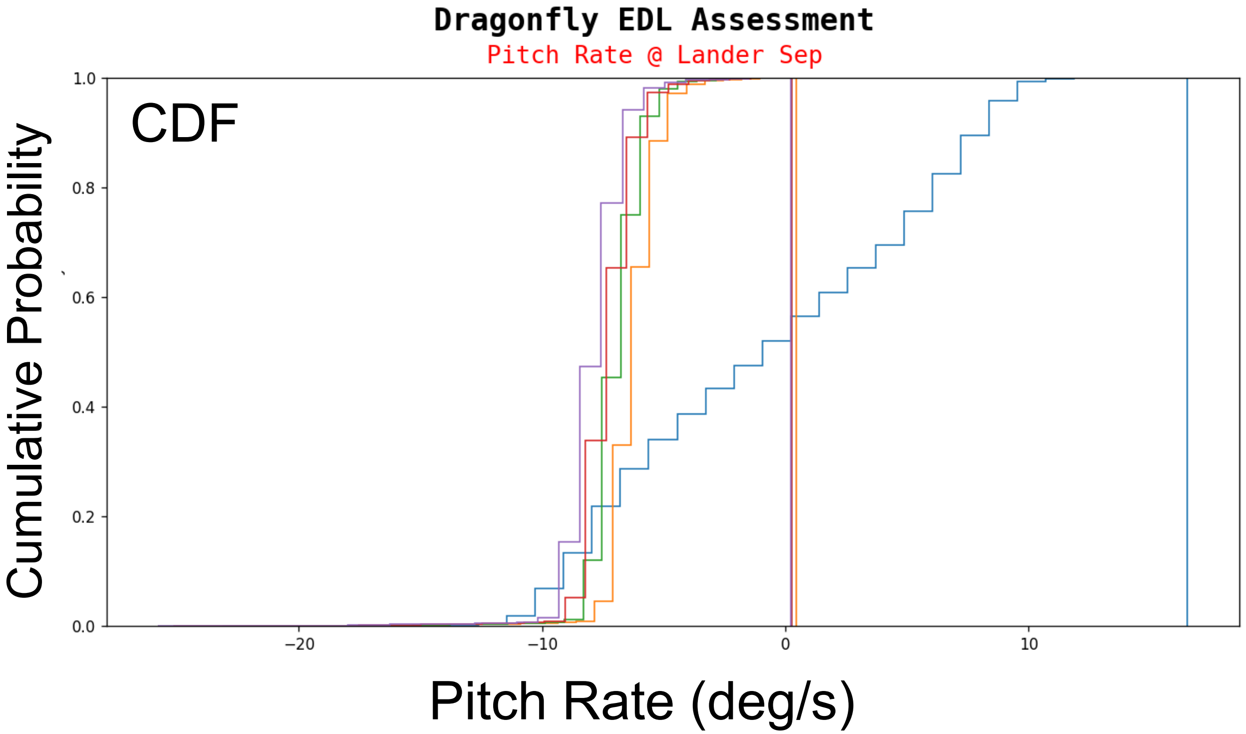


Release Trigger Logic



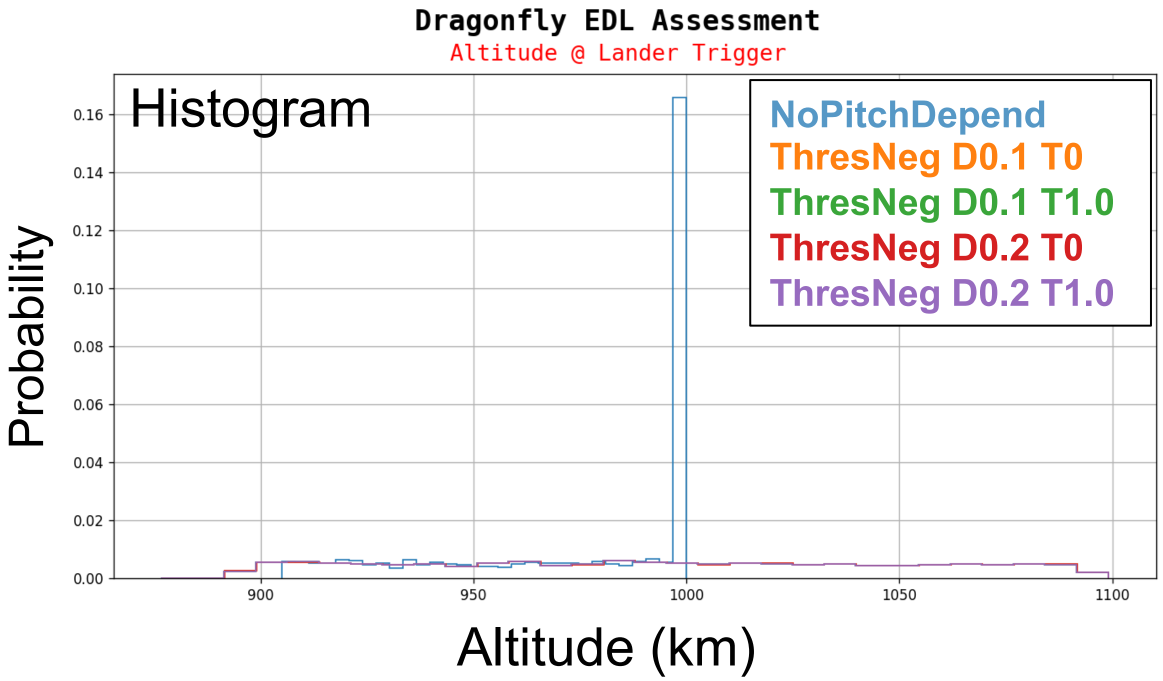
POST2 Pitch Rate @ Lander Separation

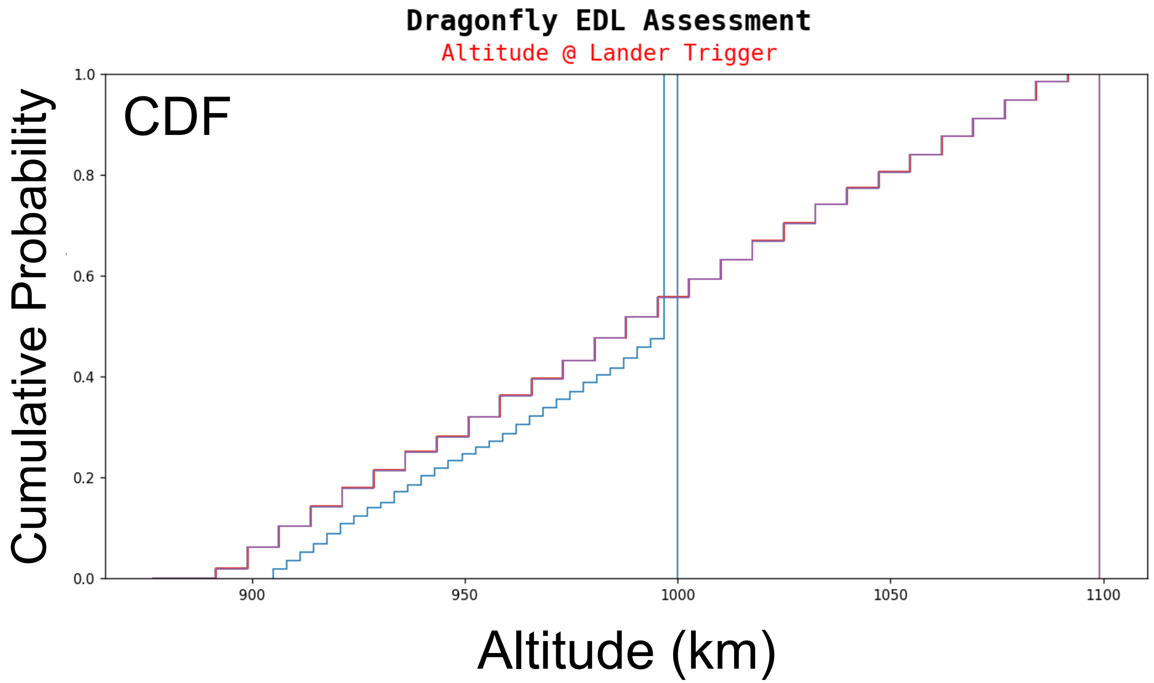




- D0.1 & D0.2 refer to a trigger delays of 0.1 s & 0.2 s respectively, corresponding to CLS delays of 0.6 s & 0.7 s (due to 0.5 s accounting of guiderail descent)
- T0 and T1.0 refer to trigger thresholds of 0 deg/s and 1.0 deg/s pitch rates

POST2 Altitude @ Trigger





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