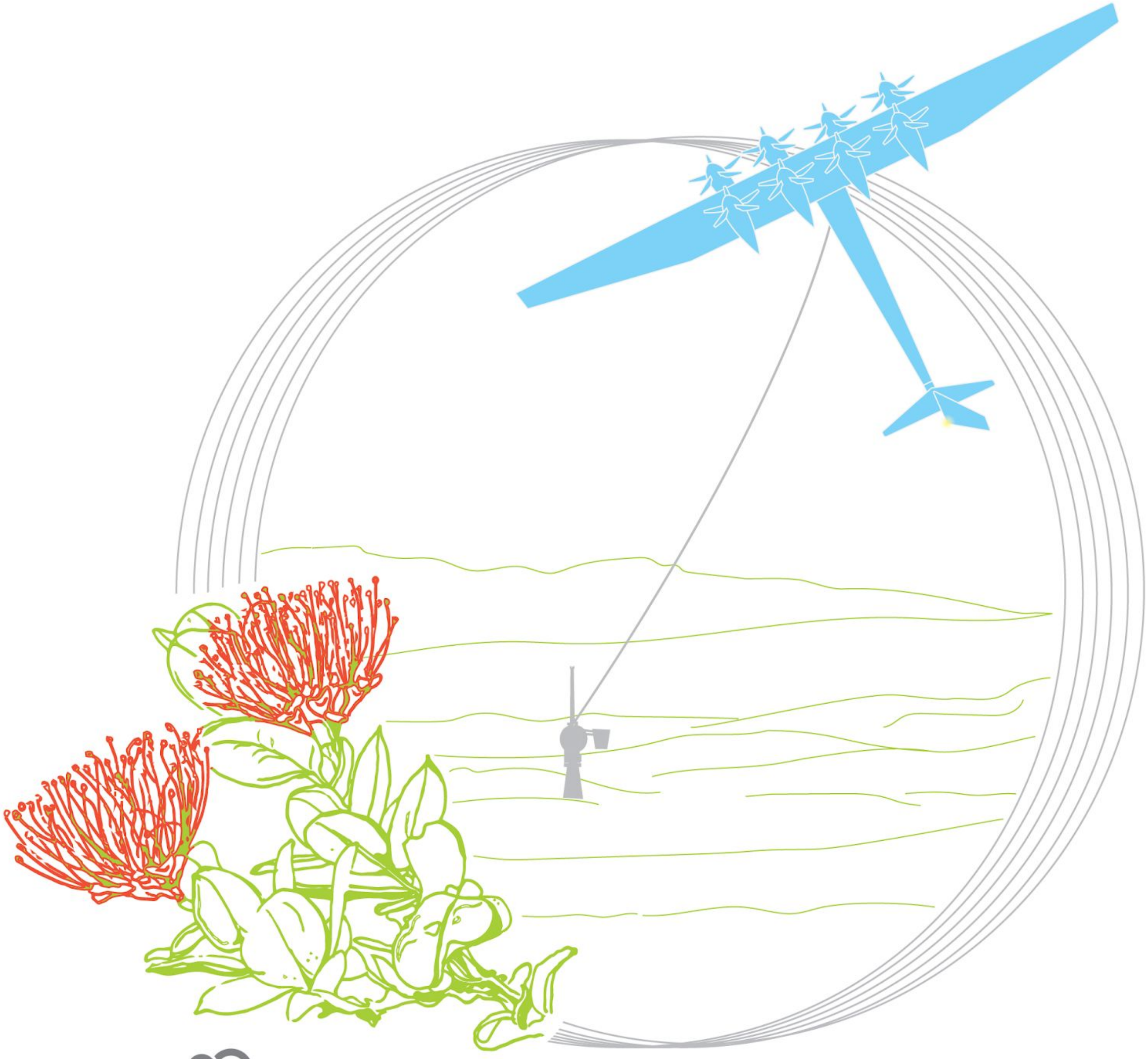
The Energy Kite

Selected Results from the Design, Development and Testing of Makani's Airborne Wind Turbines

Part III, Technical Artifacts



Makani Team

The Energy Kite: Selected Results from the Design, Development, and Testing of Makani’s Airborne Wind Turbines, Part III of III / by Paula Echeverri, Tobin Fricke, Geo Homsy, Nicholas Tucker, on behalf of the Makani team.

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DNV-GL Design-Accompanying Assessment for Certification:
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Bird and Bat Conservation Plan **381**

Makani Team, Akinaka & Associates (consultant), and Rana Biological Consulting (consultant)

A report prepared in consultation with Rana Biological and Akinaka & Associates, outlining potential impact to threatened species at the Makani test site on the island of Hawai‘i as well as specific measures to ensure flight testing operations would minimize and mitigate impact.

Note: These artifacts were produced as Makani internal work products and are presented here as they were written. They may contain references to other material that has not been released or that no longer exists.

Selected Decks From RPX Lessons Learned Reviews

Contents

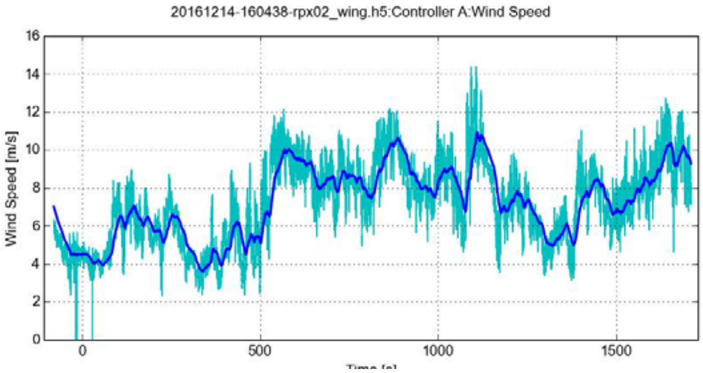
MAKANI

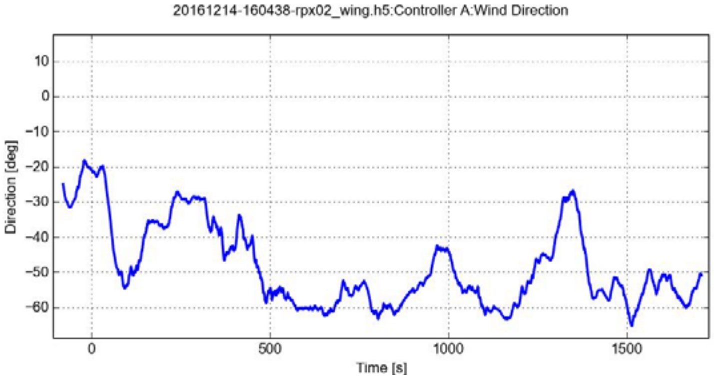
Controls
RPX-02 Flight Review

January 2017

Flight Conditions Weather and Wind Dec 14, 2016

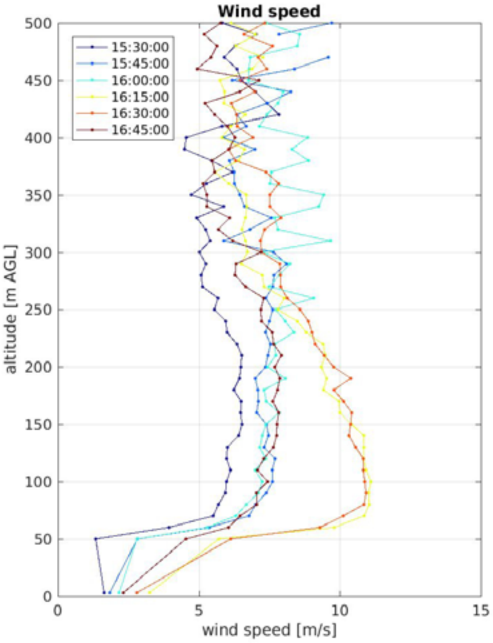
Temperature	24.0 ± 1.5	°C
Pressure	931	mbar (hPa)
Humidity	10	%
∴ Density	1.09	kg / m³

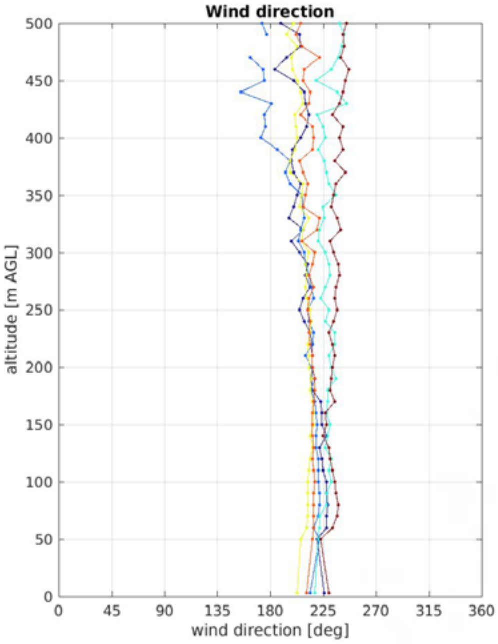




Wind on the day of flight was calm until the late afternoon. Around 4 pm a westerly wind started, heralding the arrival of a weather system. During the last 30 minutes of the year the wind entered our launch window. During the flight, the wind intensified and turned towards (from) the south.

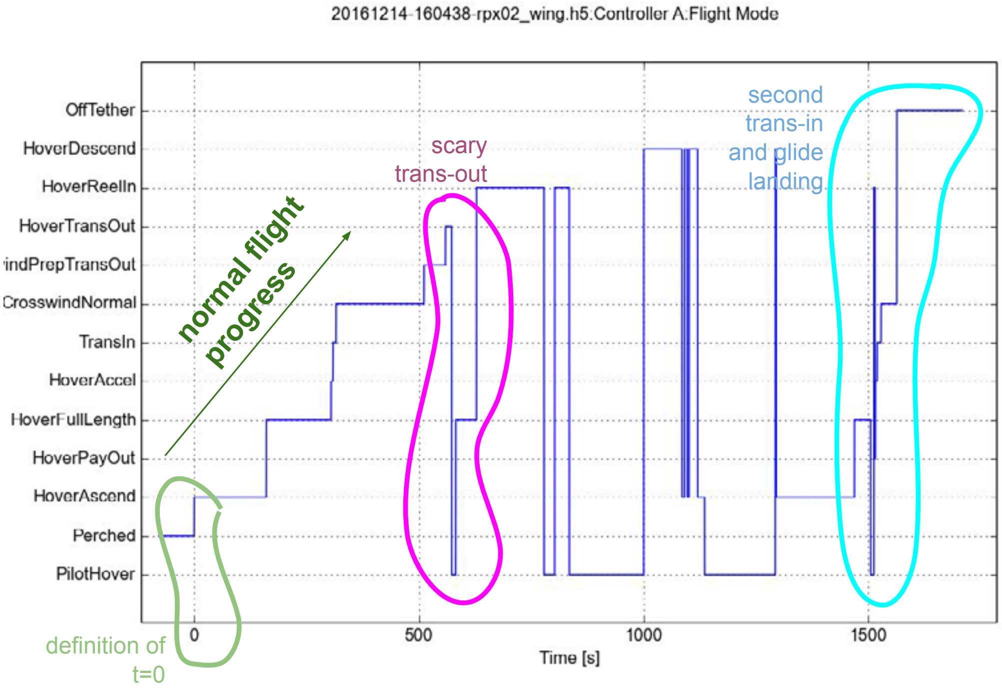
Flight Conditions SODAR data 15 minute average





Bug: 33167800.

Flight Mode Summary



The initial flight mode progression to crosswind was as planned.

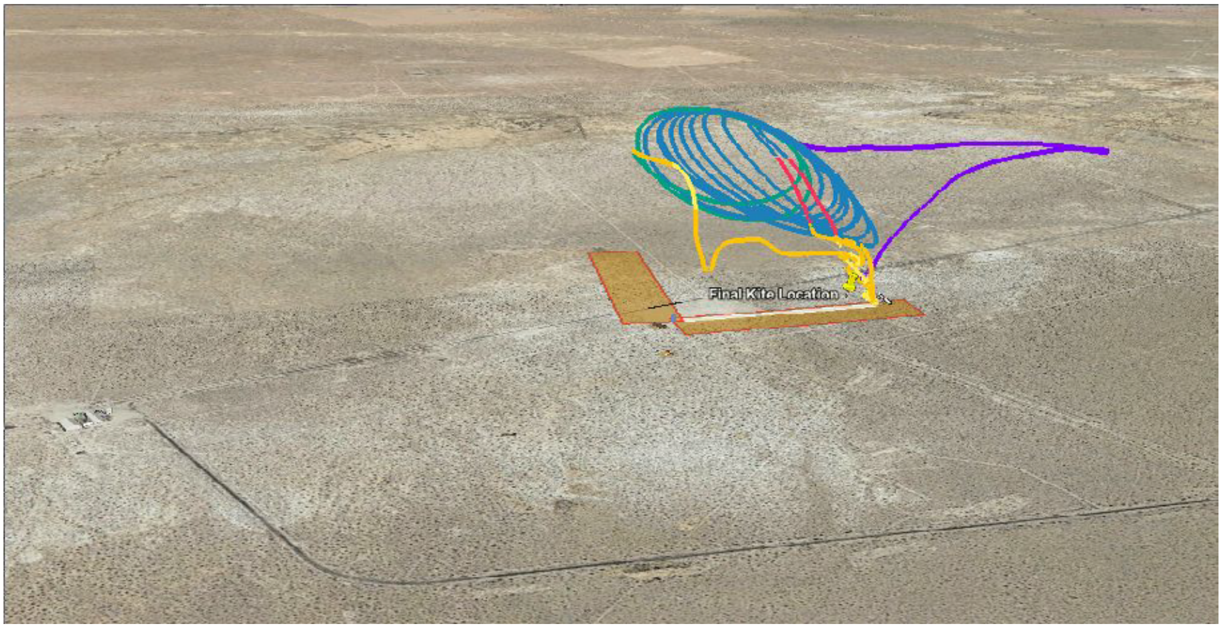
Trans-out was scary. The descent nearly hit the ground.

We switched to PilotHover often to increase tension.

Tail spike was lost in collision with Containerhenge.

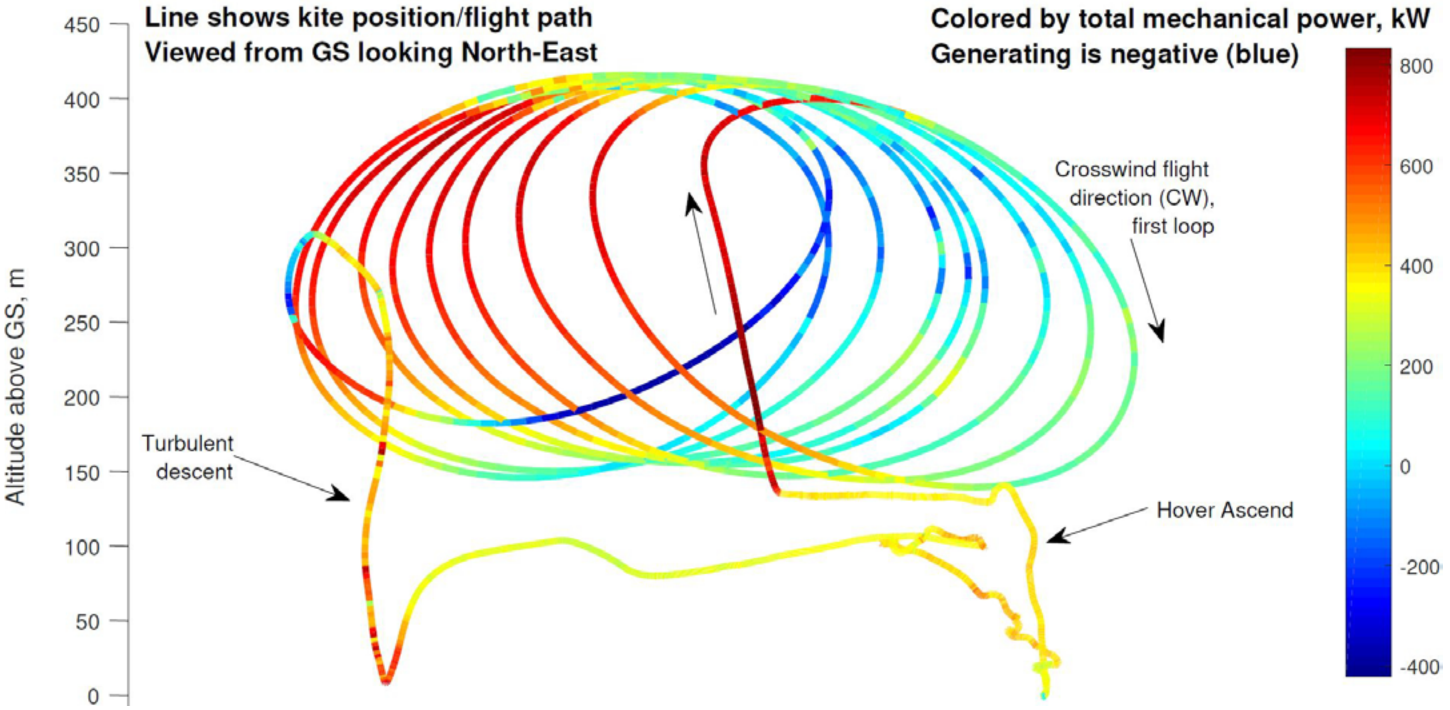
Elected to trans-in again and do a tether release and glide landing.

Google Earth flight path

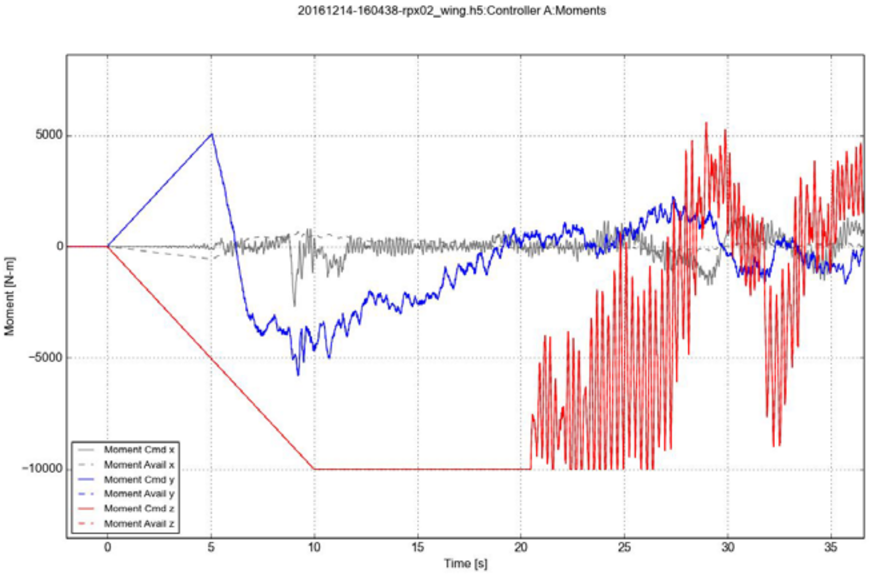


Bug: 33672197 ← **Get it here!**

Power generation



Hover Yaw Oscillation



In logs analyzed post-flight, a large oscillation is observed in the motor yaw command.

Not yet addressed.

- Approximately 5 Hz.
- Appears on pqr_f.z (estimated angular rate) before it appears in the yaw moment command.
- Any sign of this mode in rpx-01?

Bug: 33783041

Hover Pitching Moment

- During RPX-01 we had a "phantom pitch moment" of 5-6 kNm.
- Can explain almost all of that via previously-unmodeled moments on the rotors.
- Is there a similar phantom moment in RPX-02?

Bug: 33415363

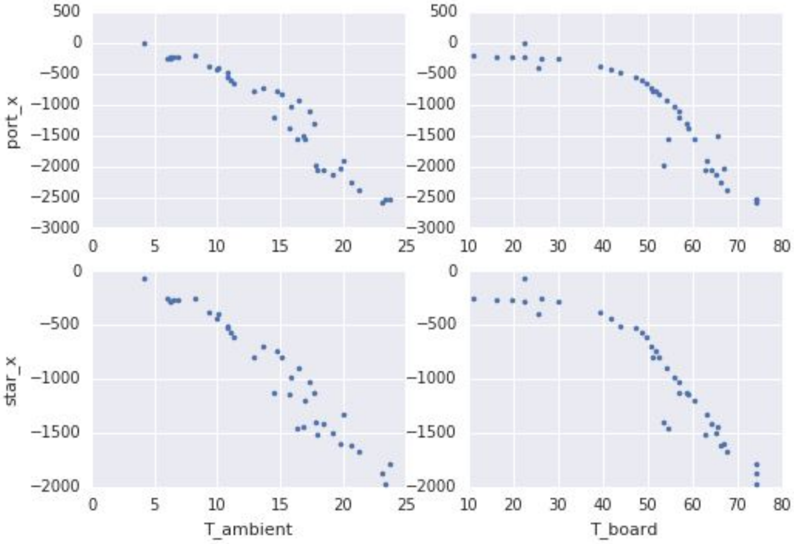
Hover Tension Loadcell Bias

Loadcells drift with temperature.

Significant (5 kN) with respect to hover tensions. (But not crosswind tension.)

Only on the x-axis, not yz-axis.

Measurements plotted here show measured x-axis tension with respect to ambient and avionics temperatures during the wait-for-wind period.



Bug: 33528773

Hover Active Roll Control?

+1	-1	-1	+1
-1	+1	+1	-1

+1	-3	+3	-1
+1	-3	+3	-1

actuation pattern
(change in thrust)

⊙	⊗	⊗	⊙
⊗	⊙	⊙	⊗

"double reverse rainbow"

⊙	⊗	⊙	⊗
⊙	⊗	⊙	⊗

"vertical stripes"

By changing **rotor direction**, we can use these actuation patterns to actuate roll.

See "notes on roll control with rotors."

Nathan is organizing an M600 active roll control brainstorming group.

But… "About **8 times less control moment** as we can produce on the pitch axis. With the difference in inertias taken into account, this is roughly **30 times less angular acceleration** than we can produce on the pitch axis."

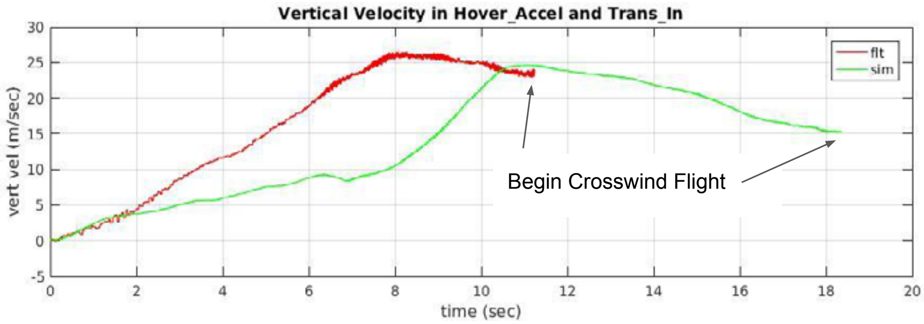
Hover Accel and Trans-In

The flight test vertical acceleration is about 3.6 m/s/s, and the time in accel/TI is about 11 sec.

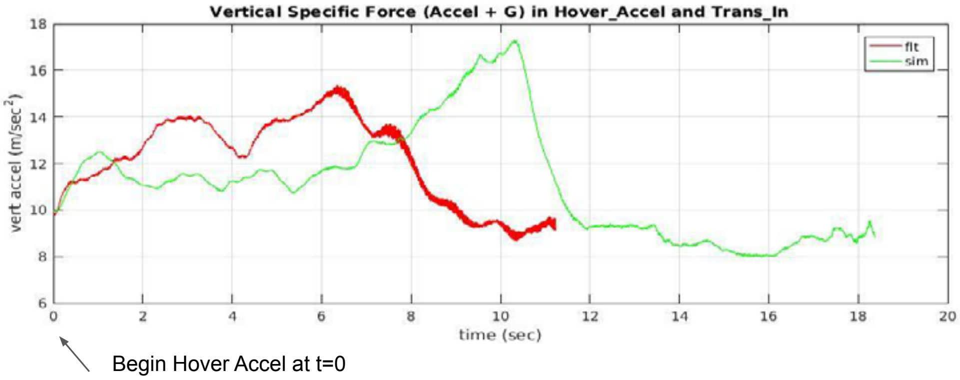
The simulation vertical acceleration is about 1 m/s/s and the time in accel/TI is about 18.5 sec

Hence, the flight crosswind mode was entered at a lower altitude that predicted (300 m vs. 370 m)

Bug: 34221526



Begin Crosswind Flight

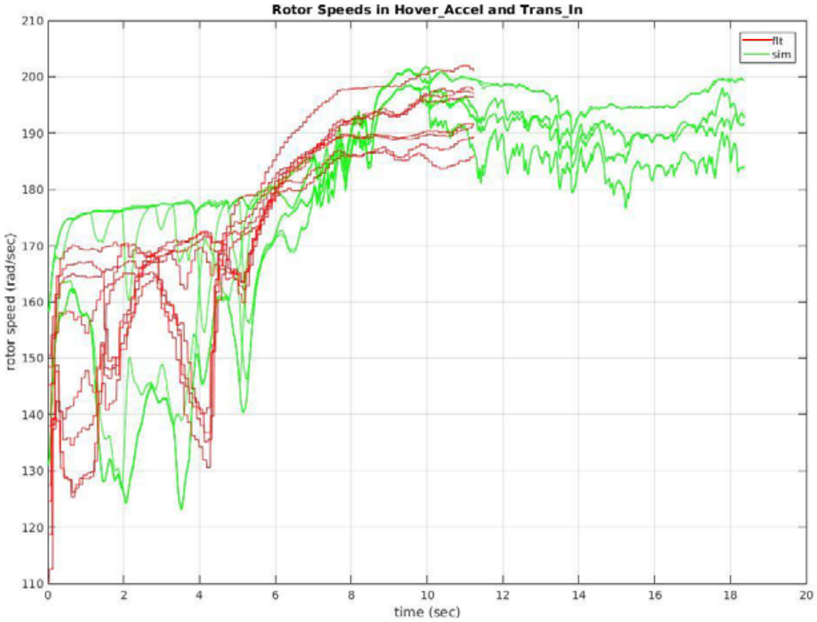


Begin Hover Accel at t=0

Hover Accel and Trans-In

The flight and sim rotor speeds in accel and TI don't look fundamentally different.

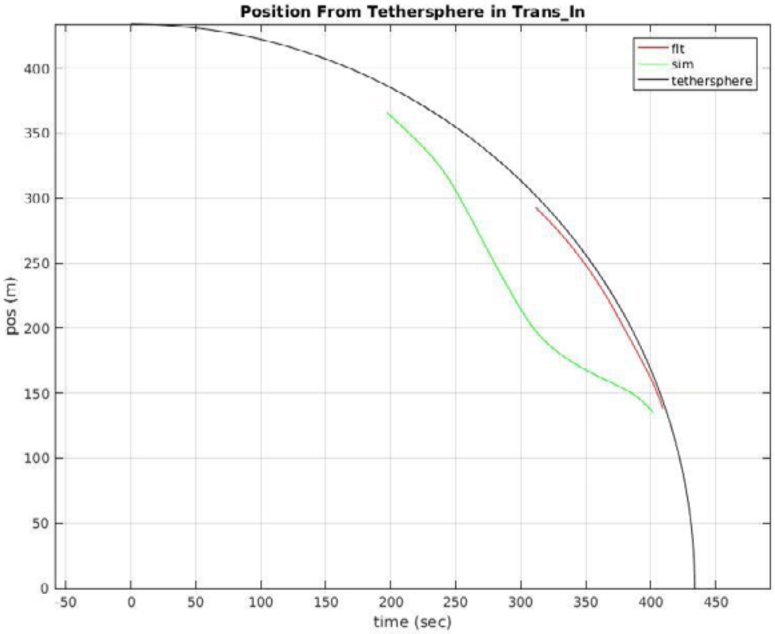
Each individual rotor speed is not labeled, for clarity.



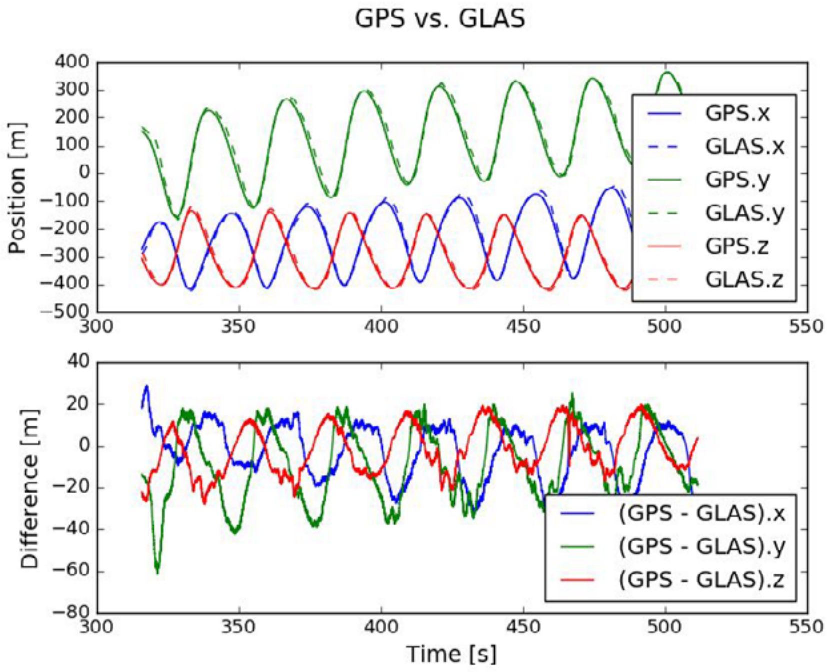
Trans-In

The kite started trans-in much closer to the tethersphere than the sim.

The kite remained much closer to the tethersphere during trans-in than the sim.



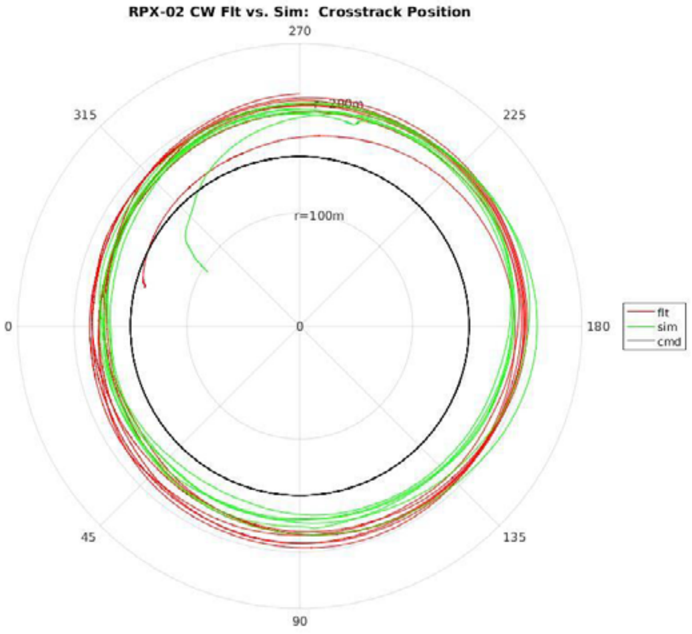
Ground Line-Angle Sensing



- Excellent qualitative agreement
- Errors up to O (10 m)
- GLAS estimate lags GPS estimate by about 0.65s

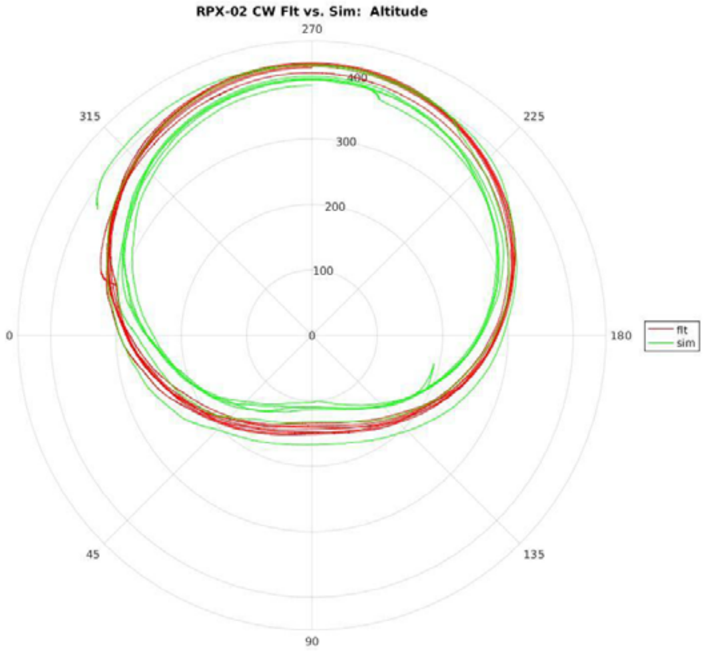
Crosswind Crosstrack Position

The crosstrack position in the flight test and sim match quite well.



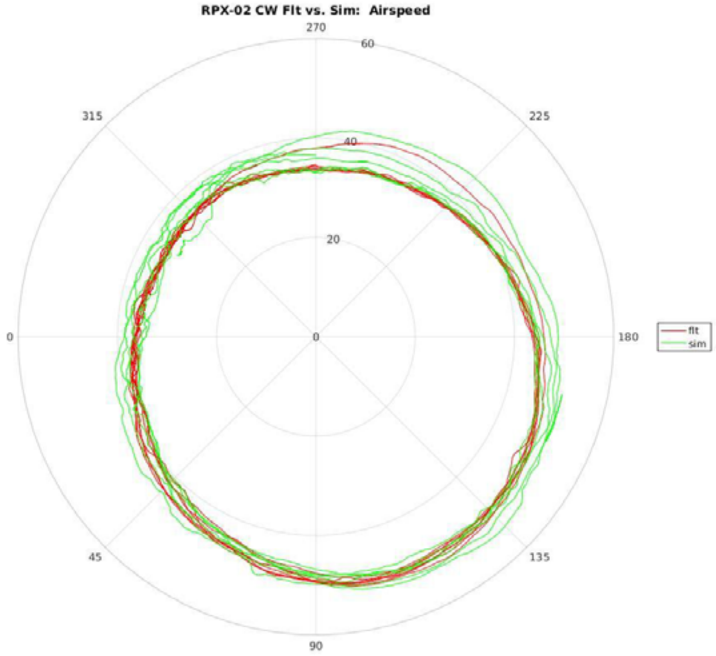
Crosswind Altitude

The altitude in the flight test and sim match quite well.



Crosswind Airspeed

The airspeed in the flight test and sim match quite well.

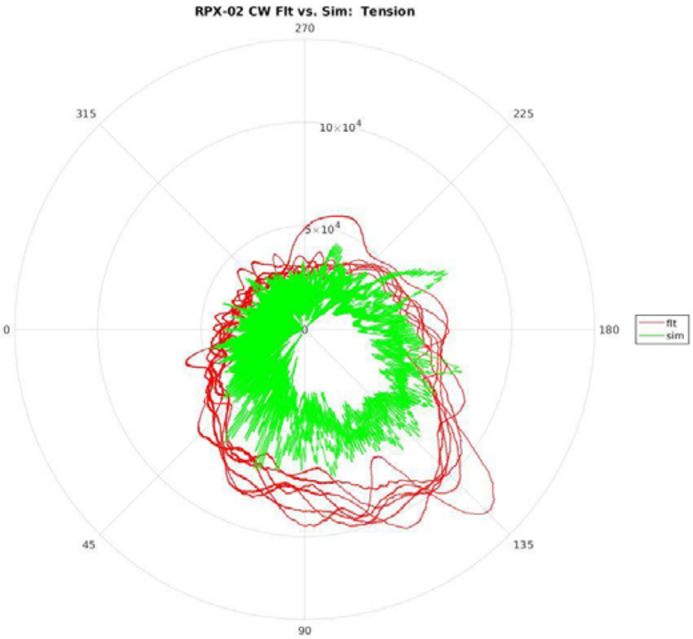


Crosswind Tension

The flight test tether tension is systematically a factor of 2 or greater in the flight test than the sim in the downstroke (near the 5 o’clock position).

The cause is not yet known. Possible reasons are:

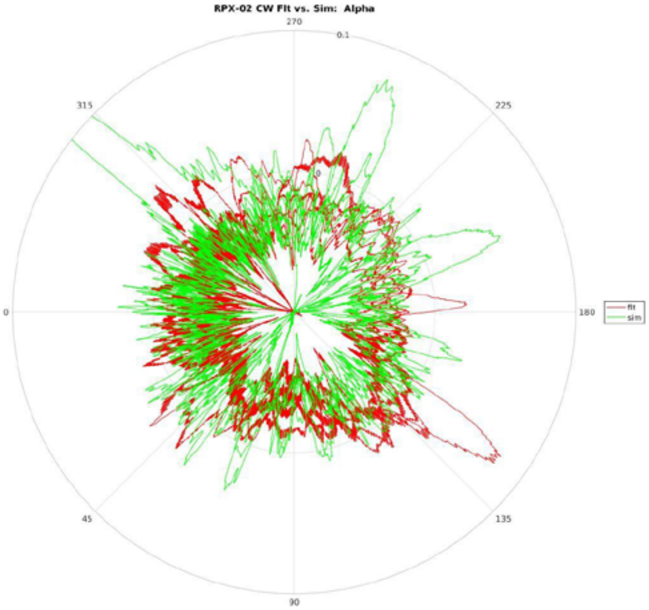
1. Higher lift than predicted
2. More tether dynamics than predicted
3. Error in the load cell measurements



Bug: 34221767

Crosswind Angle of Attack

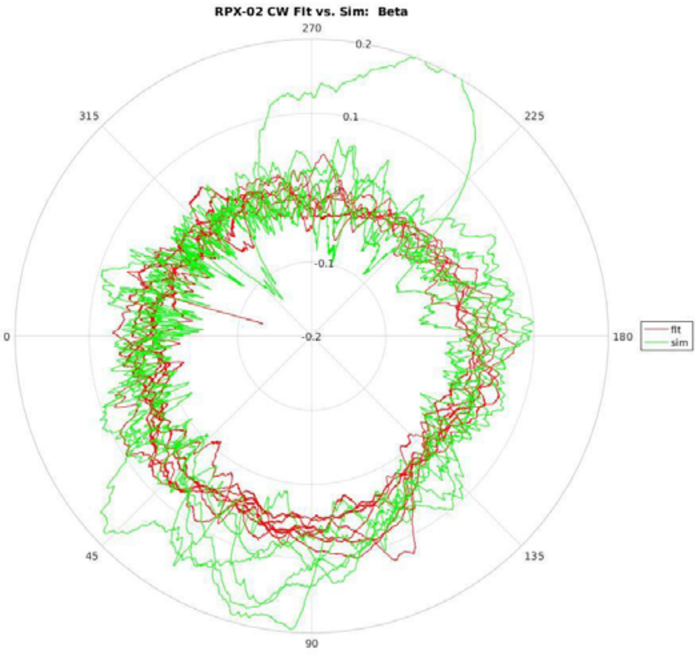
The angle of attack in the flight test and sim match quite well, in general. There is one large spike in alpha at the 4:30 position that correlates to the large measured tension spike in the tension plot.



Crosswind Angle of Sideslip

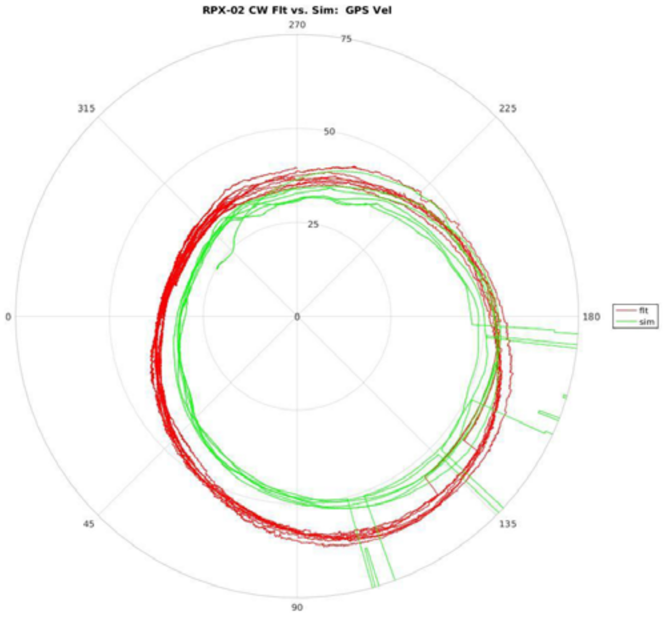
The angle of sideslip in the flight test and sim match quite well, in general. The flight beta has much less excursion than the sim data.

The flight beta was in the range -0.02 to 0.1 rad (-1 deg to 5 deg), which is well within reasonable limits of +/- 8 deg.



Crosswind Groundspeed

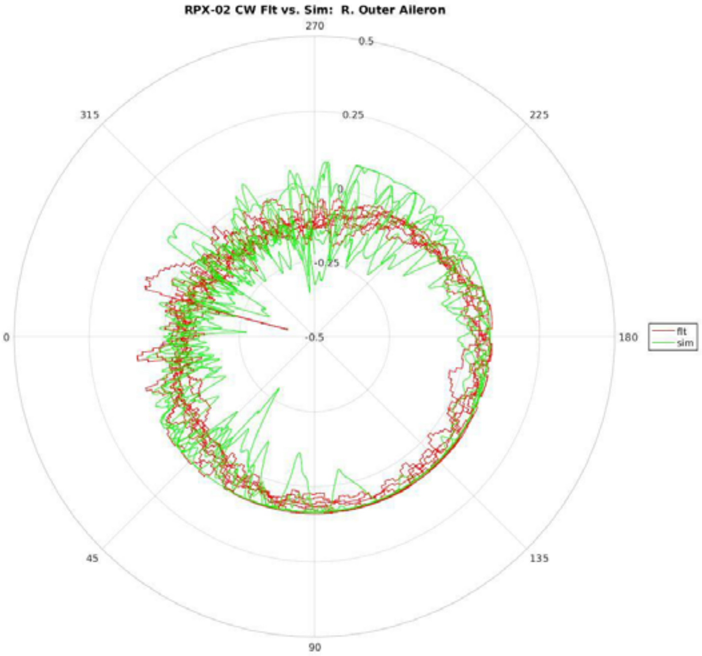
The flight groundspeed is higher than the simulated groundspeed in the lower portion of the loop. This difference could be due to higher actual windspeeds than simulated.



Crosswind A8 (Right Outer Aileron)

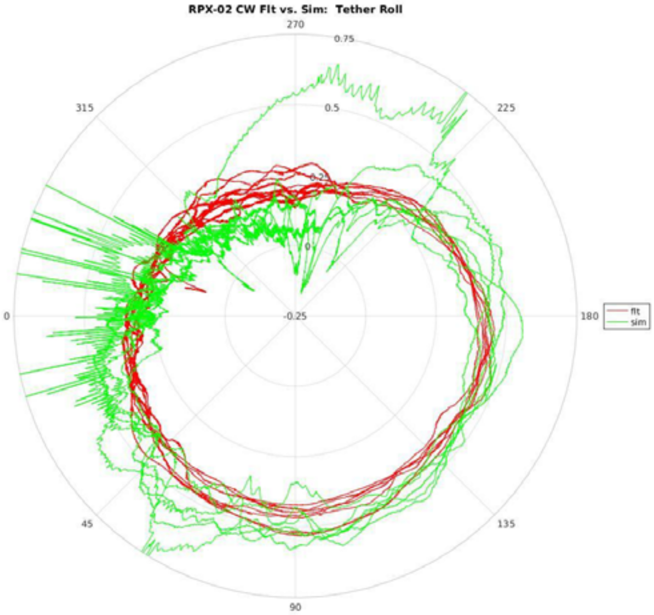
The flight right outer aileron is not saturating quite as much on the downstroke as in the simulation.

This suggests that the roll gains could be increased slightly to decrease the turn radius.



Crosswind Tether Roll Angle

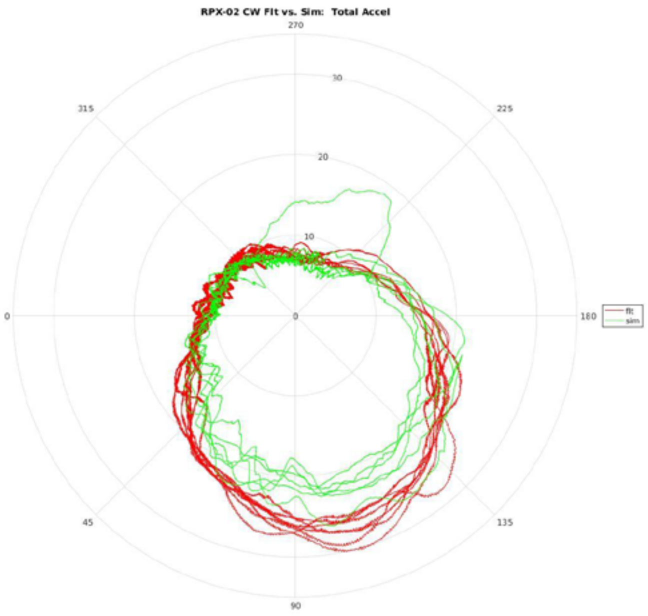
The tether roll angle in the flight test and sim match quite well, in general. The flight test roll angle is much more steady than the simulated roll angle.



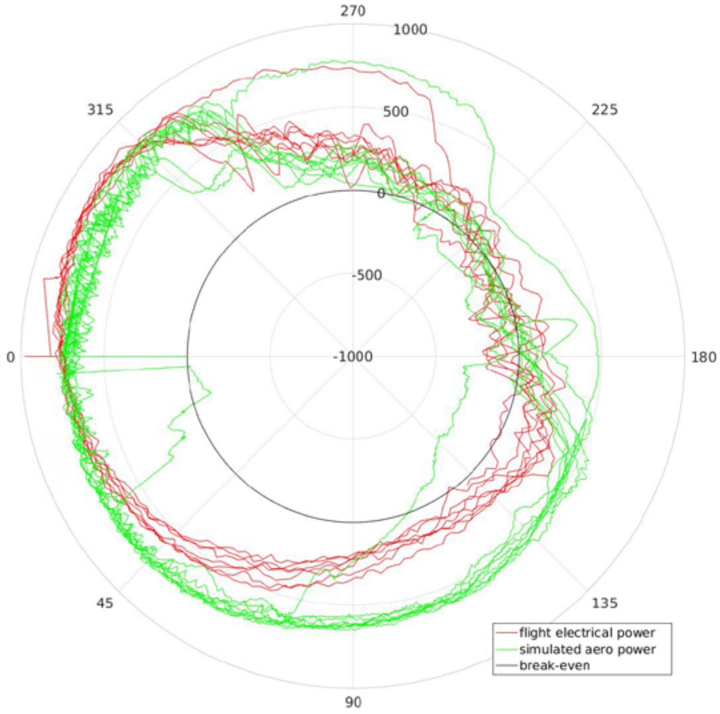
Crosswind Total Acceleration

This is a plot of the magnitude of the measured acceleration vector, which includes both true acceleration and gravity.

The flight measurements are systematically higher in the downstroke than in the simulation. Is this an indication of unmodeled tether dynamics?



Crosswind Power Actual vs Predicted



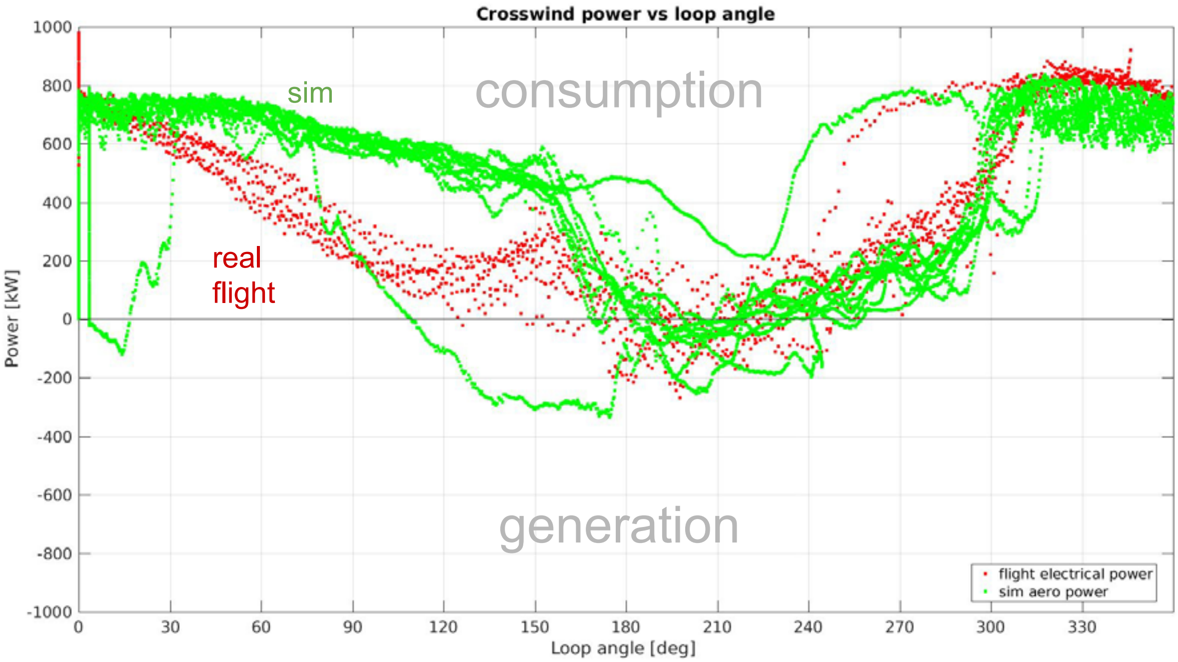
Caveats

- Need to add efficiency factor between electrical and aero powers (apples/oranges).

This plot made with simulation version 06.

Positive values (larger radii) indicate consumption.

Crosswind Power Actual vs Predicted



Loop angle definition is the same as on the previous slide. "0 degrees" is at 9 O'Clock on the upstroke, and the angle decreases as the kite flies around the loop.

Crosswind Tail Loads

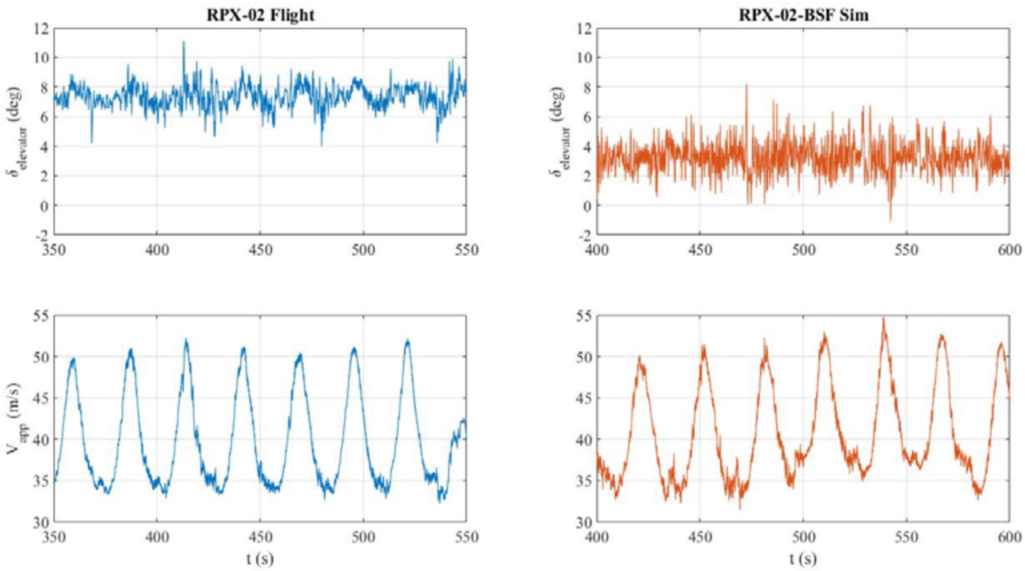
Comparison:
Flight test tail loads vs.
BSF Sim loads predictions vs.
Design loads

- Yaw forces and are very well predicted (within 5%).
- Yaw and roll moments are predicted within 30%.
- There is a large discrepancy between the predictions and measurements of elevator vertical shear and pitching moment (100% error).

		RPX-02		Design
		Flight test	**BSF Sim**	**rpxHALB**
time	s	357.5	N/A	N/A
azimuth	deg	152	N/A	N/A
airspeed	m.s^-1	48.3	48.3	66.5
aoa	deg	-1.33	-1.33	5.2
aos	deg	-0.46	-1.055	-20.6
tension	N	80428	80430	150000
bank angle	deg	24.8	24.8	14.9
pitch angle	deg	-4.2	-8.9	4.6
ab_x	m.s^-2	2.9	2.9	7.2
ab_y	m.s^-2	-16.7	-16.7	-25.2
ab_z	m.s^-2	-0.6	-0.6	-6.1
wb_x	deg.s^-1	-1.15	0.00	4.01
wb_y	deg.s^-1	1.72	0.00	13.18
wb_z	deg.s^-1	-18.33	-18.30	-48.70
wdotb_x	deg.s^-2	0.95	0.00	32.66
wdotb_y	deg.s^-2	**2.29**	**-101.60**	**-242.36**
wdotb_z	deg.s^-2	-6.05	-39.00	-14.32
Fy	kN	5.3	5.1	8.671
Fz	kN	**-2.2**	**-1.0**	**-2.5**
Mx	kN.m	1.5	1.1	10.3
My	kN.m	**-15.2**	**-4.1**	**-14.2**
Mz	kN.m	-36.4	-21.9	-67.5

Crosswind Tail Loads

- The elevator force discrepancy appears to be associated with an offset in the elevator trim angle.



Bug: 34221977

Rotor Loads - Inputs

HoverAscend / HoverFullLength:

- Top motors draw approx. 1.7 more phase current than bottom motors but do not saturate.
- Peak thrust at 3.4 kN.
- Peak hover loads well enveloped by design load case (HNO).

HoverAccel / TransIn

- Top rotors (STO, STI and PTI) saturate first.
- Max thrust occurs right at the beginning of HoverAccel: 4.1 kN, 174 rad/s, V_axial=0.06 m/s.
  ⇒ Update HNO hover load case to a maximum thrust of at least 4.1 kN.
- Trans-in loads within design loads.
- The rotor thrust is saturated all the way through Trans-in and for 8 seconds at the beginning of CrosswindNormal.

CrosswindNormal

- Max rotor speed limit of 215.3 rad/s never reaches the software limit (220 rad/s, M=0.75).
- Rotor thrust peaks at 2.2 kN in motoring mode and -1.4 kN in generation mode.

HoverAscend / HoverFullLength:	**Time (s)**	**Max thrust (N)**	**Omega (rad/s)**	**In-plane app. wind (m/s)**
RPX-02 STO (**flight**)	298.0	3390	157	4.75
HNO: Hover Nominal (**design**)	N/A	3500	168	15.0

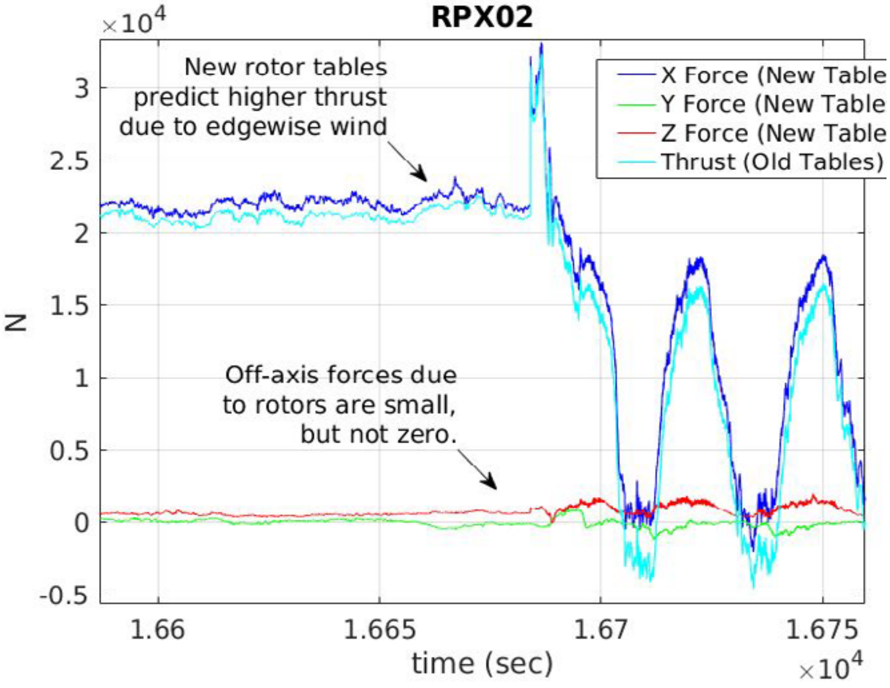
HoverAccel / TransIn	**Time (s)**	**Thrust (N)**	**Omega (rad/s)**	**Pitch rate (rad/s)**	**In-plane app. wind (m/s)**
RPX-02 PTI (**flight** - max thrust)	308.9	3142	181	0.034	5.44
RPX-02 STO/STI (**flight** - max pitch rate)	310.1	2694	190	0.326	6.93
TNO: Trans-in Nominal (**design**)	N/A	3800	188	1.00	13

CrosswindNormal	**Thrust (N)**	**Omega (rad/s)**	**Body yaw (rad/s)**	**Axial app. wind (m/s)**	**In-plane app. wind (m/s)**
RPX-02 STO (**flight** - max thrust)	2192	199.8	-0.13	32.6	0.6
RPX-02 PBO (**flight** - min thrust)	-1430	148.4	-0.34	45.3	2.7
GNO: Generation Nominal (**design**)	-2800	200	-0.75	79	14

Rotor Loads - Analysis

Rotor Table Force Lookups applied to RPX02 Data:

- Plot shows the net forces from all 8 rotors written in b frame components (X is thrust)
- These are results from the new tables
- Thrust from old tables is shown for comparison
- New tables predict steady thrust due to edgewise wind in RPX02 to be ~7.5% higher than the old table lookups

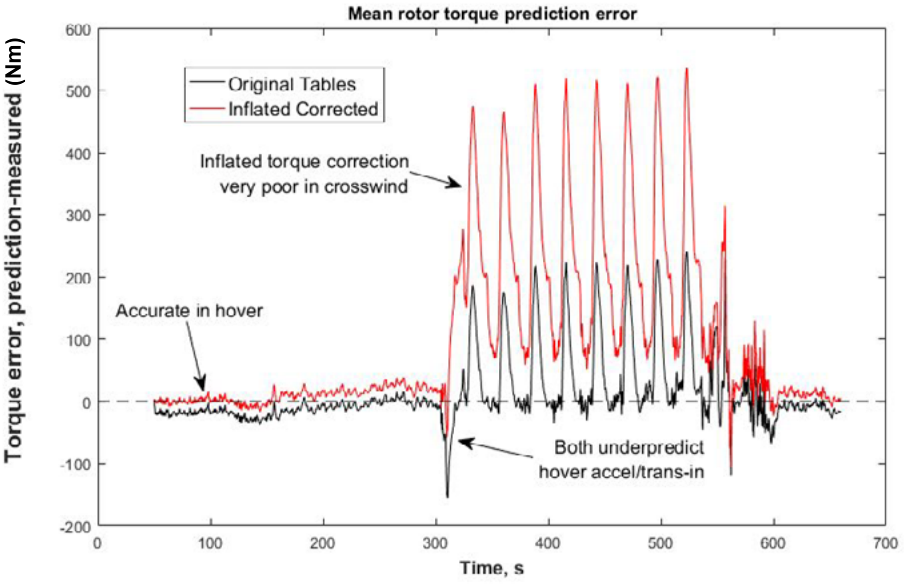


New rotor tables predict higher thrust due to edgewise wind

Off-axis forces due to rotors are small, but not zero.

Rotor Loads - Analysis

- Individual mechanical motor torque calculated from motor current measurement.
- Axial inflow velocity from estimator, assumed equal at all rotors.
- Omega and velocity from flight used to call torque values from the 2D rotor lookup tables.
- Two tables compared:
  - ○ Original: this is still what the flight controller uses.
  - ○ Inflated Corrected: best guess prior to RPX, extrapolated from lollipop stand tests.



Inflated torque correction very poor in crosswind

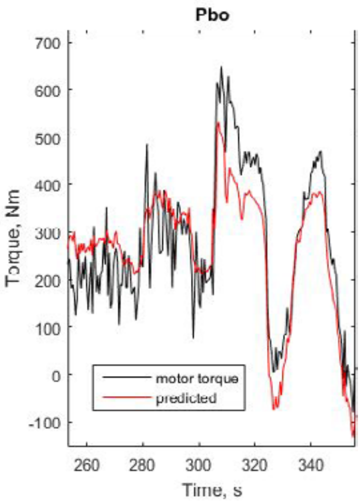
Accurate in hover

Both underpredict hover accel/trans-in

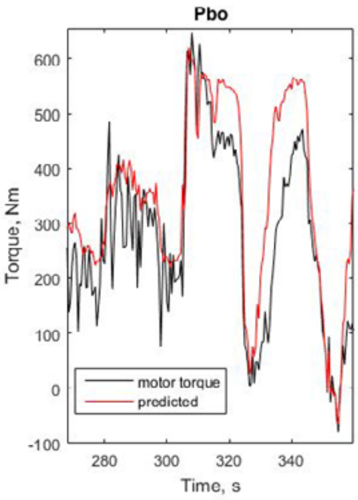
Rotor Loads - Analysis

- Both tables do decent job in hover.
- The inflation correction does better in accel/trans-in, but poorly in crosswind normal.
- Original tables under-predict trans-in.
    - Some evidence of wing lift effect slowing the relative airspeed for the bottom rotors in crosswind.

Original tables



Inflated-Corrected



Rotor Loads - Analysis

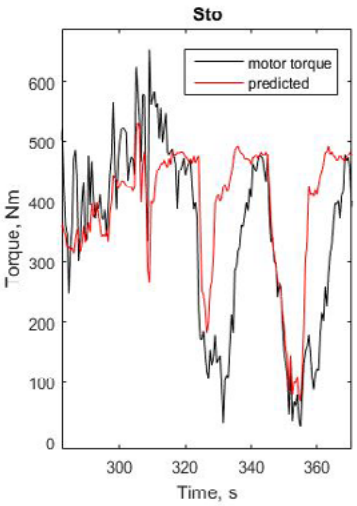
- Top rotors are even worse for the inflated-corrected tables.
- Original tables show much less peak-to-peak error in crosswind.
- Rising torque behavior is not well-captured in either tables for top rotors.

Takeaway: The original tables overall more accurately capture behavior. Small modifications could be made.

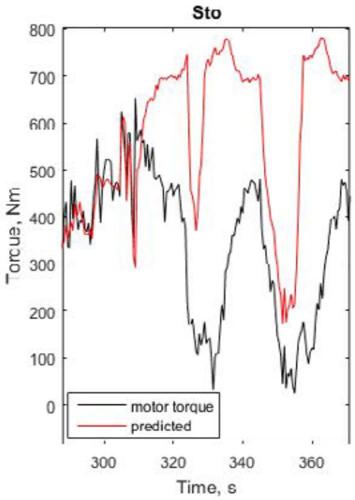
Todo: check in-plane velocity effect on torque.

Also: need measured rotor thrust in flight!

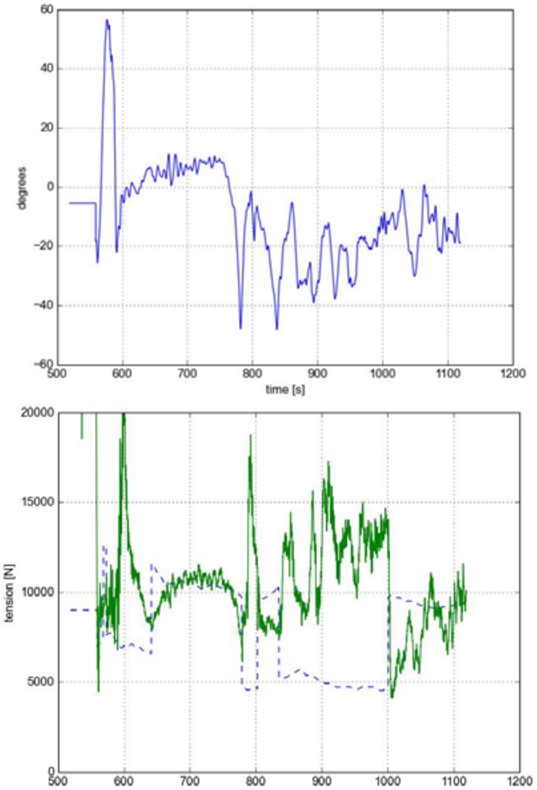
Original tables



Inflated-Corrected



Hover Tension and Roll



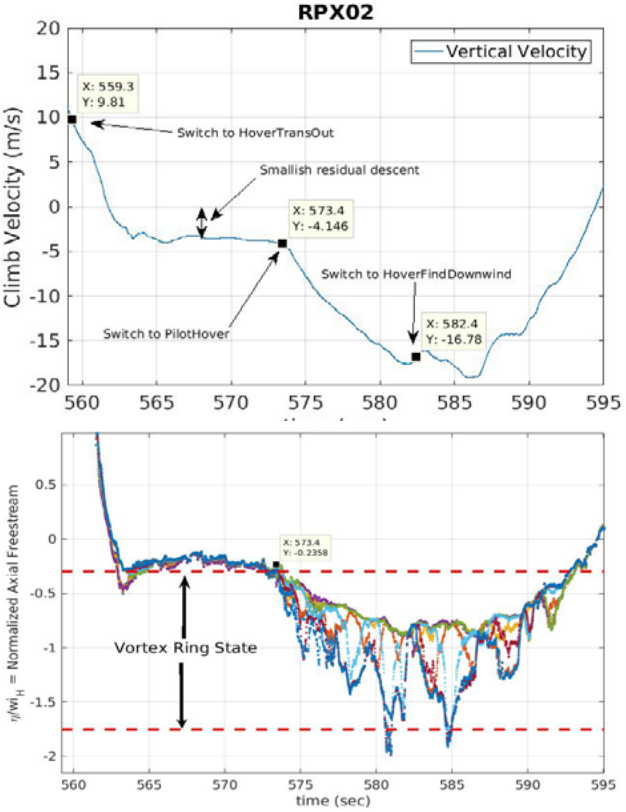
- After trans-out, there were many instances of roll excursion due to inadequate tension.
- Switched to PilotHover to command immediate pitch-back.
- Loadcell bias was a contributing factor.
- Near-crash after trans-out.

What to do about it:

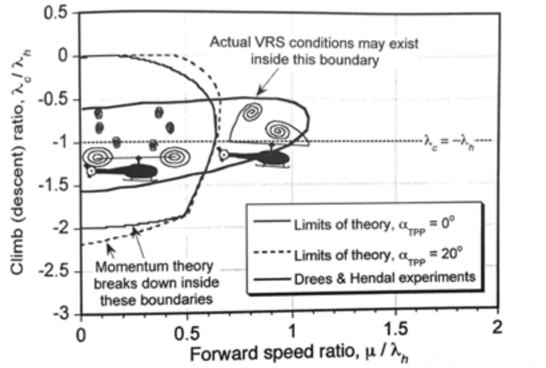
- Resolve loadcell bias problem.
- Revisit horizontal tension setpoint.
- Consider pitch feed-forward.
- Consider supplemental active roll control.

Bug: 33667081

Trans-Out Vortex Ring State



- After mode switch from CrosswindPrepTransOut to HoverTransOut, there was a residual descent velocity: ~4 m/s. Not a big problem yet...
- On mode switch from HoverTransOut to PilotHover, the net thrust abruptly dropped. Descent velocity increased and the rotors entered Vortex Ring State for ~20 seconds



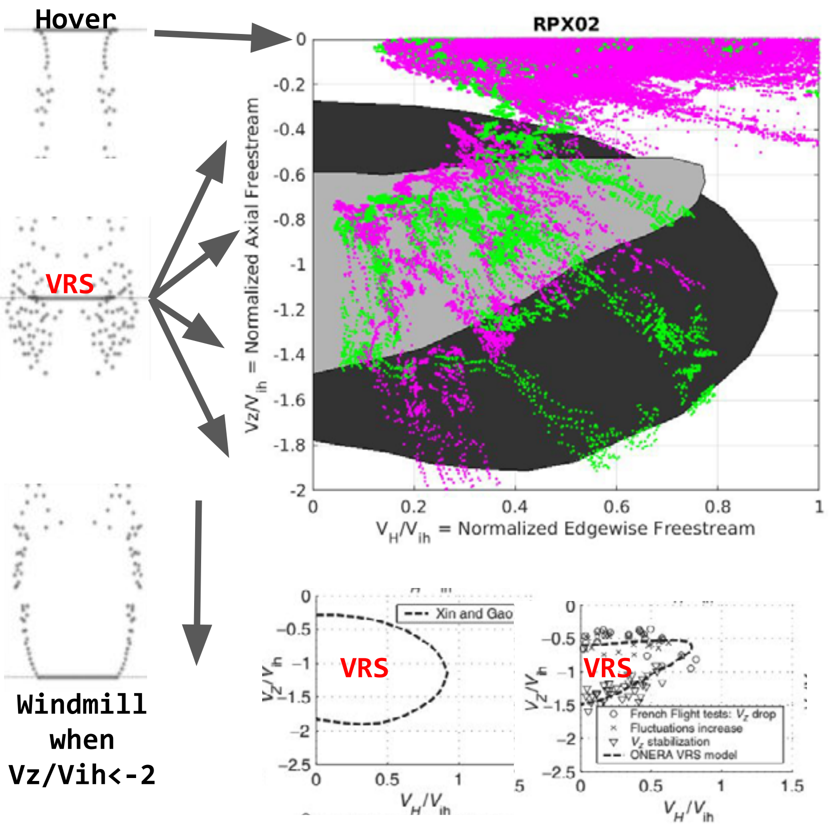
Bug: 33664639.

Trans-Out Vortex Ring State

- Recovery from VRS *began* on switch to HoverFindDownwind, likely well before any ground effect began to help.
    - Anything that changes the wake geometry helps

- Plot at right shows RPX02 rotors on top of VRS boundary definitions from the literature
    - Magenta = HoverTransOut
    - Green = PilotHover

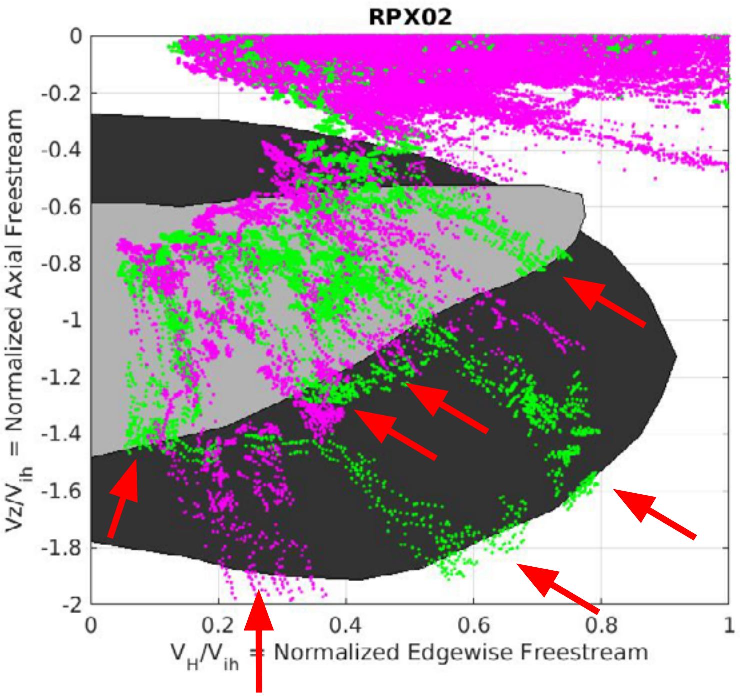
- All VRS indicators are present
    - Relative wind @ Rotors is exactly inside VRS boundary
    - “Suck In” effect (hard to stop once it starts)
    - Highly unsteady aero loads



Bug: 33664639.

Trans-Out Vortex Ring State

- Flight in VRS is unsteady, often described as “negative thrust damping”
- This effect tends to suck vehicles deeper into VRS upon entry
- Vehicles which enter VRS often traverse to the opposite side of the VRS boundary before recovering
    - If we touch -6 m/s or so in a Hover mode, we will likely enter VRS and accelerate toward the ground
- Data from RPX02 shows rotors recovering AT the VRS boundary published in literature
- Using edgewise speed to exit VRS is known to be effective. Fly laterally out of it if possible.



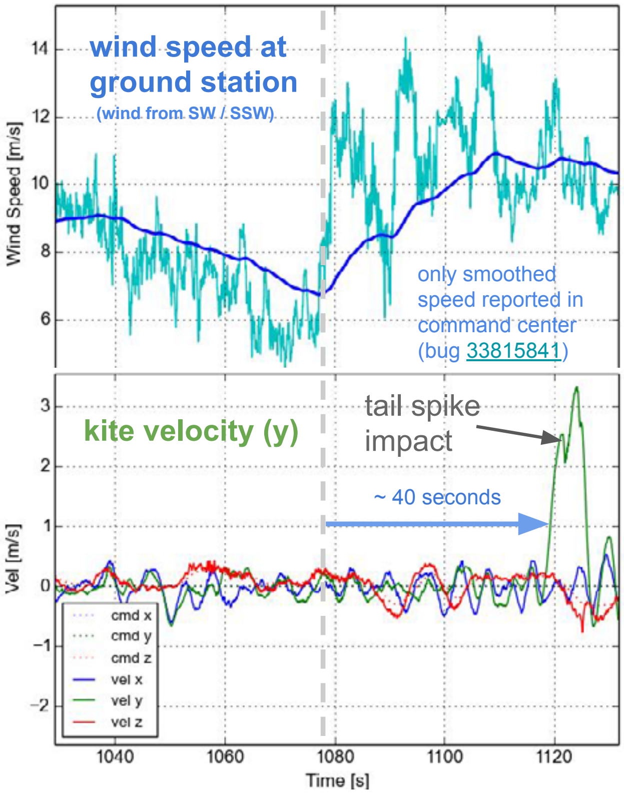
Bug: 33664639.

Loss of Tail Spike

While attempting to land on the perch, a sudden position excursion to starboard knocked off the tail spike.

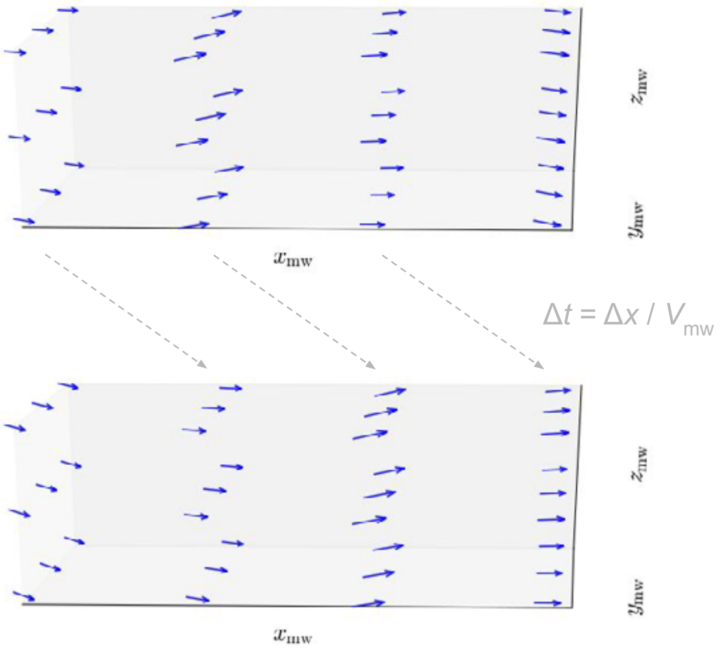
This was due to a strong gust of wind. We felt the gust at the command center and intended to wait it out, but did not wait long enough.

t = 1067	"Big gust, big gust"	Tobin
1077	"Big gust"	Tobin
1082	"We might wait out this gust."	Johnny
1103	"I think I'm going to let it go, it looks fine."	Johnny
1119	Ascend! (Excursion starts)	Johnny
1122	Tail spike impact, "Tail spike's gone."	



Simulation Advected Wind Field

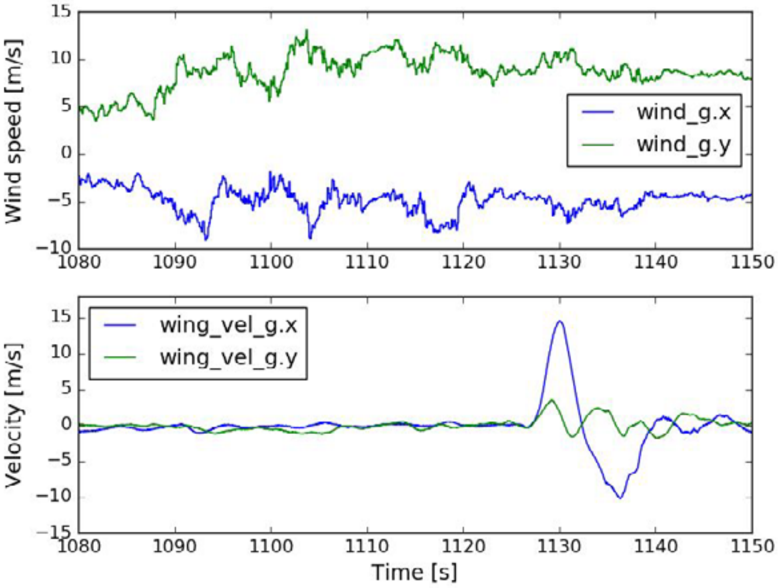
- Wind velocity recorded at the wind sensor is:
    - Extruded perpendicular to the mean wind direction
    - Advected in the mean wind direction at the mean wind speed



Simulation Advected Wind Field

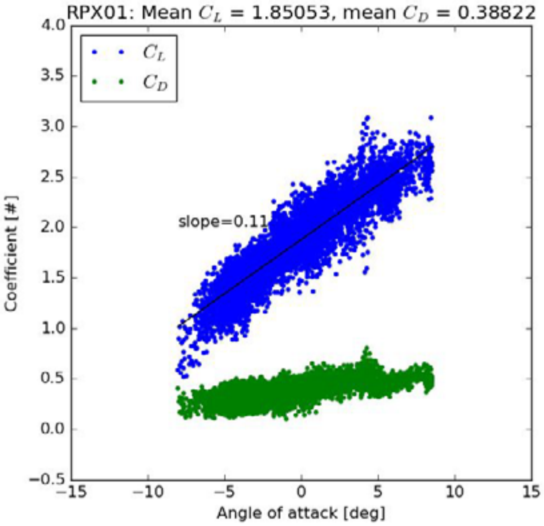
"Tail spike gust"

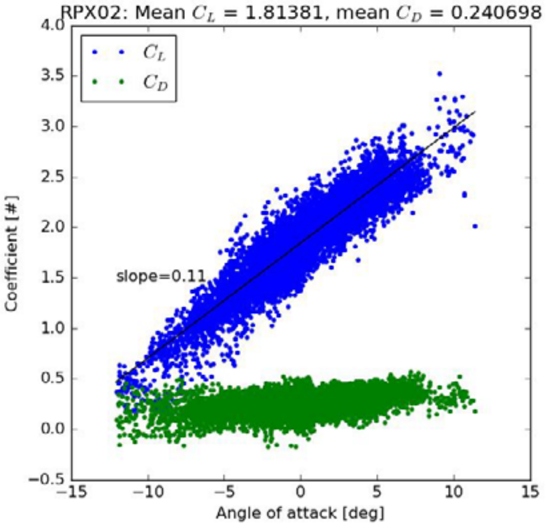
- Similar interval between gust and excursion (~40 s)
- Similar magnitude of y-velocity excursion (~3 m/s)
- Inconsistency: Large x-velocity excursion, which is opposite to wind direction. TODO: Why?



Off-Tether Glide Ratio

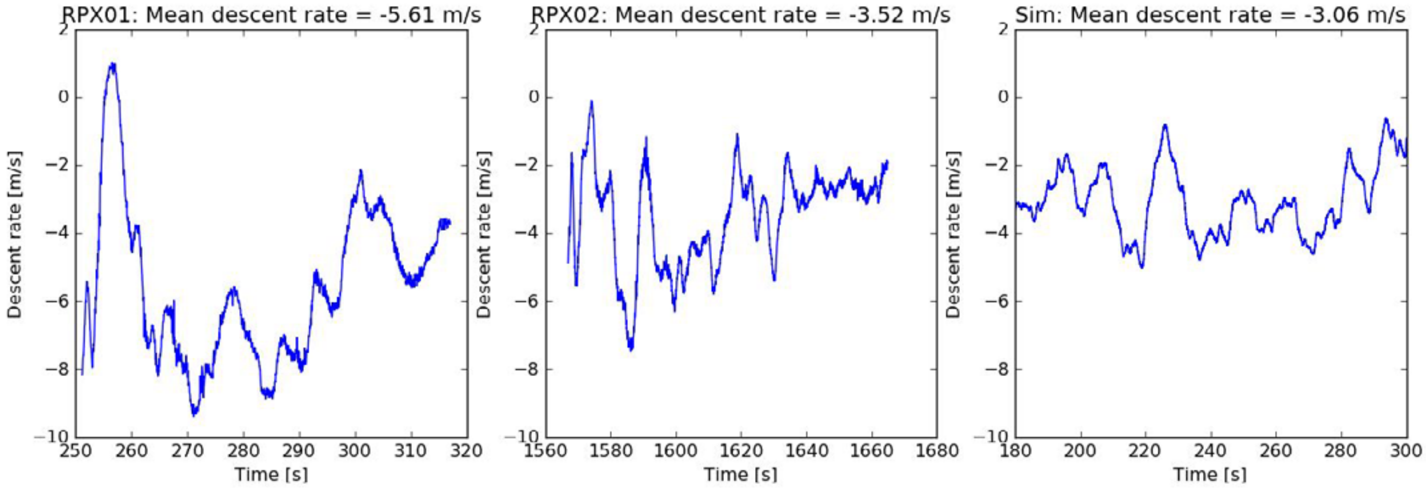
- ~38% reduction in apparent C_D
- Coarsely-estimated $C_{L,\alpha}$ in good agreement with sim's value at zero (α, β, flaps): 0.11 #/deg
- Future: In-depth validation of aerodynamic model


RPX01: Mean C_L = 1.85053, mean C_D = 0.38822


RPX02: Mean C_L = 1.81381, mean C_D = 0.240698

Off-Tether Descent Rate

- Average descent rate reduced by ~37% (caveat: non-scientific windowing)
- Sim (with fixed wind field) is still a bit optimistic



Simulation RPX-02 Best So Far

Sim log on GDrive: rpx-02_sim.h5

Sim build: Build #851 (Dec 21, 2016 11:36:00 PM)
Git revision: 53ea94c
Overrides:

- "Wind_database":
  - "Name": rpx02_wind.h5"
  - "wind_database_initial_time": 68.55
  - "wind_direction": -0.88962334062302506
  - "wind_model": "kWindModelDatabase"
- Joystick overrides:
  - t=0s of wind_db and joystick_sim.py are adjusted to match at the beginning of HoverAscend.
  - Joystick is scheduled for 6 crosswind loops, HoverPrepTransouts, two more loops and Transout.

Known limitations:

- This simulation does not include any glide landing.
- The HoverFullLength duration is longer than in the flight test.

What Did We Not Present?

Things we looked at but did not present:

- Kite angular velocity & angular acceleration document

Things we would like to look at but haven't yet:

- Vibratory loads at pylon nacelles: hover vs. crosswind
- Kite tension-angle position determination
- Catenary tether model vs tension
- Wing bending loads

What Do We Want to Learn Next Crosswind Flight?

- Measure individual rotor thrust
    - how: using the rotor blade strain gauges + the wireless v-links
    - why: to correlate the Sim rotor tables; to resolve the thrust discrepancy during HoverAccel
    - TODO(airframe): integrate the V-Links, validate blade root strain gauge accuracy

- Hover descend out of vortex ring state
    - how: penalize a critical descent rate; detect vortex ring state and get out of it
    - why: to validate the HoverTransOut and HoverReelIn controller
    - TODO(controls): implement control change

- Hover in various wind azimuth angles
    - how: in China Lake or at the E-Lot, hover under constraint
    - why: to verify the in-plane moment predictions of rotors in edgewise flow

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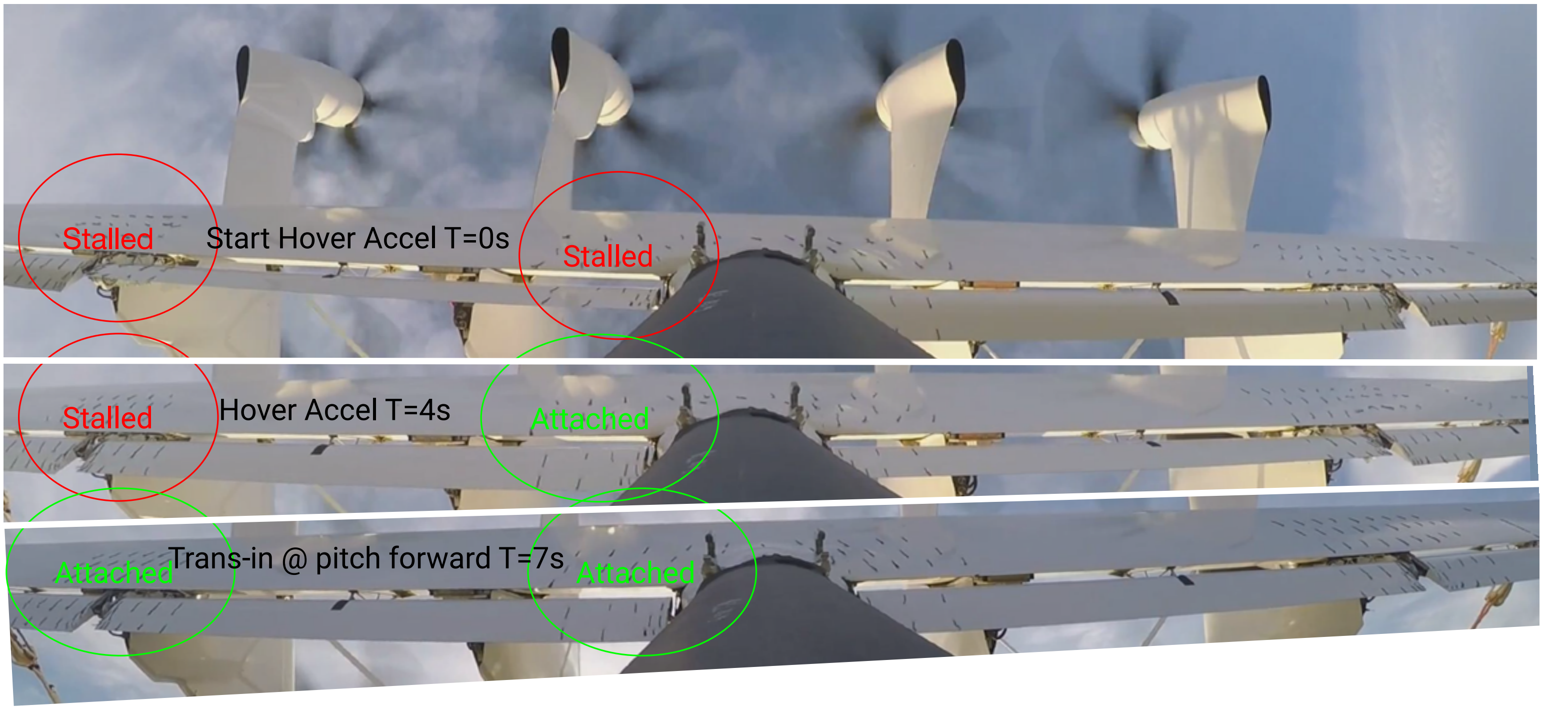
RPX-02 Lessons
Airframe

Jan 18, 2017

RPX-02 Executive Summary

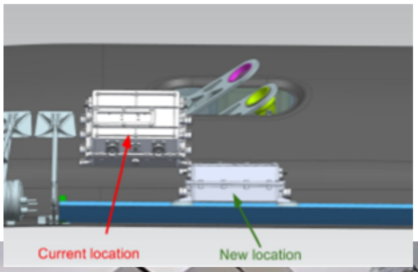
- Nothing looks scary...let's keep flying!!

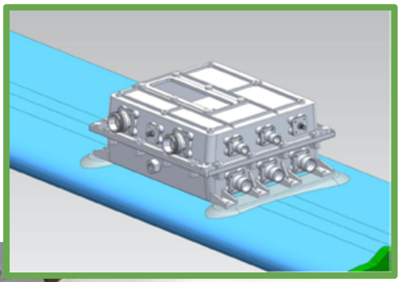
RPX-02 Trans-In/Crosswind Tuft Videos

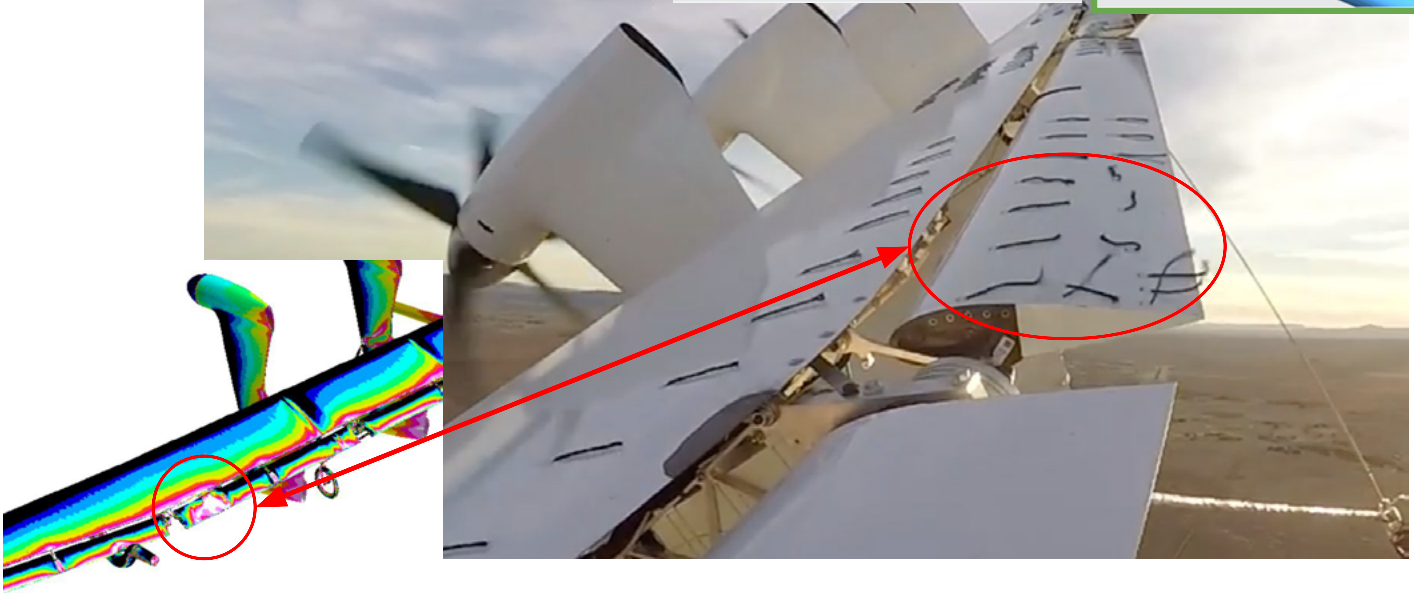


RPX-02 Bridle Box Stall

- Notice stalled flap section
    - Fix planned for RPX-03 ECR166







RPX-02 Trans-Out Tuft Videos

- Working as expected
    - Consider changing elevator behavior after trans-out is complete (point towards the wing)

RPX-02 Glide Landing Tuft Videos

- Asymmetric Stall right before touchdown
    - TODO: What alpha and speed did that happen?
    - Does that match predicted stall speed/alpha?
- Worth noting that the starboard side of center is often the first to stall in CFD as well. Under investigation

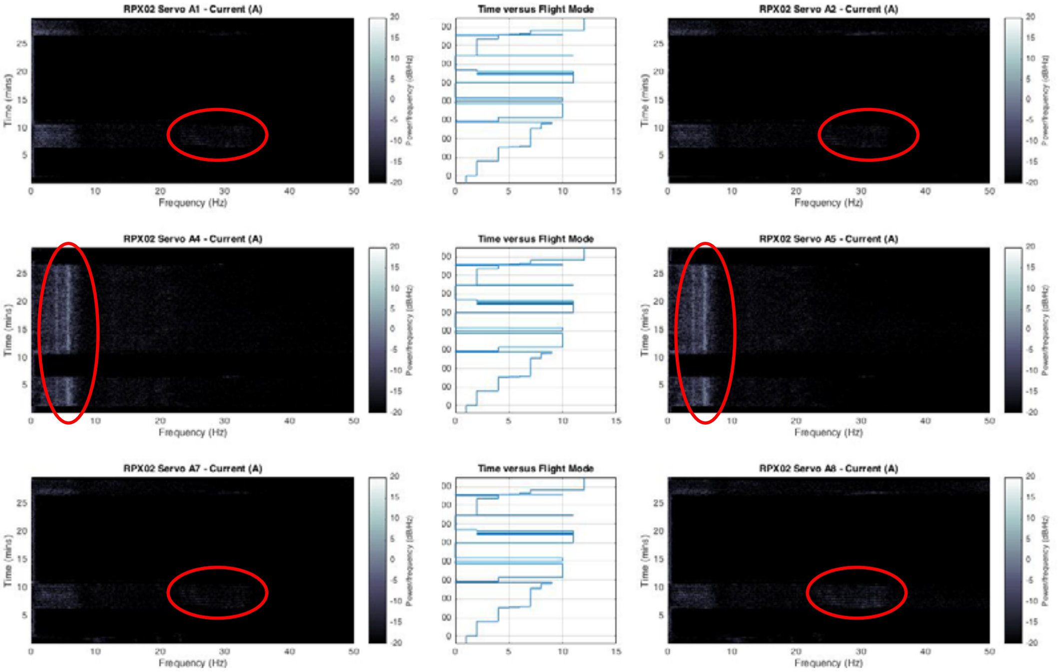
RPX-02 Thermal Summary...If We Flew at 40 C not 24 C

Component	Notes
FCUs	FCU Duct due to be installed before RPX-03
Bridle boxes	Mismatched thermal tests; more investigation required, multiple solutions possible, not high risk
Servos	No recorded tests done on servos in high heat -- unquantified risk
Tether	No temp. measurement to validate model; will discuss
GS slip ring	No temp. measurement to validate testing; will discuss
DC-DC converters	No temp. measurement; test in upcoming flight
Motors	No temp. monitoring on YASA 2.3 stator coils; likely OK but most limiting component; *be careful* w/power increase from Ozone and Gen4/5 props
Motor controllers	Go back and analyze GDB component thermal limits for allowable test/hover time
Servo boards	Looks good
Battery boxes	Check again on acceptable board temps.
Satcontainers	All good to go
Groundvionics	All good to go

RPX-02 Servo Current Ailerons

- A1, A2, A7 and A8 show noise in x-wind and off tether (signal oscillates between ~25 and ~ 35 Hz)
- A4 and A5 show noise in all hover modes (also have pronounced peaks at ~4 and ~6 Hz)

Spectrograms calculated with 1024 samples per FFT and 50% overlap in Matlab
(underlying data was resampled at 100 Hz with an equal spaced time vector before running spectrogram)



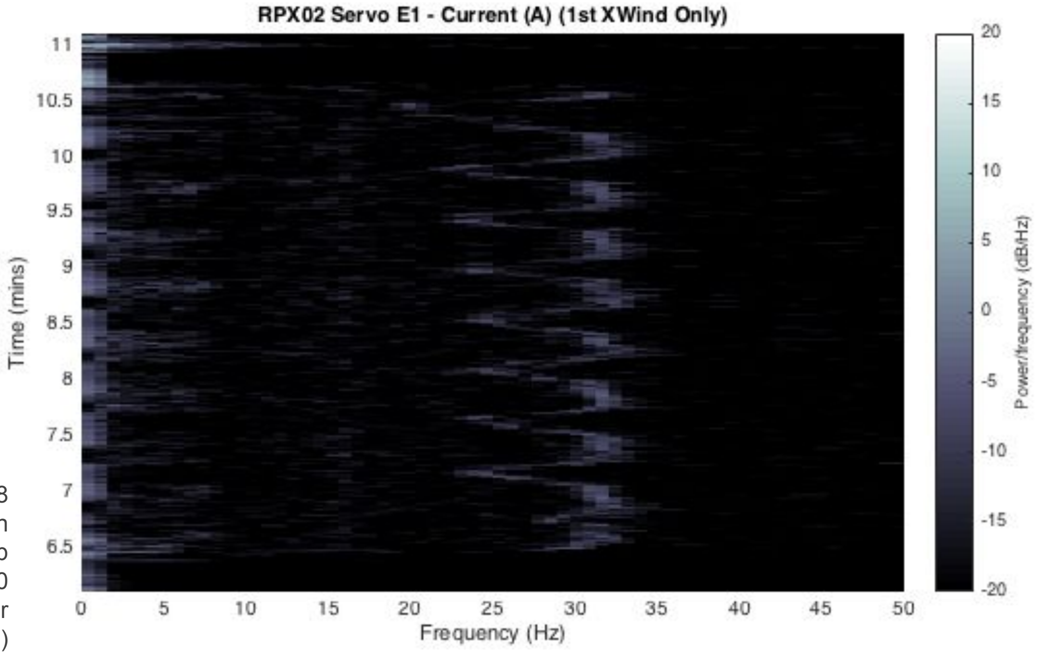
b/33783041 (5 Hz issue)

b/34471361 (25 - 35 Hz issue)

RPX-02 Servo Current Crosswind

- Typical high frequency content present in following servos in crosswind flight
    - Flaps - A1, A2, A7, A8
    - Elevator - E1 (shown), E2
    - Rudder - R1, R2

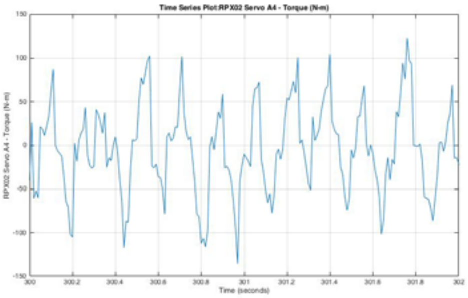
Spectrograms calculated with 128 samples per FFT and 50% overlap in Matlab (underlying data was resampled at 100 Hz with an equal spaced time vector before running spectrogram)

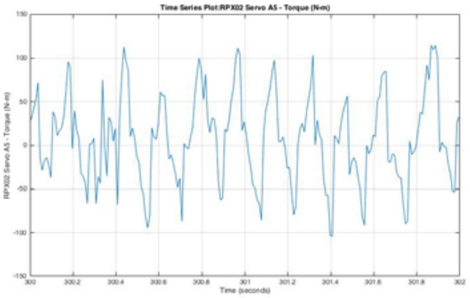


b/34471361 (25 - 35 Hz issue)

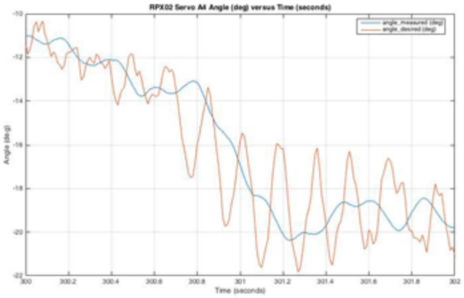
RPX-02 Servo Current Ailerons

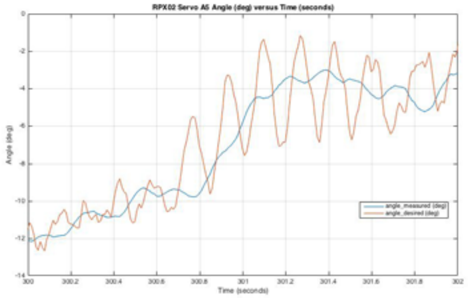
- A4 and A5 hover noise
- (typical behavior)





- Are there plans to tweak servo controller to reduce this behavior?

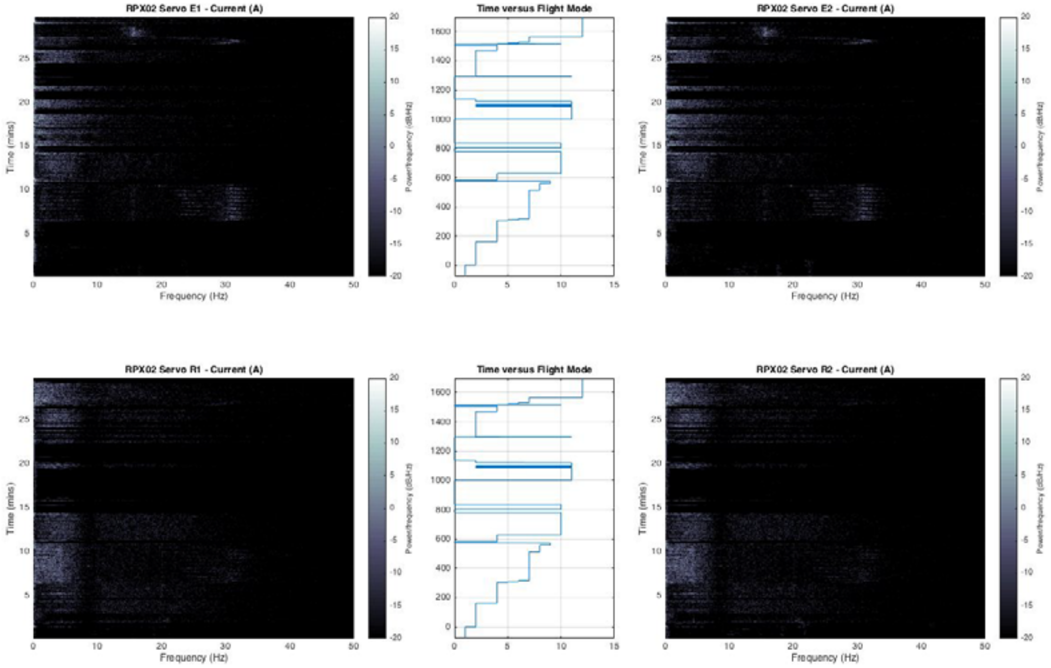




b/33783041 (5 Hz issue)

RPX-02 Servo Current Elevator & Rudder

- Elevator and Rudder show broadband noise in some flight modes and not others

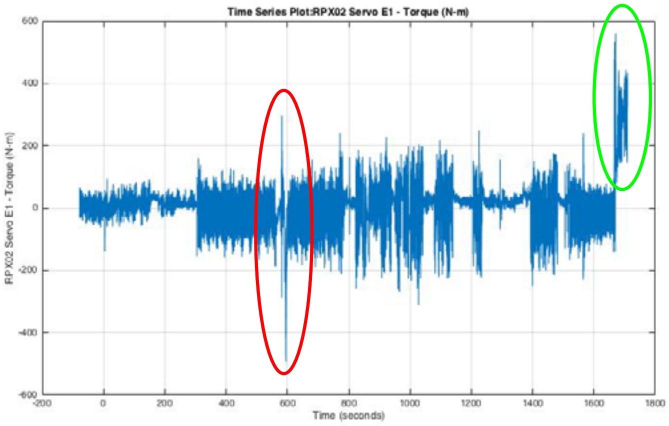


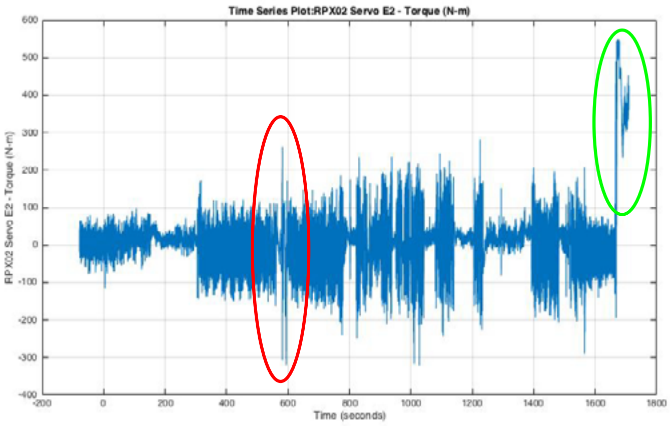
Spectrograms calculated with 1024 samples per FFT and 50% overlap in Matlab
(underlying data was resampled at 100 Hz with an equal spaced time vector before running spectrogram)

b/34471361 (25 - 35 Hz issue)

RPX-02 Servo Torques Elevator

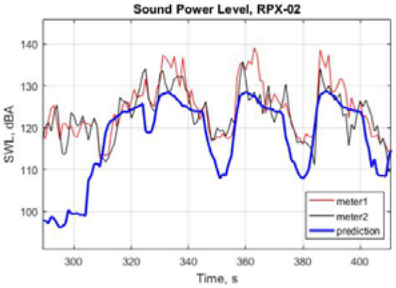
- Elevator servo torque spike during trans-out
- Elevator dragging on the ground

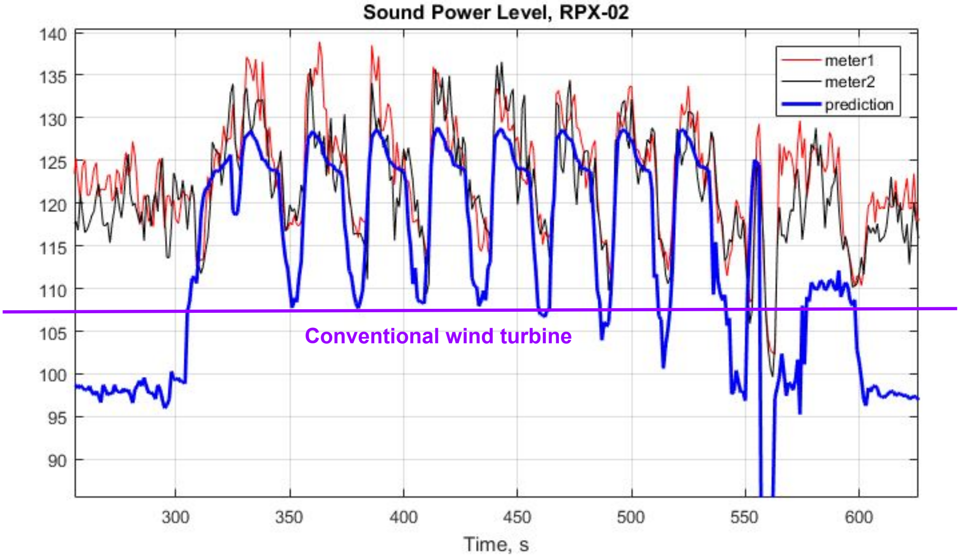




RPX-02 Noise Kite Measurement and Correlation

- Noise Measurement Deck
- Measurements conform to IEC 61400-11 standard
- Predictions from lookup table based on axial velocity and omega for each rotor using Xrotor noise module





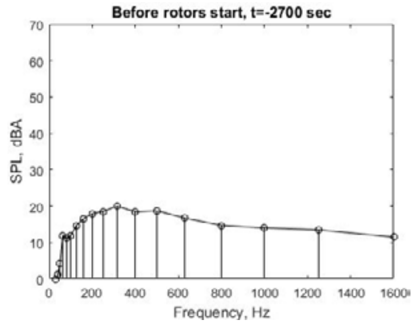
Crosswind detail

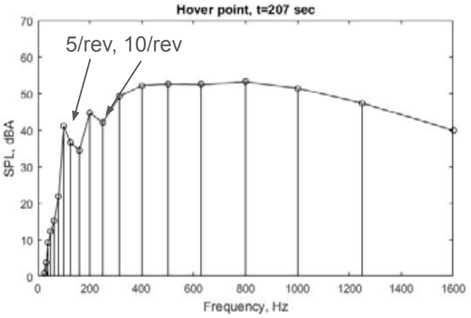
RPX-02 Noise Kite Measurement and Correlation

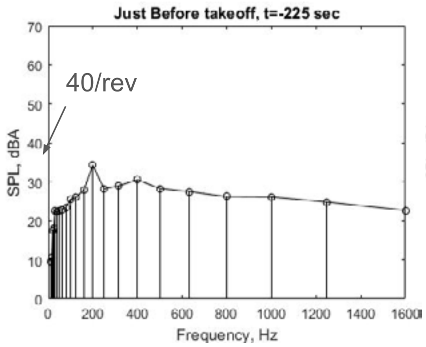
- Frequency content in 1/3 octave bins
  - denoted by the vertical lines
  - 9 seconds per measurement
- 40/rev shows up when all rotors are synced (i.e. just before takeoff at 30 rad/s)
- Otherwise peaks at 5/rev and 10/rev
- More higher-frequency (>600 Hz) content than expected, even in hover

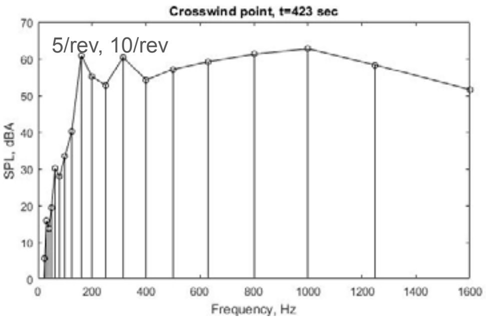
- Too coarse in time and frequency bins
- Need calibrated audio signal for next test

- TODOs
- Correlate Xrotor-predicted frequency content, process to 1/3 octave bins as well
- Process video camera audio from RPX
  - Won't be calibrated, but will be finer in time and frequency resolution... might learn something
- Set up calibrated audio signal measurement for RPX-03









RPX-03 What do we want to learn/do?

- IMPROVEMENT - Do the Gen4 props make power as predicted?
    - First Gen4 due 1/23; (x4) by 1/30, ship set (x8) by 2/13
- IMPROVEMENT - Can we keep the FCU’s cool?
    - FCU ducts in place ECR169
- IMPROVEMENT - Did the bridle box move reattach air to the downstream flap section?
    - Move bridle box’s ECR166 and video tufts(already in place)
- IMPROVEMENT - Did active roll control help as predicted?
    - Implement active roll control ECR164 scheme before RPX-03
- INSTRUMENTATION - How accurate is our crosswind velocity measurement?
    - Wingtip pitot tube ECR170, crosswind position
- INSTRUMENTATION - What is the wind speed at the kite during hover?
    - Wingtip pitot tube ECR170, hover position (needed for hover->thrust correlation)
- INSTRUMENTATION - Does our mainplane work as expected?
    - ZOC box ECR171 installed
- INSTRUMENTATION - What is our measured thrust in Hover and Crosswind?
    - Vlinks and hub strain gages ECR167 installed, correlate hub strains to thrust

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Avionics
RPX-02 Lessons Review

Jan 11, 2017

Executive summary

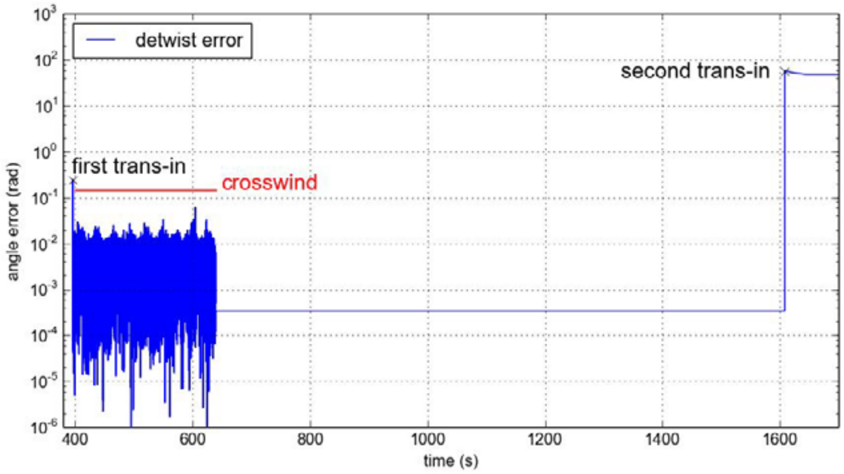
- All avionics nominal, except for:
    - JS radio link intermittent
    - Loadcells, FCUs running hot
      FCU fix in the works, bridle boxes to be addressed;
      provides opportunity to separate enclosure housing loadcells from power converters/ radios.
- Detwist did detwist.
  At rated crosswind tensions, we may experience more torque than the detwist can handle.
- GPS performed as expected during Crosswind.
  Both receivers reacquired satellites during the upstroke and lost satellites during the downstroke.
- Out/midboard ailerons not extensively used, often at nominal positions.

Questions to answer

- How did the detwist perform?
- How did the radio links do?
- How reliable was the GPS during the flight modes?
- Did the tail servos operate in their linear range in all the flight modes?
- How reliable was the network?
- What was the thermal performance? Why were the loadcells so hot?
- Did the Recorders capture all the important data?

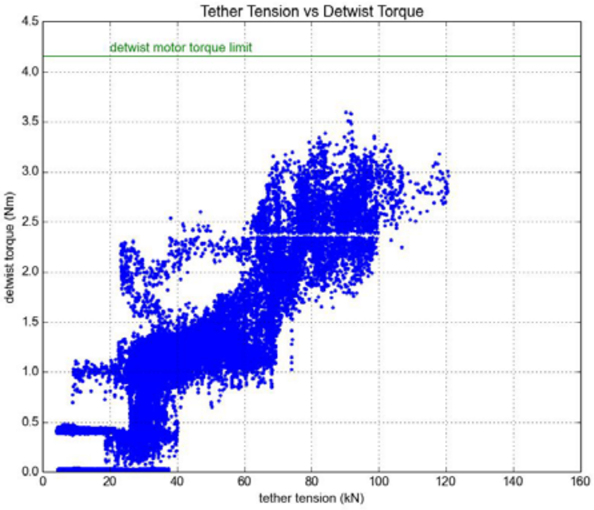
Detwist Performance

- Followed commanded angle during regular crosswind
- Errored out and disarmed upon second trans-in
  (expected because flight controller resets to a multi-turn angle of zero)
- First nonzero detwist command was -0.25 radians. This was larger than expected and did not cause an error, but larger discontinuities in the position command could be problematic. (Follow up with Controls.)

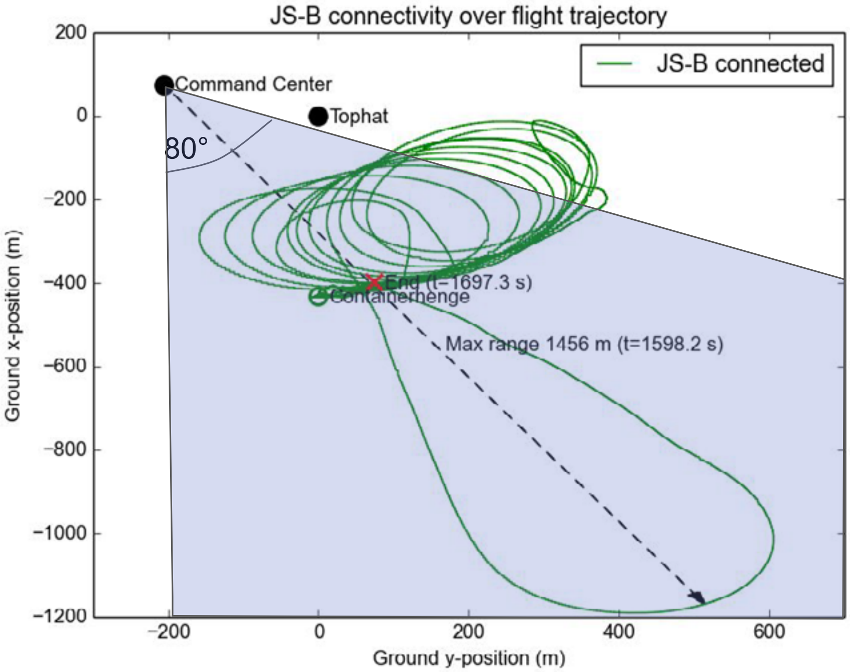


Detwist Torque

- High-load testing of detwist was skipped prior to RPX
- The torque required to rotate the detwist appears correlated with tether force
- At rated crosswind tensions the torque may exceed the gearbox limit of 4.16Nm
- Mechanical solutions are being considered



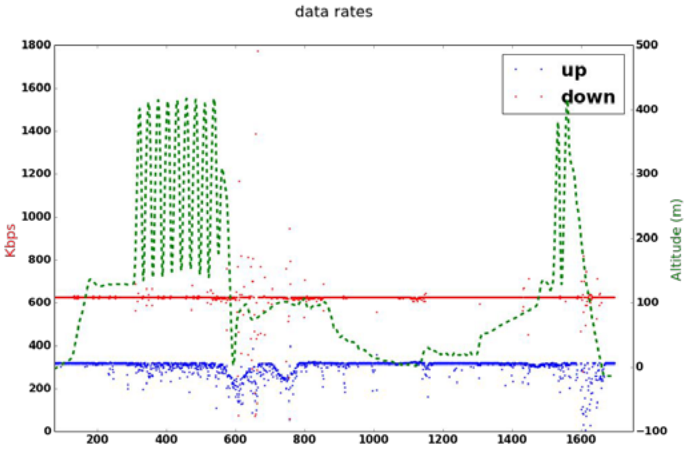
Joystick Radio Radiation pattern

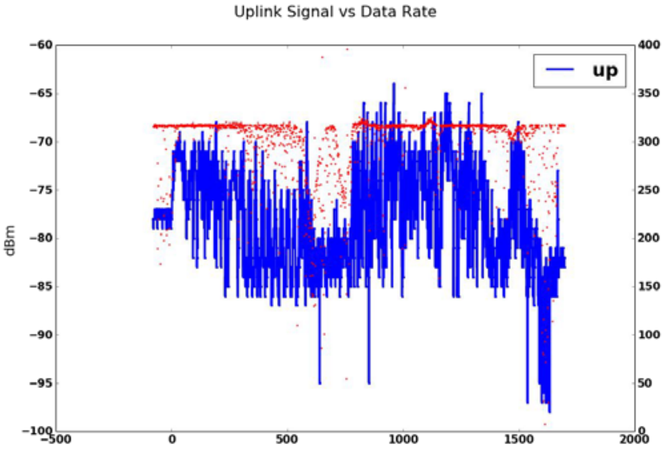


- Shaded region indicates radiation pattern of 10 dBi antenna on joystick antenna
- Omnidirectional RX diversity antenna

Joystick Radio - Packet Drops

- Correlated with RSSI drop.
- Asymmetry (up vs. down) may be due to antenna diversity being RX only.
- Worse near at the end of the glide than last flight
    - May have been difficult to control landing on only JS link.
    - No danger of triggering scuttle.





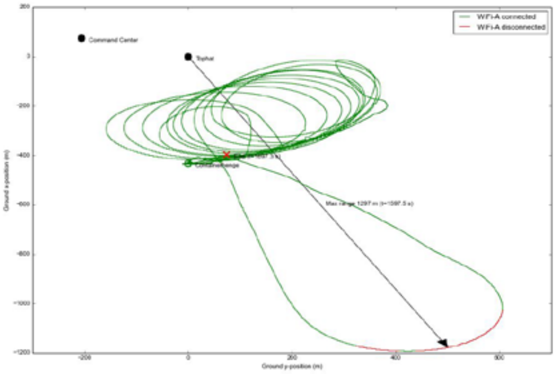
Joystick Radio - “bad days”

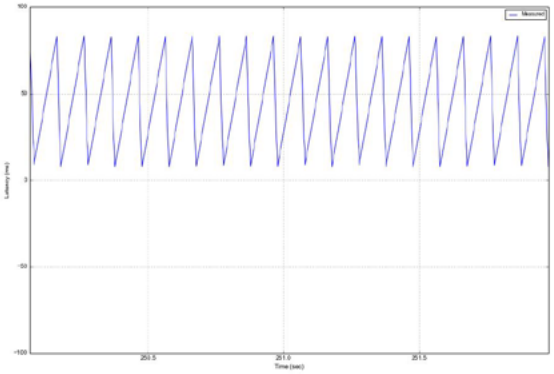
4	5	6	7 ☹	8	9	10 🙂
11	12 😩	13 😅	14 😋	15	16 🍾	17

- b/33428388
- New failure mode seen only after rpx-01
  - Joystick radio would not connect all day.
  - Complete power cycling of the systems would not bring it back.
- Attempts to debug in situ were limited in order to make/keep kite ready for wind.
- Theories put forth:
  - RF interference from other test site users.
  - Parameter flash wear/corruption.
  - Mechanical issue from first landing and/or heating and cooling cycles.
- Actions
  - Log serial communication with radio.
  - Limit writes to flash.

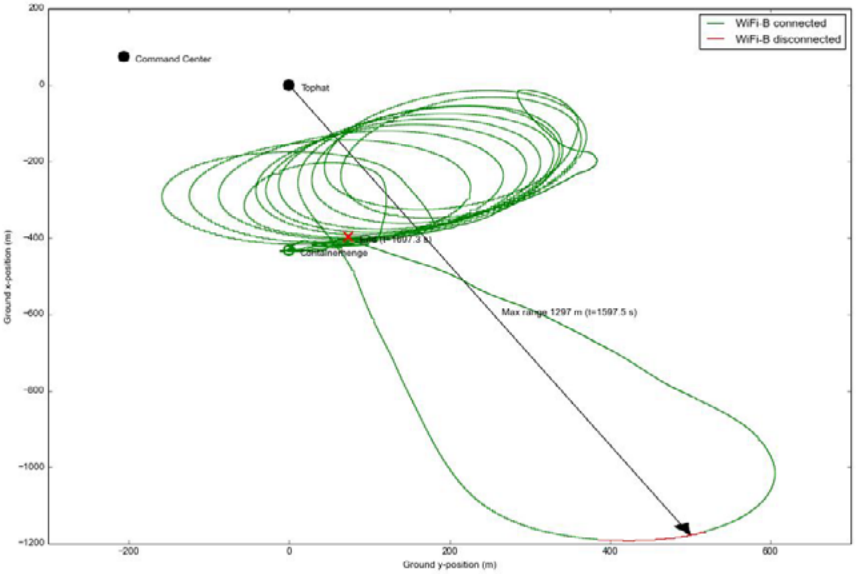
Wideband-A (Proxim) performance

- Proxim exhibits similar behavior as RPX-01:
  - Latency measurements vary between 2.5 ms to 90+ ms on downlink, and exhibit a periodic behavior (ControlTelemetry?) -- this was solved in the birdcage post flight and due to the WORP sync feature
  - Lost comms for 13 seconds during glide landing (at similar distance as RPX-01)
    To do: Disable WORP sync on the Proxim radios at CL and limit SU units to 1





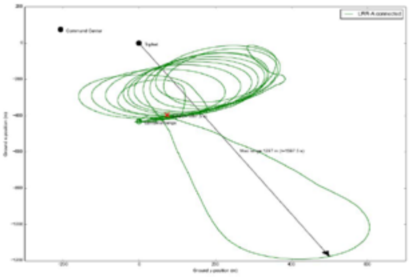
Wideband-B (Silvus) performance

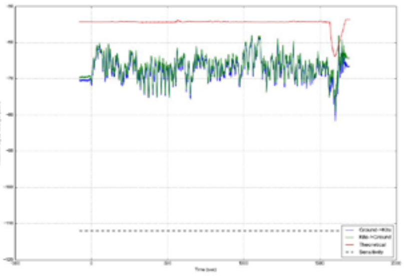


- Consistent with RPX01
- Wideband radios work with link margin of 10 log (1200m/600m)^2 = 6 dB

Long range radio performance

- Long range radio performed well
    - No extended dropouts
    - 35+ dB of link margin
    - RSSI within 15 dB of free space path loss estimate
- Consistent performance with RPX-01

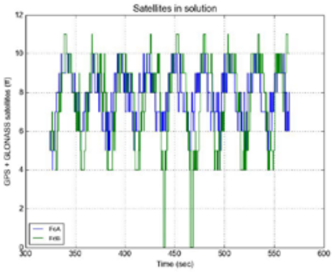


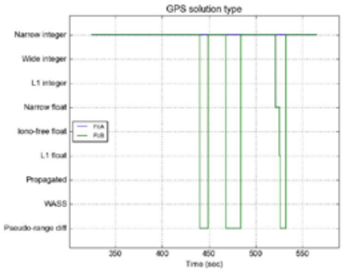


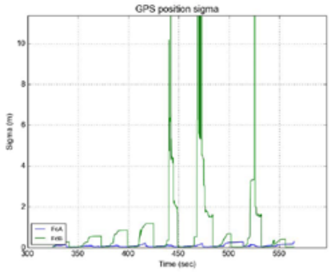
No changes necessary

GPS performance in crosswind

- GPS performed as expected.
    - Crosswind oriented antenna maintained an RTK narrow integer solution (awesome)
    - Hover oriented antenna dropped to a differential solution and reported large sigmas (expected)
    - Both receivers reacquired satellites during the upstroke and lost during the downstroke
- Next flight: compare performance to wing tip location
    - Placing receivers at the wing tips provide strong observability of IMU-to-body rotation and attitude



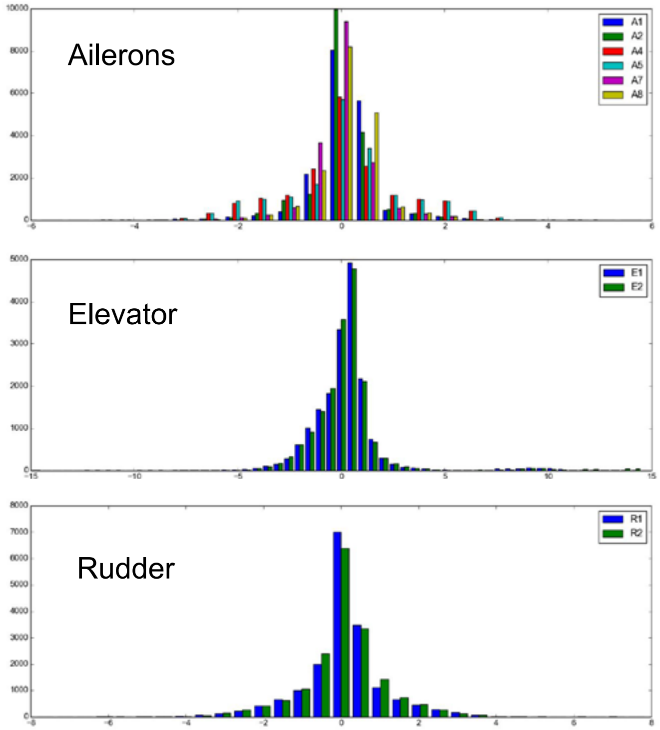




Servo Winding Current

- Ailerons experience typically small loads, with no observations outside 6A, and typical values inside 3A.
- Inboard ailerons show higher loads due to increased use.
- Elevator typically inside 5A, except when stuck and limited other cases.
- Rudder had no observations outside 8A, with typical values inside 4A.

Servo current limits were designed with peak torque load cases in mind—our usage is still less than half of these limits.

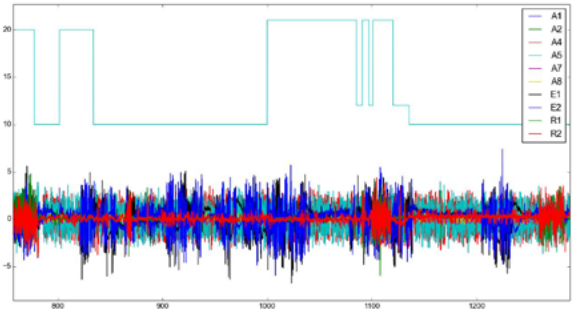


Histogram of winding current in amps, over entire flight

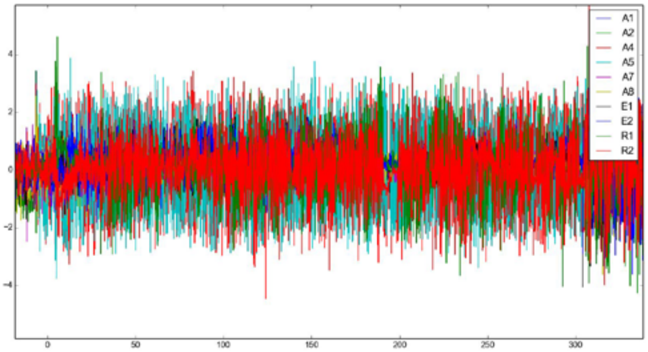
Servo Winding Current

- Hover ascend currents are around 1-2 A mean, with occasional 4 A peak.
- Crosswind currents are higher—2-3 A mean and peaks around 4-5 A.
- The descend phase shows high elevator loads, peaking around 5-7 A in pilot hover.

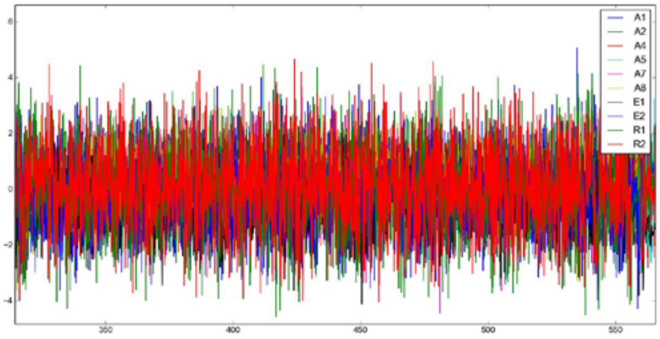
Descend/pilot hover after trans out



Hover ascend to trans in



Entire first crosswind of flight

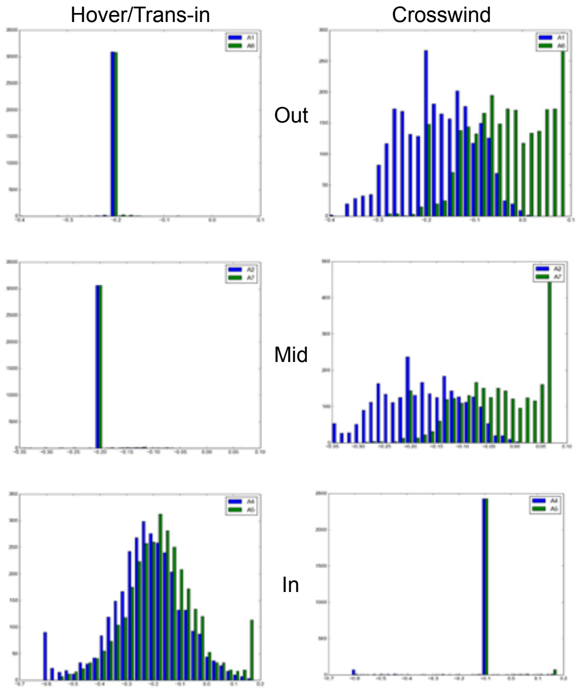


Winding current in amps, all servos

Flap Angular Positions

- Starboard out and midboard ailerons saturate in crosswind—may need more range in positive deflection.
- Inboard ailerons used over full range in hover, some saturation. Mostly unused in crosswind.

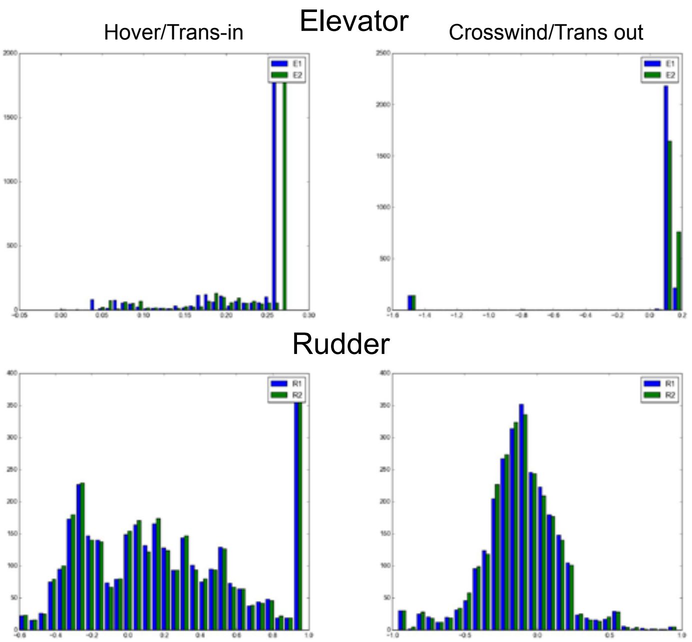
Ailerons



Histogram of deflection angle in radians, over entire flight

Flap Angular Positions

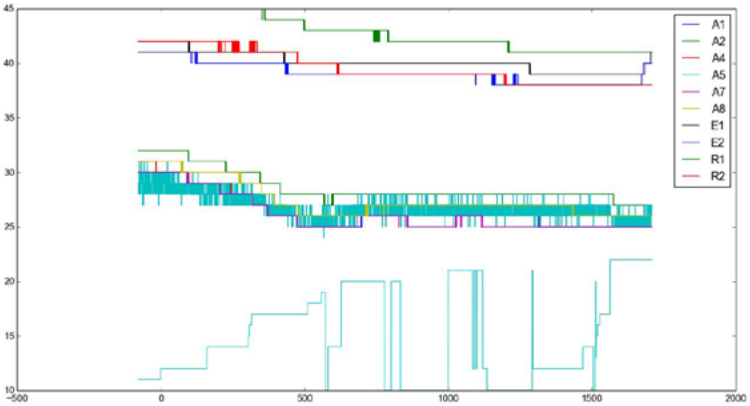
- Rudder saturates often with full positive (port) deflection in hover, likely due to crosswind takeoff configuration, usage is well distributed in crosswind.
- Elevator used over extremely limited range until trans out (then extensively slewing during recovery/pilot hover)



Histogram of deflection angle in radians, over entire flight

Servo R22 Temperatures

- Due to the decreasing ambient temperature over the flight, servos remain cool and actually get colder over the flight.
- Ailerons begin around 28-32C, and cool to about 25-28C by the end of the flight
- Tail is warmer, starting at 41-45C and cooling to 38-42C by the end. Elevator begins to warm after landing due to locked control surface.

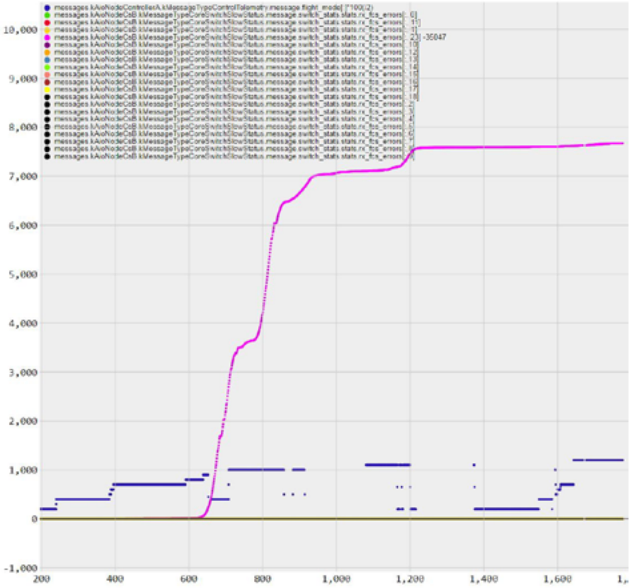


R22 temperature in degrees Celsius, and flight state, over entire flight

Network Performance

- No Frame Checksum errors in RX packets on the network *except* for port 23 on CSB, the JS radio.
- No dropped TX packets due to congestion

To Do: verify proper link setup between JS radio and CSB http://b/33413959



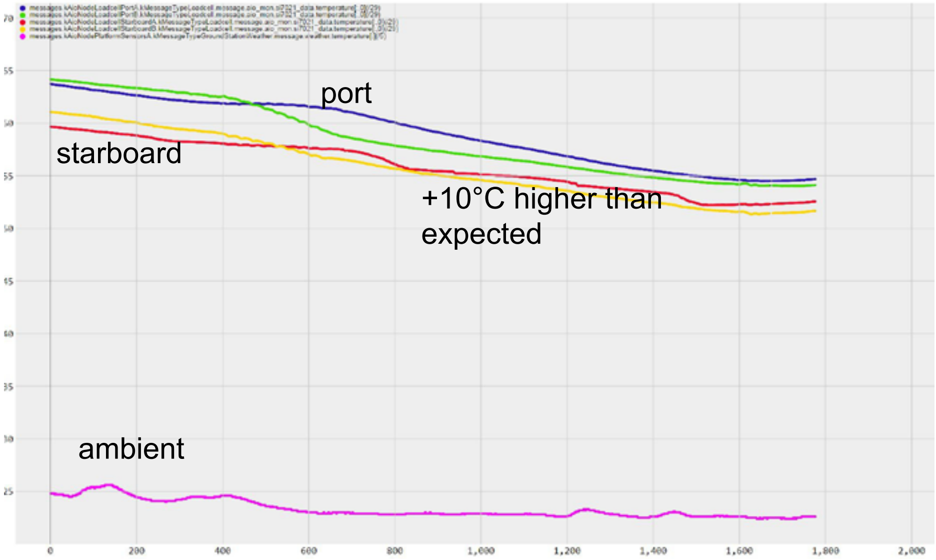
Frame Check Sum errors: only the JS radio accumulated errors

Bridle Enclosure Temperatures

- Both Bridle enclosures run about ~10 °C hotter than expected based on validation tests
- Jeff Reed’s RPX-02 THERMALS compares against temperature chamber measurements

To Do:

- Repeat thermal characterization with radios transmitting
- Improve packaging to allow better cooling



Flight Recorder

- We dropped **3 total packets during RPX-02** from on-wing sources (two motors), verified by packet rates and sequence numbers.
- All missing packets were at a point about 7 ms into the first log, before anything interesting was happening; the mechanism of the drops (at recorder or network) is unknown.

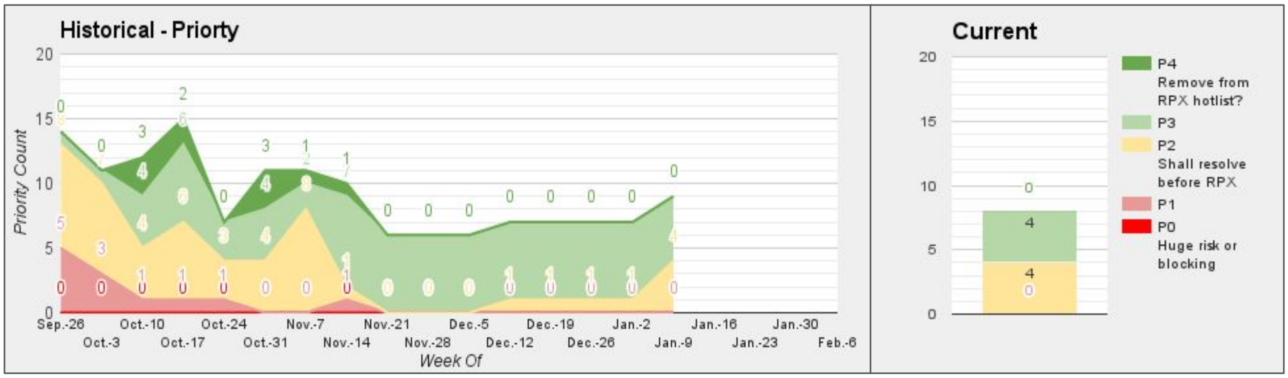
Candidates for Autochecks

- Radio connectivity
- Radio rssi
- Radio transmission rate
- Tether release sequencing
- Missed packets
- Recorder packet loss
- Core and Access port statistics for L2 frame receive errors
- Core and Access port statistics for packet dropped errors due to congestion
- GPS satellite loss during hover with hover antenna (below some threshold)
- GPS RTK mode during hover with hover antenna (want L1 float or better)
- GPS satellite loss during crosswind with crosswind antenna (below some threshold)
- GPS RTK mode during crosswind with crosswind antenna (want pseudo-range diff or better)
- Temperature checks
- Detwist error and torque

RPX-03 What Do We Want to Learn/do?

- Gather data from wing tip GPS receivers to:
    - Gauge improvements in GPS reception due to less obscured receiver placement
    - Data collection for INS development
        - Provide strong observability to attitude, alleviating the requirement to hokey-pokey
        - Provide strong observability to sensor-to-body rotation, thereby relaxing mounting requirements

Avionics Dashboard



RPX-02 Lessons
Power Systems

Jan 11, 2017

Executive Summary

Ground Power:
- Robust
- Perfect shutdown / self preservation behavior

Kite Power:
- Bearing issues? Under investigation
- Power and torque are within limits
    - Only barely (trans-in)
    - Some control subtleties (rapid cmd changes when mode switching and in trans-out)
    - Structural oscillations causing current oscillations
    - Possibly relax omega limit?
- Top vs. Bottom motors
    - Still fighting some pitch back
    - Leaving power “on the table”
- Flux weakening problems persist

Control:
- Feedback motor cmds ←→ IMU

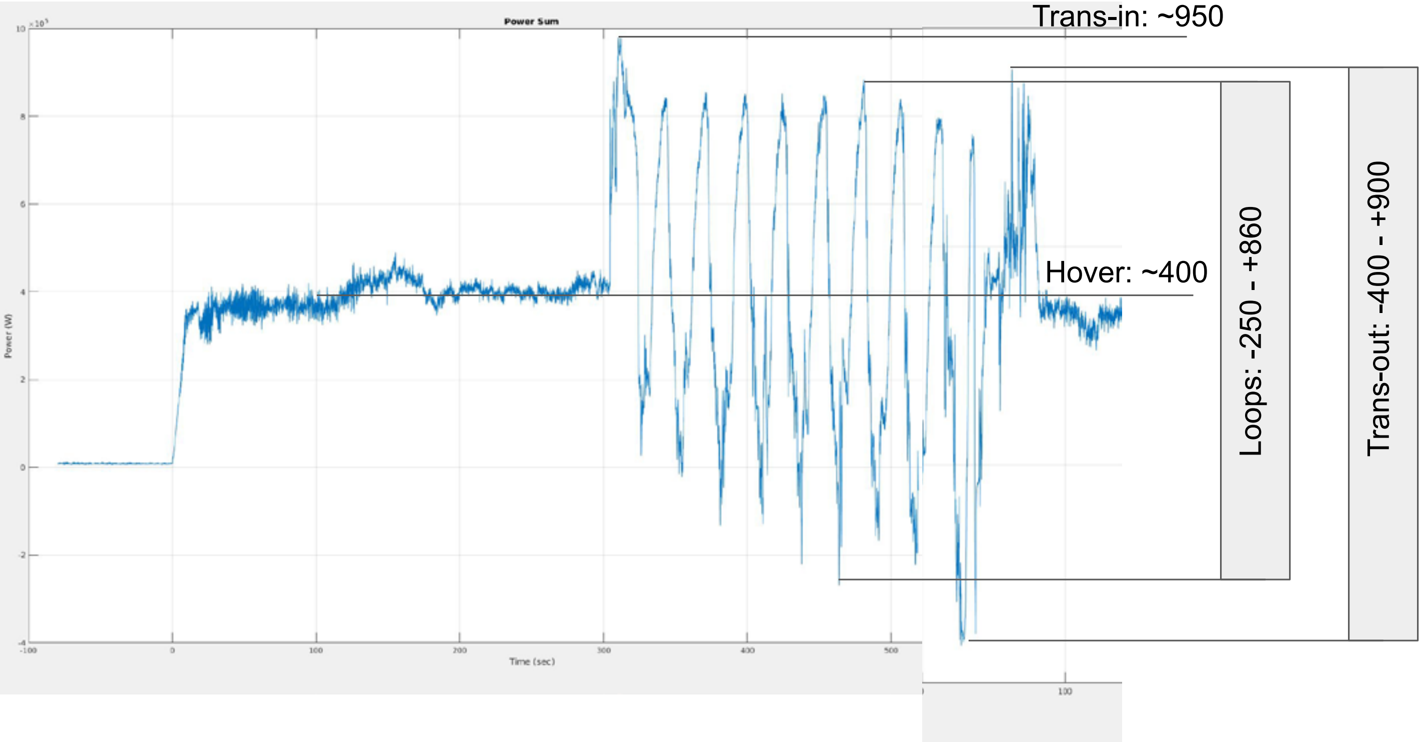
LV bus:
- As predicted, we have plenty of excess capacity

Motor Power and Torque Maxima During Flight (approximate)

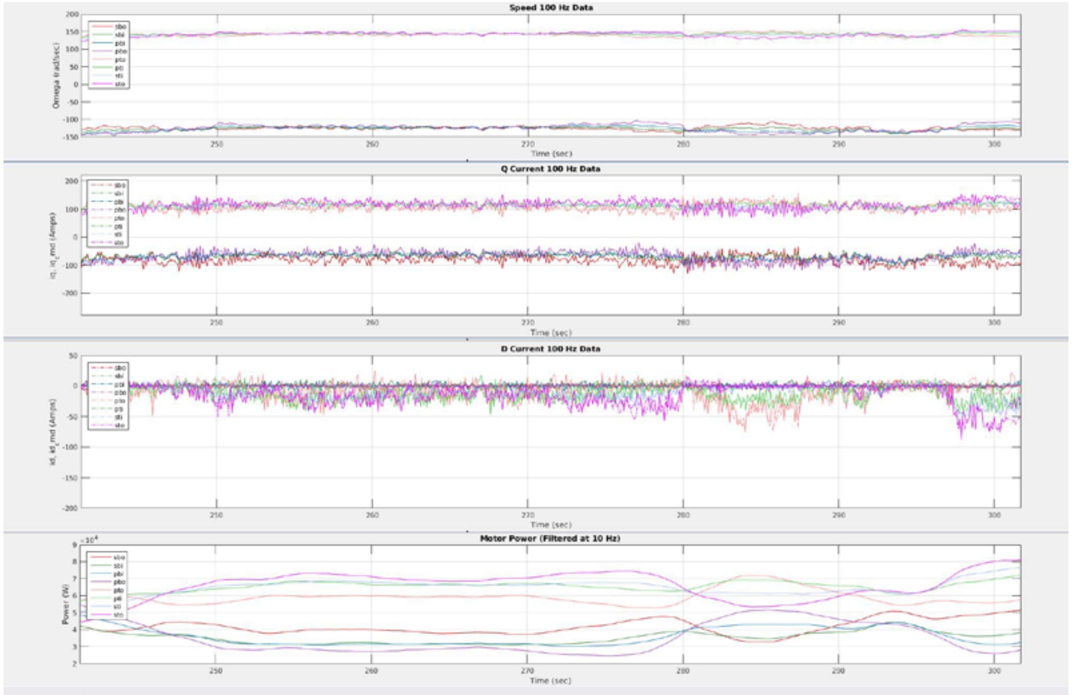
	Hover (bot/top)	Trans-in	Crosswind	Trans-out
Current (pk) [A]	70 / 100	220	160	140
Torque [Nm]	250 / 350	600	440	350 (-350)
Power (elec) [kW]	35 / 65	115	95	60 (-40)
Speed [rad/s]	125 / 150	200	215	200

- Performance limit is still in trans-in
- Significant pitch-back during hover
- Omega limit is too low to draw max power from motors with forward inflow (crosswind)
    - Revisit?
    - Can the props handle higher omega?

Power Summary

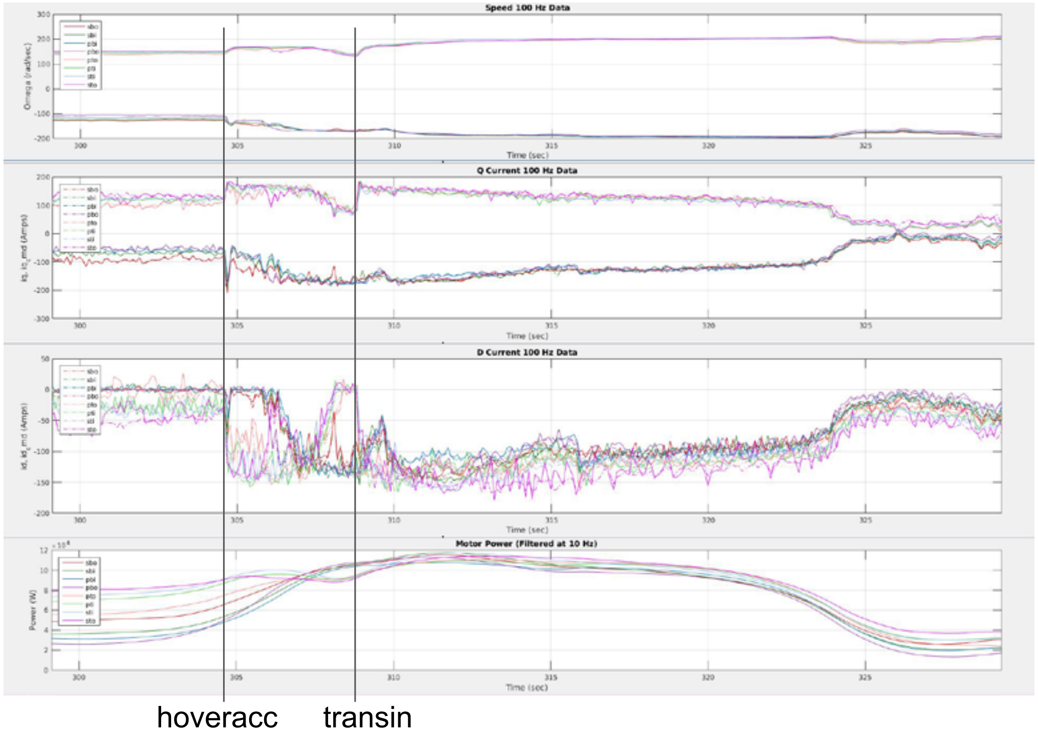


Hover detail



Still fighting against pitch-back moment

Trans-In Detail

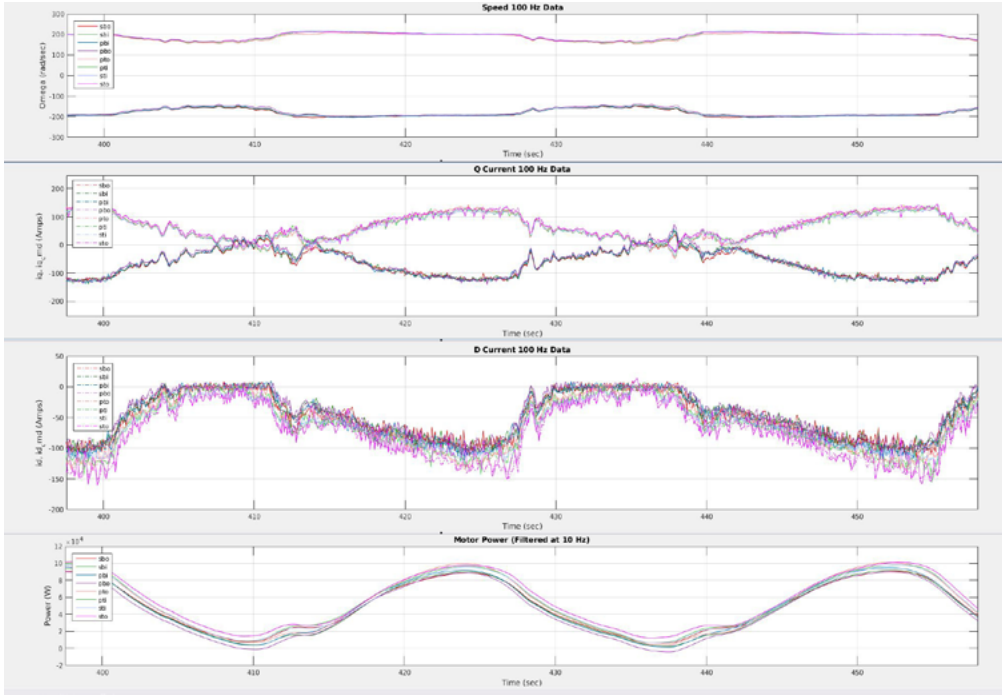


All motors operating at or near controller current limit as flow attaches

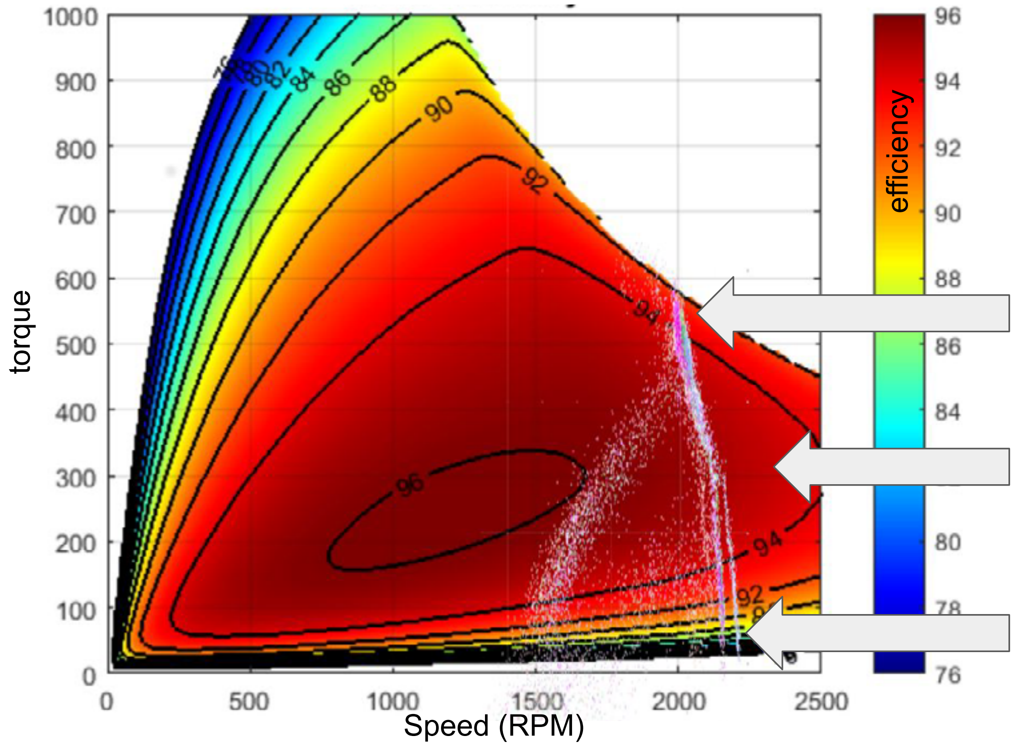
Command changes do not ramp smoothly (crossfade commands?)

At present limits of ground power

Crosswind detail



Crosswind detail

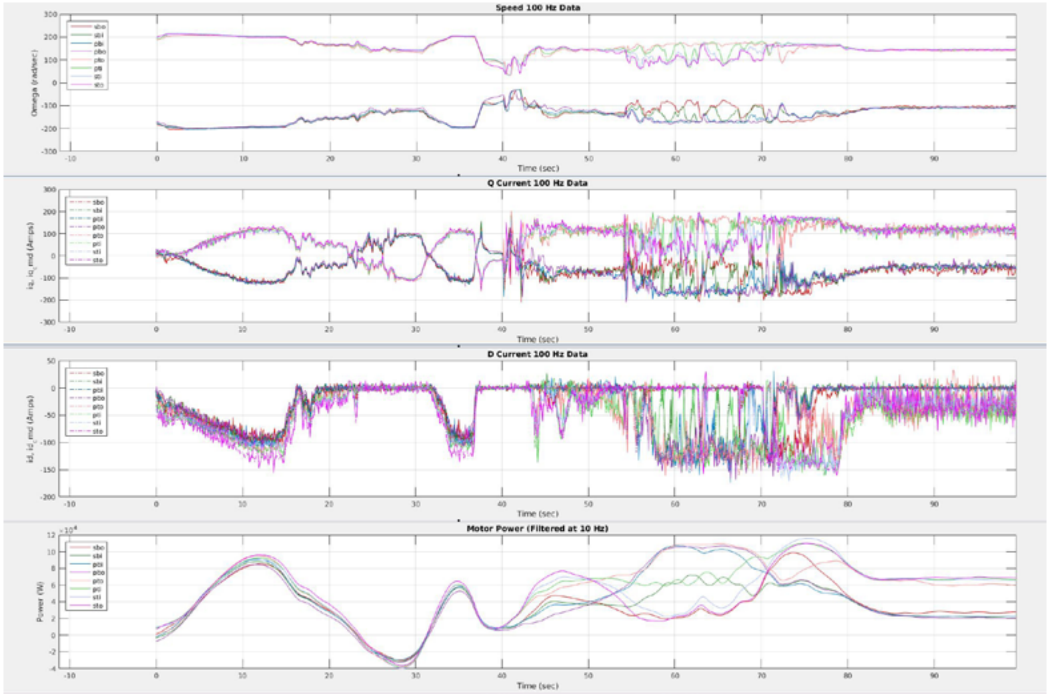


Longest dwell time at max power

Leaving power “on the table” due to omega limit in control code

Can see loop curvature as differences in prop speed across wing

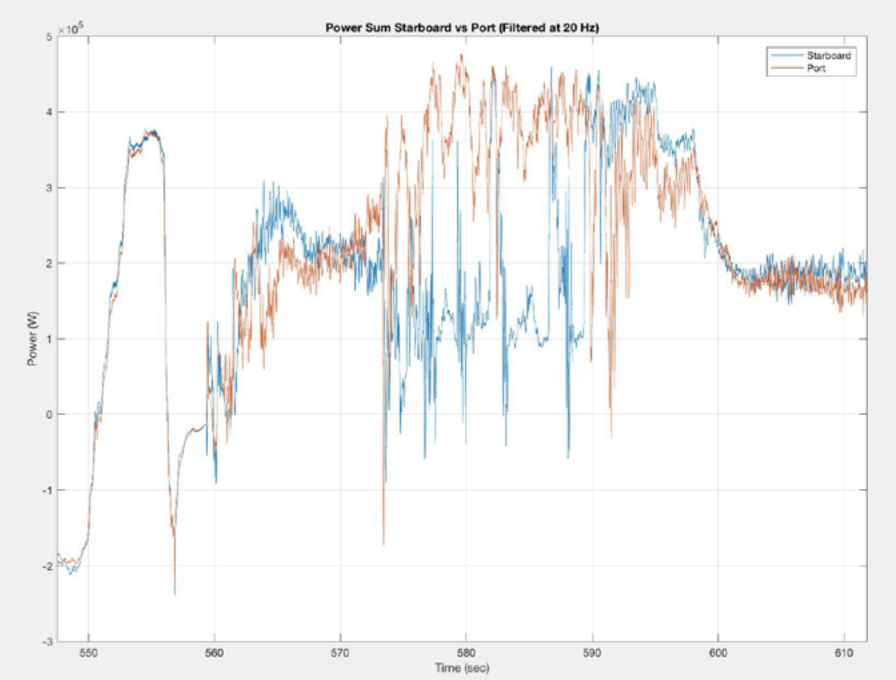
Trans-out detail



Rapid command fluctuations; can probably be improved

Battle between thrust and attitude during stationkeeping after trans-out

Port *vs* Starboard Power Diff during the Trans out fall



Large lateral difference in speed commands

BUT

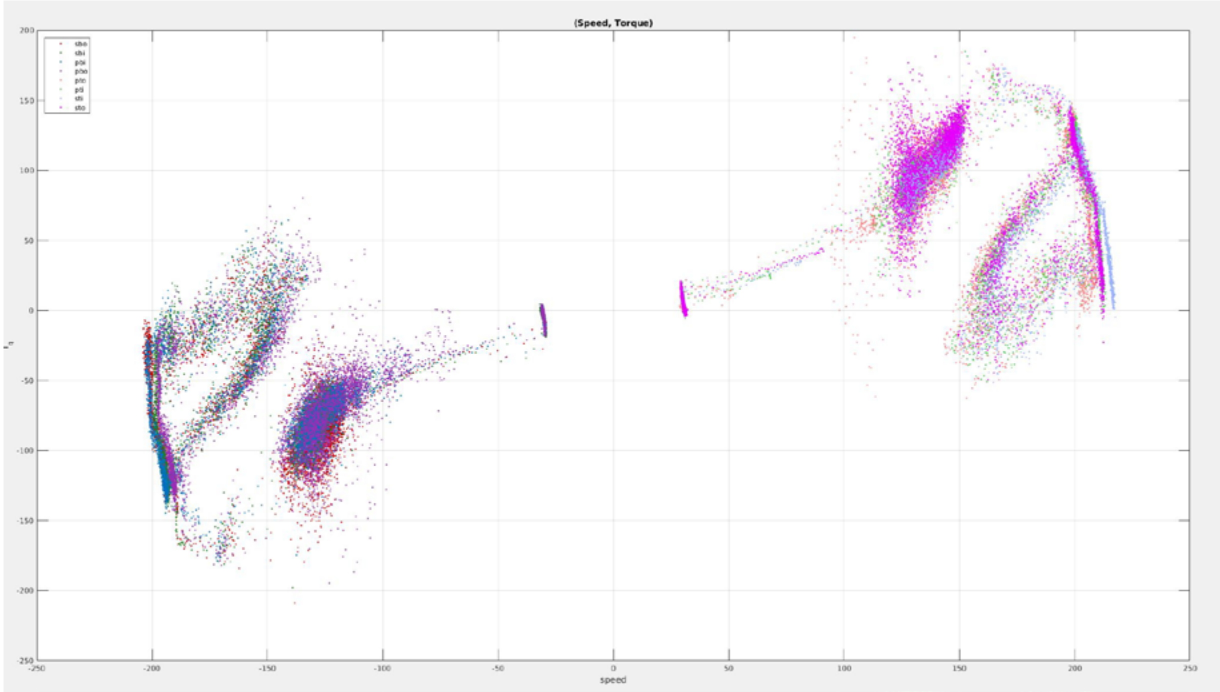
Difference in power is of the opposite sign

→ in extreme roll, are the downwind props less effective?? (same effect as pitch back during hover)

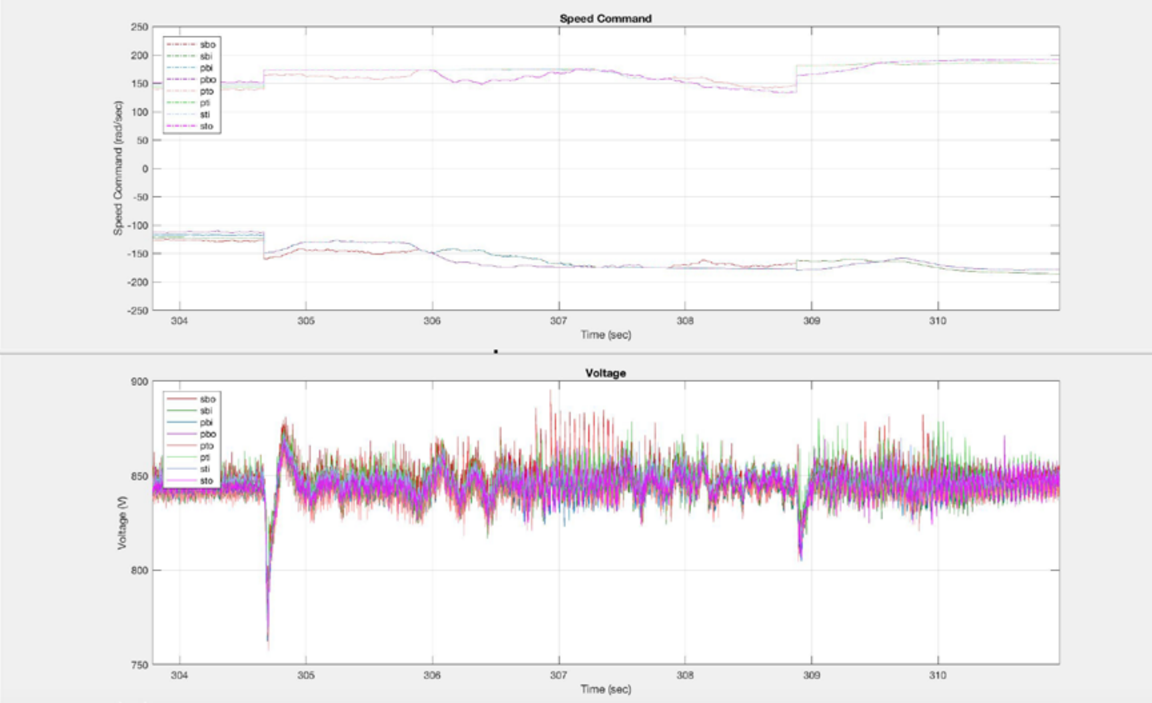
ALSO

Functional problem in hover tension controller at extreme roll angles

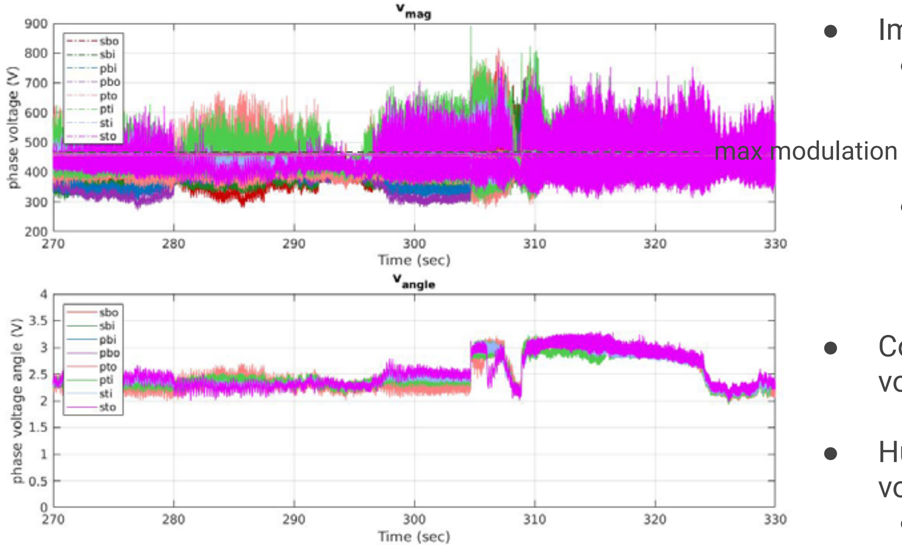
Speed and Torque (per motor)



Command Discontinuities with mode-switches

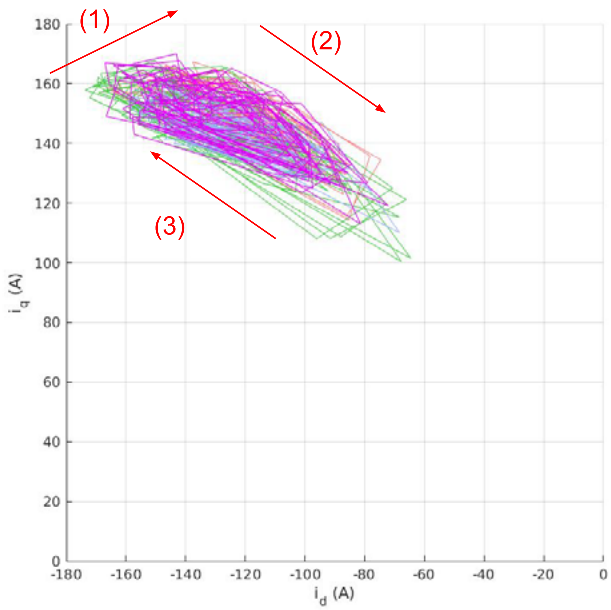


Flux Weakening



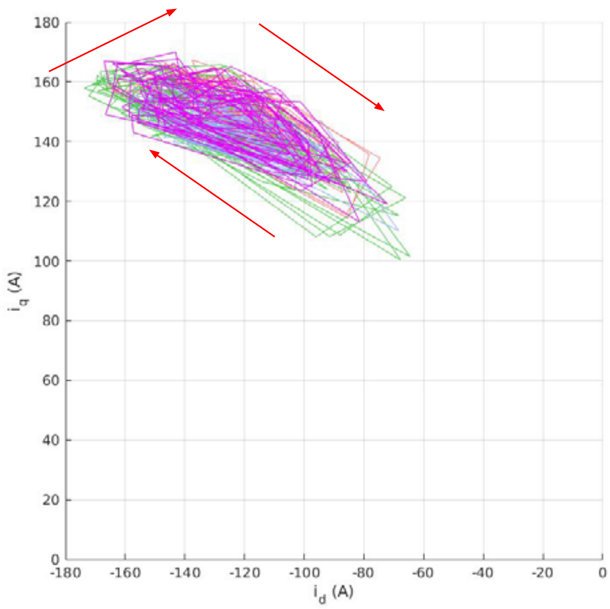
- Implementation notes:
  - Difference between pre-saturated and post-saturated terminal voltage is integrated to rotate i_d-i_q command.
  - Separate PI loops are used to control i_d and i_q in all operating conditions.
- Consistent 0.25 to 0.4 rad swing in voltage angle through all modes.
- Huge swings in pre-saturated phase voltage mag. when flux weakening
  - Consequence of poor current control.
  - Causes command to rapidly move back into the region of achievable (i_d, i_q).

Flux Weakening



- Plot to the left taken over 0.2s of trans-in.
  - (1) Angle error causes true voltage angle to decrease -> v_q increases -> i_q increases and becomes unsustainable.
  - (2) i_q and i_d collapse while the FW command angle increases.
  - (3) Command becomes realizable (and probably over corrects due to integrator and reversing angle error), resulting in rapid recovery.
- Working theory for poor control:
  - When not flux weakening, (fast) i_d and i_q PI loops are able to reject dq-frame angle errors and control phase current well.
  - When flux weakening, extra phase lag is introduced from FW angle integrator and behavior deteriorates as described.
- Known issue, but surprisingly bad during flight.

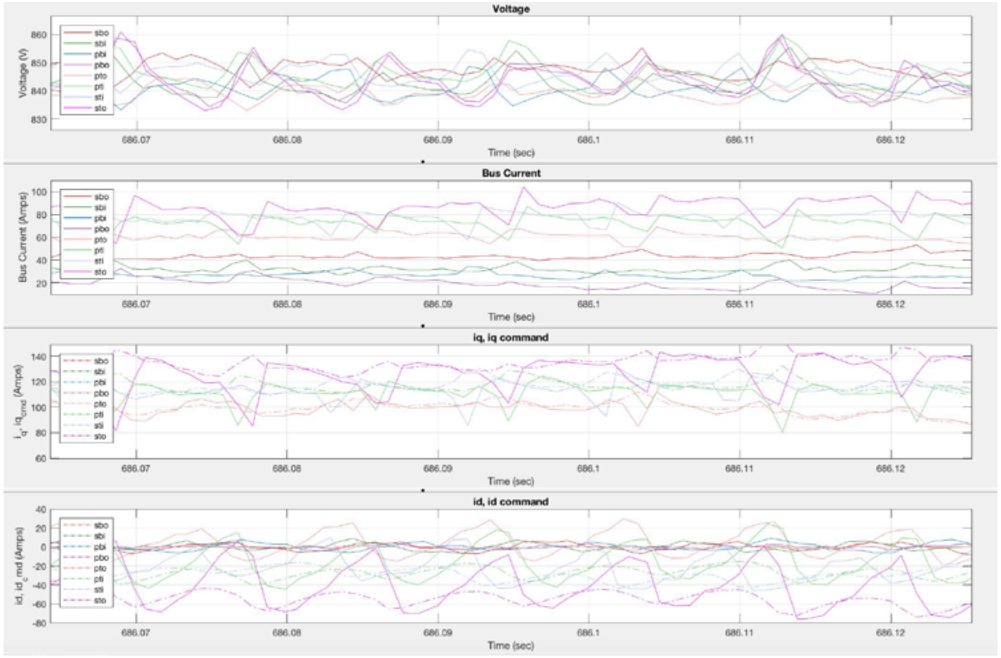
Flux Weakening

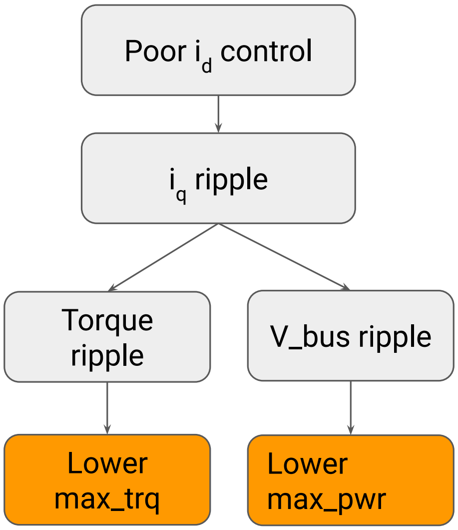


Fixes:

- Increase bandwidth of FW controller:
    - Will likely start strongly coupling into the d and q PI loops
    - Fundamentally limited by right hand plane zero for controlling actual changes in torque.
    - Not particularly well studied.
- Improve the motor state estimator:
    - Long standing TODO.
    - Angle error is dominated by 5th mechanical harmonic associated with ADC bias; relatively easy to improve existing code.
    - Complete sensor bias estimation and/or sensorless control are long term fixes.

Stacking (Half the motors in flux weakening)





Poor i_d control

i_q ripple

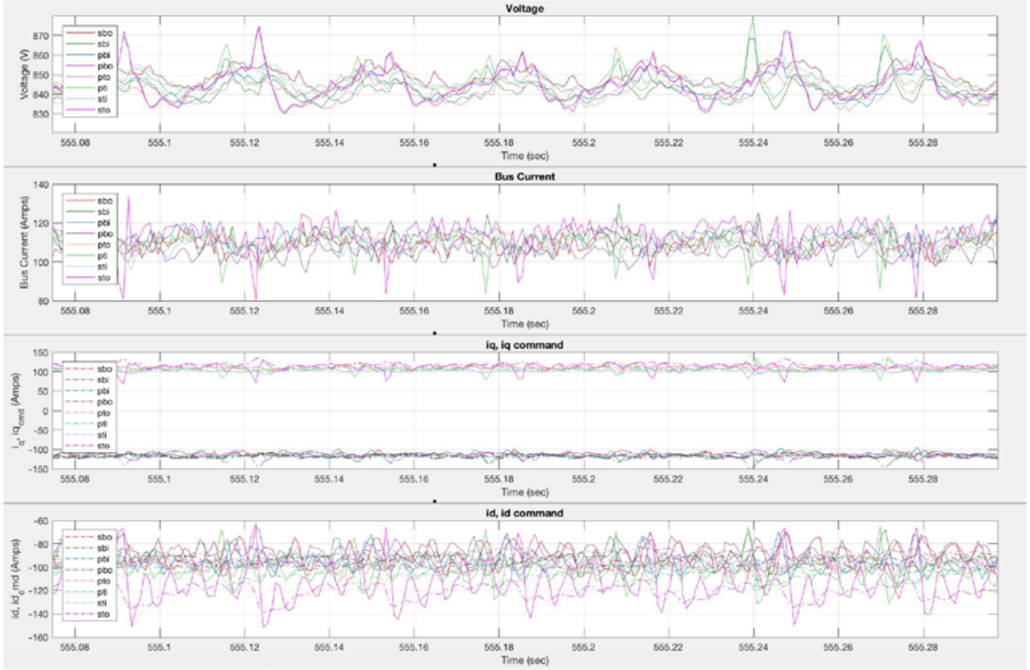
Torque ripple

V_bus ripple

Lower max_trq

Lower max_pwr

Stacking (All motors in flux weakening)

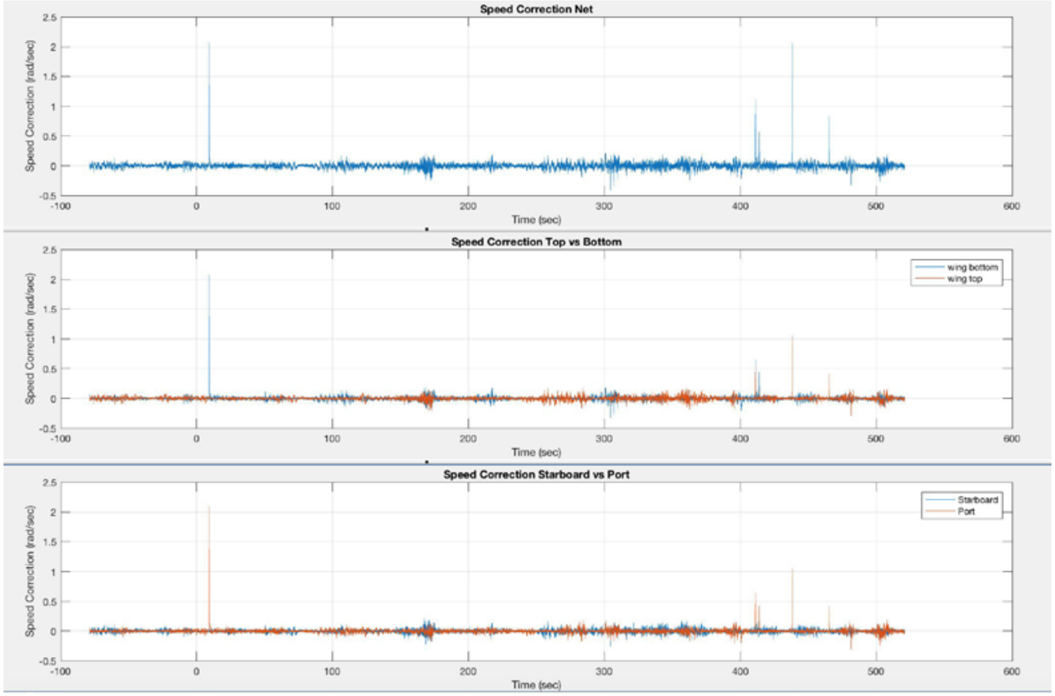


More bus voltage variation

Sync'd in pairs

At mechanical frequency

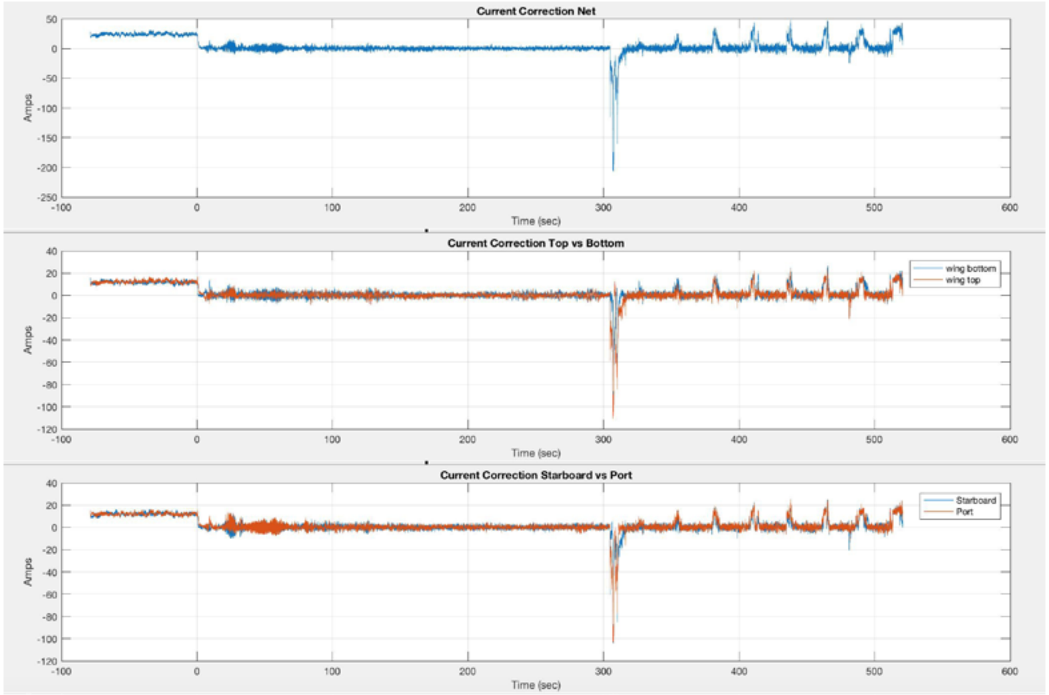
Stacking Speed Correction (first 500 seconds)



Net speed correction is minimal in Pitch, Yaw, and Thrust assuming linear prop curves. (sum of speeds)

Likely some small net contribution once prop curves and pylon locations are taken into account.

Stacking Current Correction (first 500 seconds)



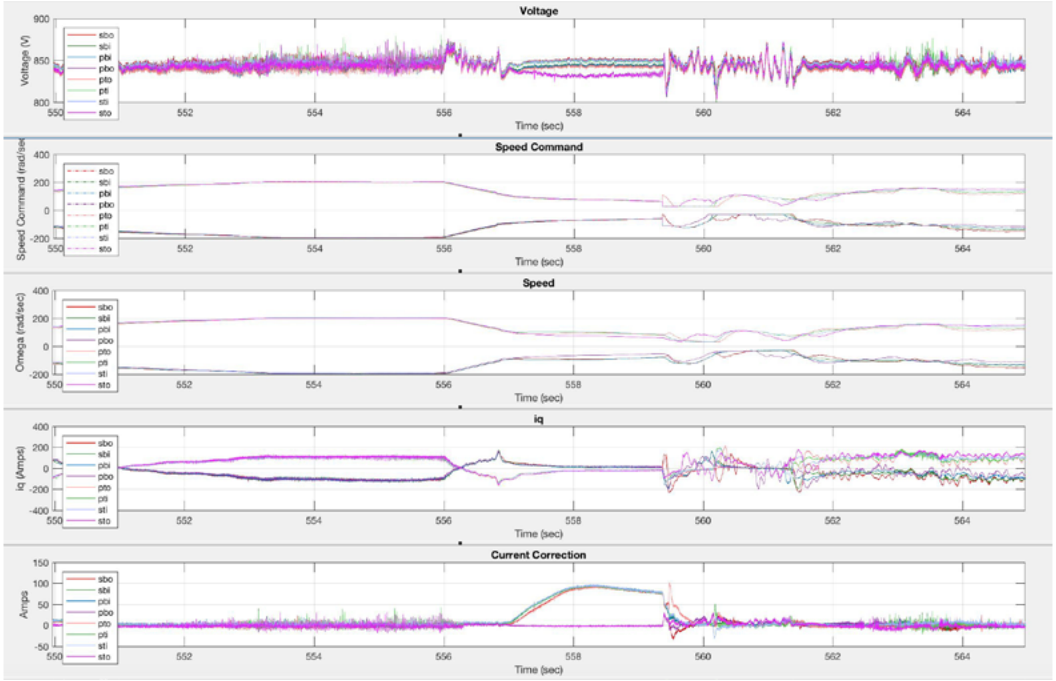
Some net correction in thrust.

Balanced in Pitch and Yaw (not weighting inner and outer motors and not including prop curves)

Big bump down reflects operation at power limit - noisy voltage from flux weakening and no room for positive corrections.

Positive bumps come from strategy to avoid stalling props in gen.

Largest Stacking Correction - Trans Out

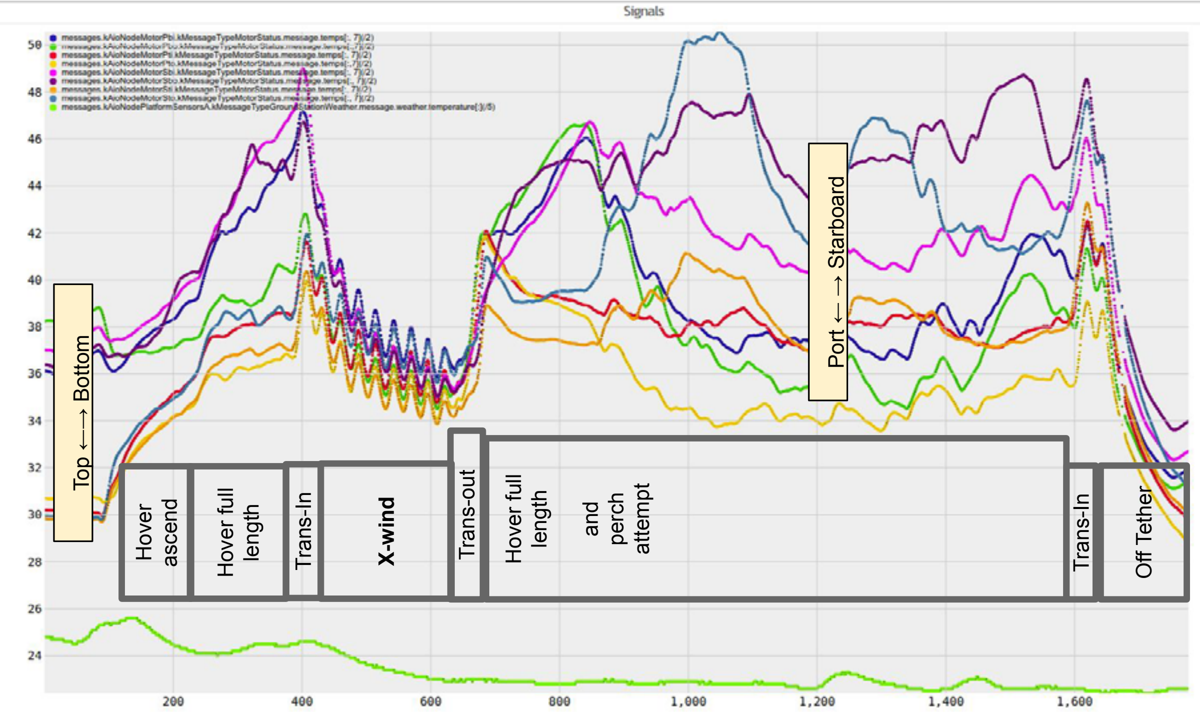


SBO and PBO end up at lower speed while stacking controller has to bump up other speeds to keep power balanced.

Bit of a mystery why that command needed such a strong correction.

Generally our command require little correction.

Motor Controller Thermal Behavior



At 40°C ambient:

Hover:

- Predict 20°C of headroom

Trans-in:

- Predict 5° headroom

Crosswind:

- Temps decrease and converge to 10-15°C above ambient.

Plot courtesy Justjeff

Motor Controller Capacitor Heat Rank by Position

1 = Hottest   8 = Coolest   ● = Gin3 Black

No discernible benefit to the higher emissivity paint

Motor Bearing Durability

“Clunking” sound now heard from SBO motor when reversing direction

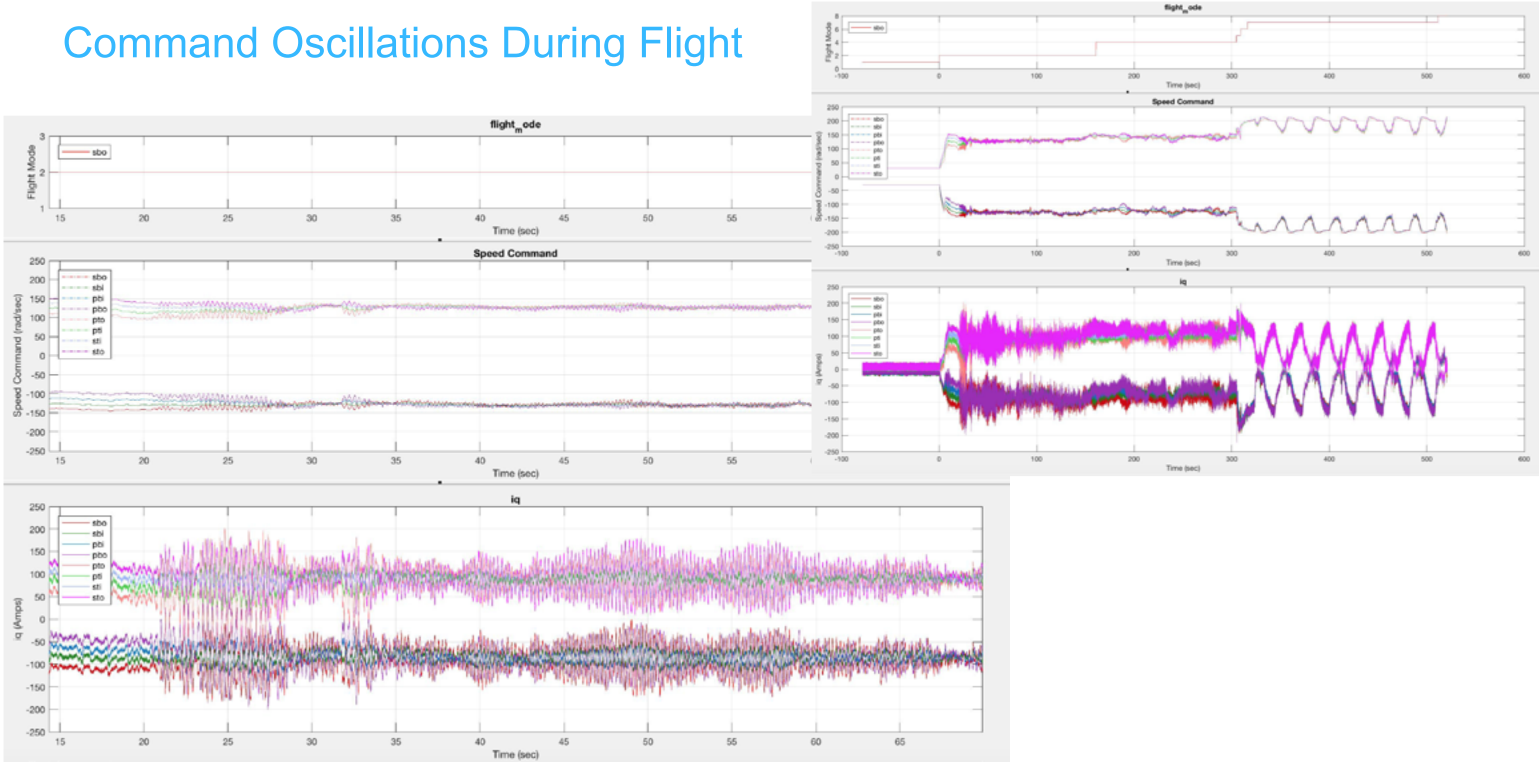
This is the motor that was hardest hit during RPX-01

YASA suspect, with limited information, the bearing

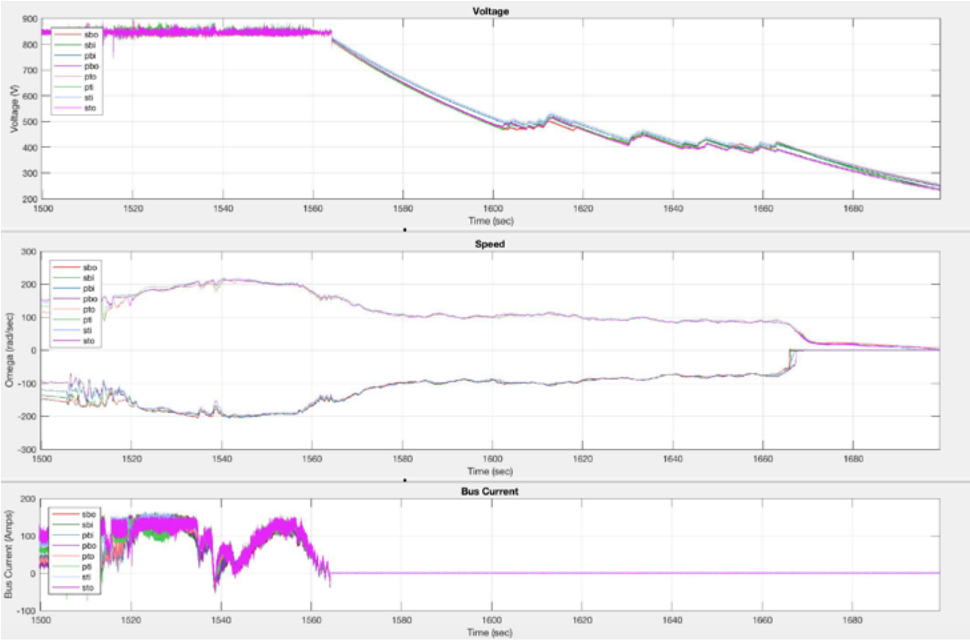
Hard landing of RPX-01 had unknown effects on bearing

- Were trying to measure for evidence of bearing deformation
- Motor gap inspection pending
- Debris check pending

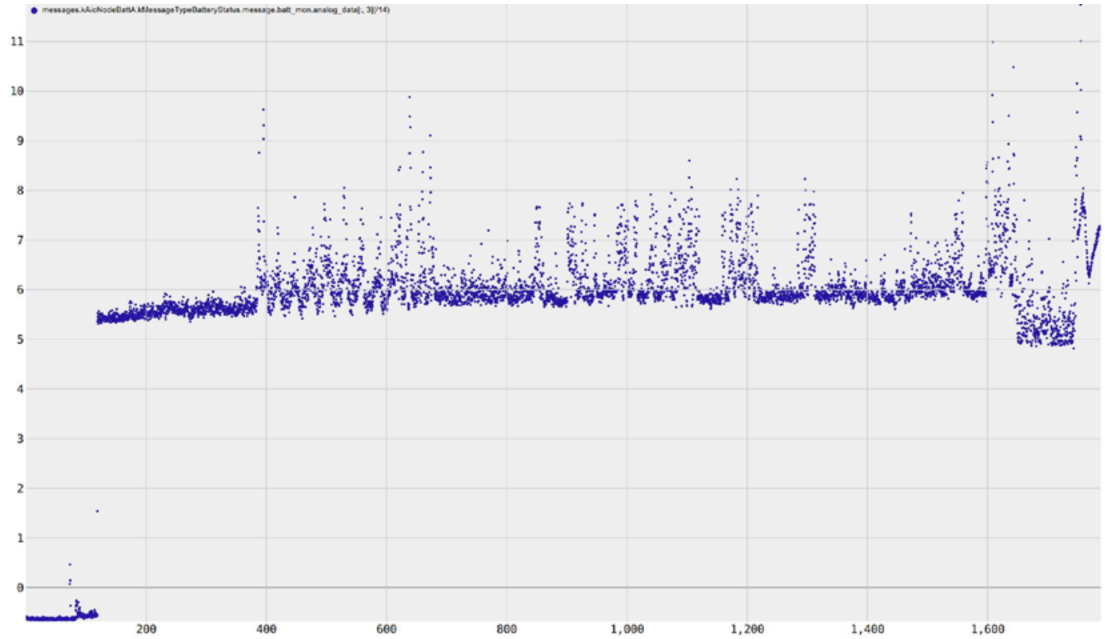
Command Oscillations During Flight



Motor Controller Post-Release Behavior



LV Bus Actual Loads / MVLV Specifications Review



LV bus designed for 15 A continuous current, 80 A surge current (duration 2 s).

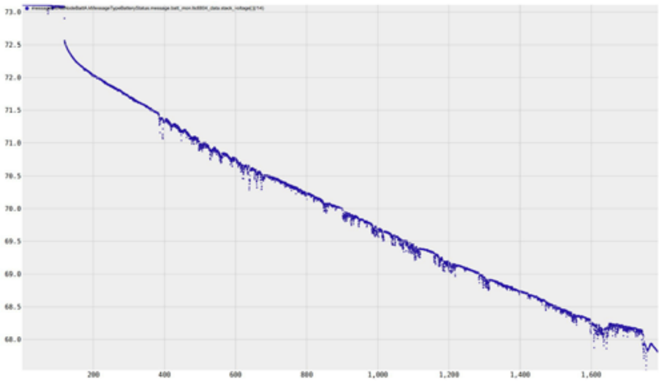
Average current, whole flight: 5.9 A

Avg current, first set of xwind loops: 6.1 A

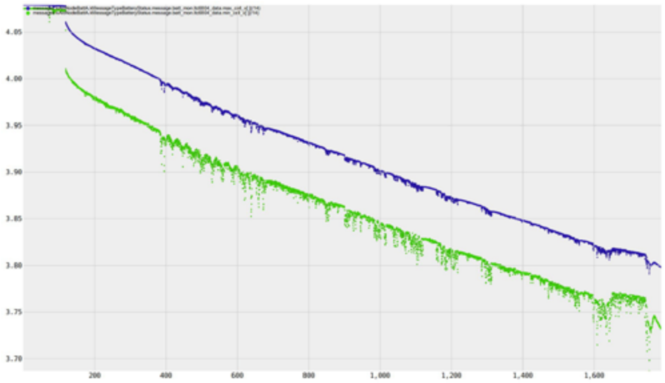
Highest instantaneous current: 14.8 A.

Battery Performance and Health Monitoring

For this flight, we flew with big box only (no small box connected to the bus -- no redundancy) because both small boxes at CL were over-discharged (new board rev to be added before next crosswind flight will eliminate the cause of this issue).



Big box discharged from 73V down to 68V over course of test (still mid-charge).



Min and max cell voltages over time.

Stuff we wanted to learn, but didn’t

Servo torque requirements at higher speeds and greater load variation

Performance with more generation

Hours, Hours, Hours...

Telemetry we don’t have, but should

(Needs more HW / SW)

- Ground power fast voltage / current logging
- Load bank / generator telemetry (proxy for grid usage)
- Better SOC estimation on batteries

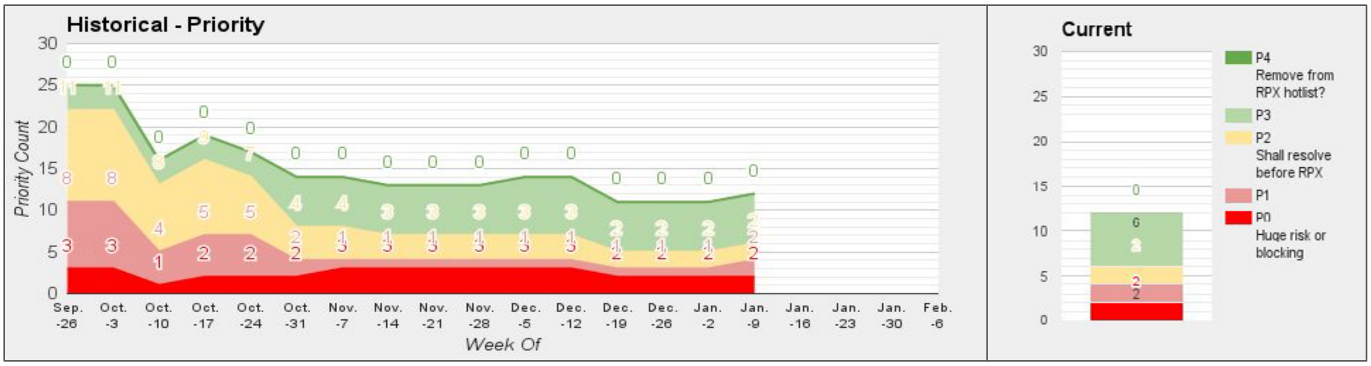
Things checked but not in this preso

Near-zero torque operation does not exhibit the torque fluctuations seen on the 8x8 dyno.

Autochecks TODO

- Detect evidence of pylon oscillation.
    - Large amplitude motor speed command fluctuations at 2-10 Hz.
    - Large 2-10 Hz swings in i_q.
- Detect premature saturation of speed commands by flight controller.
    - Not necessarily low hanging fruit; would have to compare flight computer telemetry with performance reported by motors.
    - Working on improving the motor mixing may be more beneficial.

Power Systems Dashboard



ARCHIVE

Open Bugs P0, P1, P2

- UNX controller failures
    - 2x common mode chokes (b/32118087, b/31588497) HIGH RISK
    - 1x 5 volt regulator (http://b/32312366) MEDIUM
    - 1x GDB PGOOD error (http://b/32617435) MEDIUM
- GIN3 uncertainties
    - Shoot through on controller after centrifuge testing (b/31996358) UNKNOWN
- Motor diagnostic logs on error (b/32745189)
    - Feature request / important for failure diagnosis / needs an ECR
- Grounding straps
    - Is being dealt with

UNX motor controller failures, GIN3

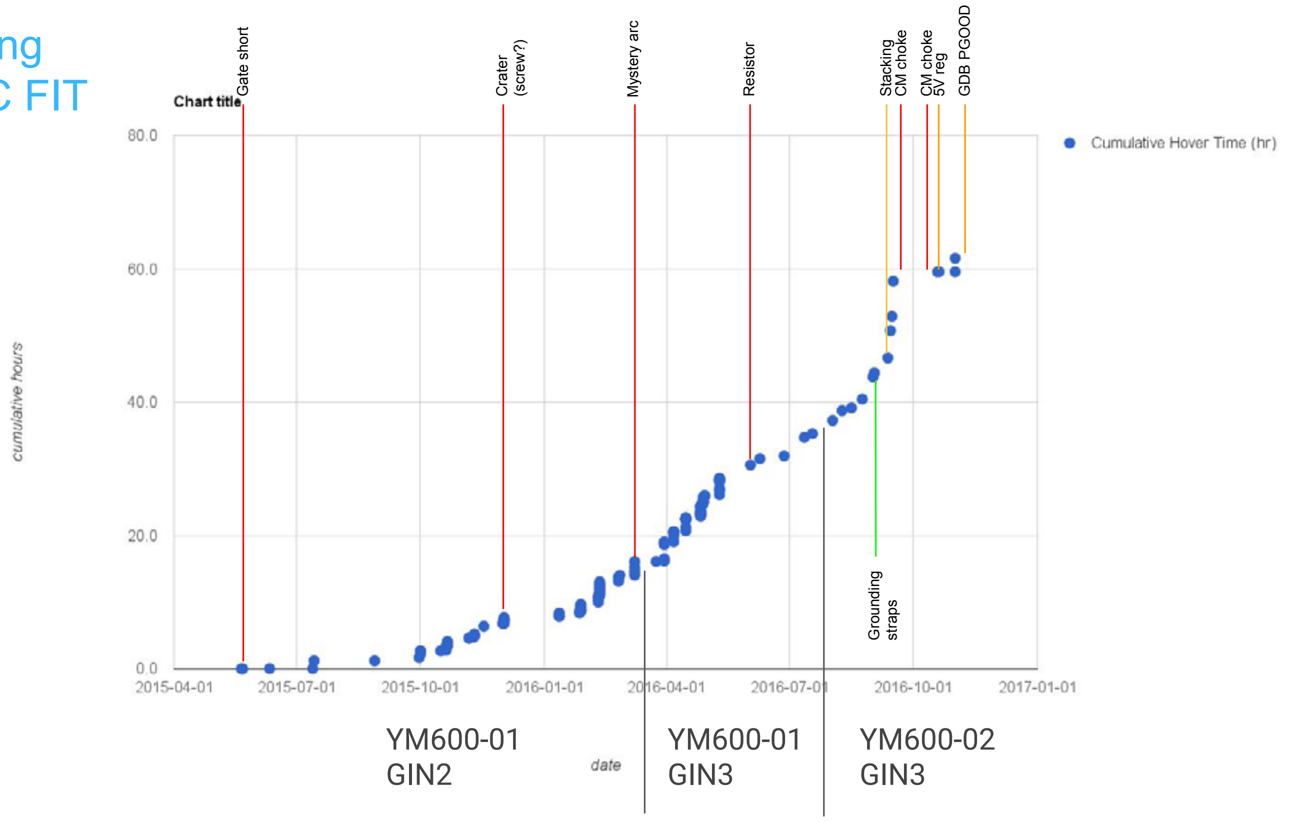
From RRR:

- b/28989455 - measurement resistor
    - UNX but has not recurred

New ones:

- b/31588497 - shorted CM choke, temp sensor, SBO, E-lot, 9/19, on powerup
- b/32118087 - shorted CM choke, pos sensor, STI, E-lot, 10/12, after shutdown
- GIN3 black:
    - b/32312366 - Failed 5V regulator
    - b/32617435 - PGOOD warning and poor current control
- Drifting angle sensor
- Power good warning on rel pylon

Wing MC FIT



Dyno

Total op time ~96 hours

Full power ~26 hours

CM chokes (full report [internal ref])

Failures:

- One on position sensor supply
- One on temp sensor supply (shouldn't normally be a severity 9 failure)

Possible causes considered:

- Stack position
- Wing position
- Partial discharge
- Chemical attack
- Vibration
- QC related:
    - Solder flux
    - Solder mask
    - Interconnect

Test approach:

- Hipot testing
- Dyno testing
- High CM testing
- Discharge testing
- Chemical compatibility testing
- Flux testing
- Dyno endurance testing
- Instrument SN1
    - Center resistor
    - Auxiliary ground straps
    - MV startup / shutdown

GIN3 black (5V regulator, PGOOD error)

Non-critical severity

Commonality considered:
- Stack position
- Wing position
- Partial discharge
- Chemical attack
- Vibration
- QC related:
  - Solder flux
  - Solder mask
  - Interconnect
- Anodized case

Test approach:
- Flux testing
- Dyno endurance testing
- Instrument SN1
  - Center resistor
  - Auxiliary ground straps

Monitoring:
- Log inspection
- i_0 warning flag
- Log analyzer (not done)

PGOOD errors

Wing
- New i_0 warning flag did NOT trigger
- → it is a failure to switch one of the power modules
- Cause currently under investigation
- Would not have crashed a wing

Rel nacelle
- Repeated problems with the Murata isolated DC-DC converter
- This is temperature related
- ALL IN SAME POSITION ???

YASA sensor drift

Tried and tried to reproduce:
- Hitting and yanking
- Calibrating at different bus voltages

Solid so far

Sensor is not likely physically loose (try to manipulate from outside)

Still working (many more high prio failures)
- Is it the motor or the controller?
- Temperature drift?

Validations (see document [internal ref])

- 8+8 dyno
    - Basic tests done
    - Augmented tests underway
    - No show-stoppers; will continue to run
- Powertrain GUT
    - Thermal characterization complete
    - Added humidity capability to REL1 container
    - Three UNX DC-DC converter failures
- 2 Tests not run
    - Thermal & GUT - LBB (although SBB is successful)
    - Trans-in stress test
        - In process, promising results
- Slip ring failures

8+8 Dyno

Dyno HITL testing status report available

Validity / fidelity
- Tested with full RPX ground power system
- Quality of prop model still evolving
- Comparison with desktop sim
  - Dynamics
  - Power throughput

Test coverage
- Basic tests
- Coverage assessment tool (need to fine-tune efficiencies)
- Stress tests
- Endurance tests

Known risks
- Prop performance unknown at high inflow rates
- Ground power system removed before completion of stress tests

To-do while waiting:
- Verify with flight gains
- More sweeps
- Investigate stacking divergence
- Better efficiency estimates
- Generation peaks bug

Powertrain GUT

Power good errors on motor controller GDB, rel nacelle
- Temperature related
- Always on A, always high side (WHY???)
- What is case temperature and capacitor temperature at moment of failure?
  - No reading hotter than 84°C
- Should be okay at ambient air temps <= 35°C (within our flight envelope)

Battery boxes

Peak load tests complete

Fuse blow tests complete

Minor risk: LV shutdown of a single box if a servo hard-faults at exactly the correct location

Faulty cell:
- Was detected by our health monitoring and replaced in time
- Working on more accurate health monitoring, but resource constrained

Slip ring hassles

Current state of affairs
- Our first “golden child” failed (leak)
- We have the last remaining “golden child” on the tophat now (many hours of current, no rotation, no temp extremes)
- Prognosis for this unit is unknown at CL (temp extremes)
- We will do hipot testing before every test day at CL
- All existing designs suffer from mercury amalgamation failure mode.

Gamma testing ongoing
- NOT LOOKING PROMISING

Developing a second source

We have two notional designs on the board -
- Better mercury design
- Traditional copper-graphite design
    - Don’t need high speed
    - Don’t need low noise
    - Problem: wear and conductive dust

Risk Registry

- 10x 1 or 0
    - None believed to be serious risk
- 3x 3
    - Motor controllers
        - Significant risk
        - Unexplained
        - Getting worse
    - Ground power failures during flight
        - Audited inverter configs and suppressed irrelevant faults
        - Retiring risk with Dyno and flight testing
        - Consider demoting to “1”
    - Slip ring
        - Retiring risk with flight testing
        - Still significant, but perhaps demote to “1”
        - Three options being pursued

What we want to learn

- Actual motor power / torque demands during flight
- Cooling effectiveness during forward flight
- Motor bearing durability
- Performance in high lateral G-loads:
    - Controller
    - Cooling system
    - Capacitor box
    - Motor and mounts
- Power variation during flight (important for flicker mgt, later)

Executive summary

RISKS:
- UNX motor controller component failures
- Slip ring

RECOMMENDATION:
- Go fly, but be aware the risk is significant

BEFORE FLIGHT:
- Take all available “simple” steps to minimize risk (grounding straps, etc)
- Test-runs on perch -- half power or whatever is available

WHILE WAITING:
- Aggressive testing, chasing down UNX failures
- Prioritize SN1 for controller testing purposes (position dependence, grounding, …)
- Prepare several spare powertrains with GIN3 (silver batch)
- Continue retiring risk with 8+8 dyno
- In parallel, rework stock of junk on shelf (can get 9 more units pretty easily)
- Centrifuge under power
- Slip ring jumper plan

MAKANI

Flight Testing
RPX-02 Lessons Review

Jan 11, 2017

Executive summary

- Waiting for wind (W4W) when forecast is marginal is resource-intensive, but was worth the results.
- Still new to M600 crosswind, so still streamlining processes and tools: cameras, command center, data tools...
- We want your input to set distinct and valuable flight objectives for the next crosswind attempt.

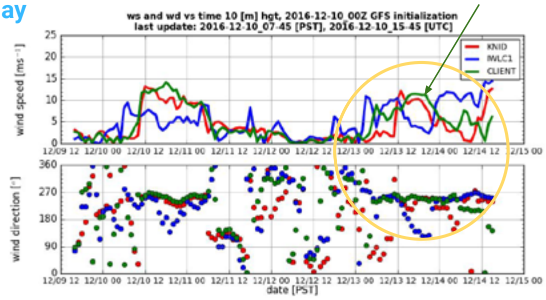
Outline

- Wait-for-wind
  - Procedures
  - Cameras
  - Overnight tie-down
- Command center operations
  - Dryrun procedures
  - Flight conduct
  - Inadvertent switch to hover-accel
  - Command center location safety
- Flight data and monitors
- Things that broke
  - BattB and the Rocketbox
  - Containerhenge net
- **Next flight objectives**

Wait-for-wind

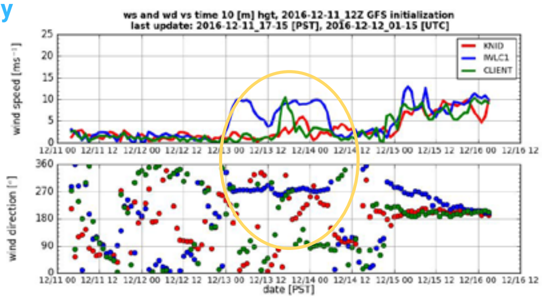
Our site is the green line.
We're looking for 3-9m/s
from 270deg.

Saturday 12-10

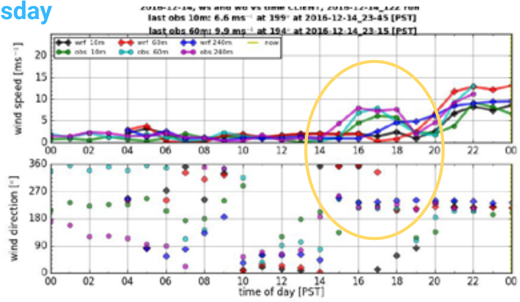


Tuesday 12-13

Sunday 12-11



Wednesday 12-14



Wait-for-wind: procedures

Waiting-for-wind overall

- 20 people on-site, MTW 7am-7pm
- Marginal forecast
- Paid off! For a high-return flight

Checklists

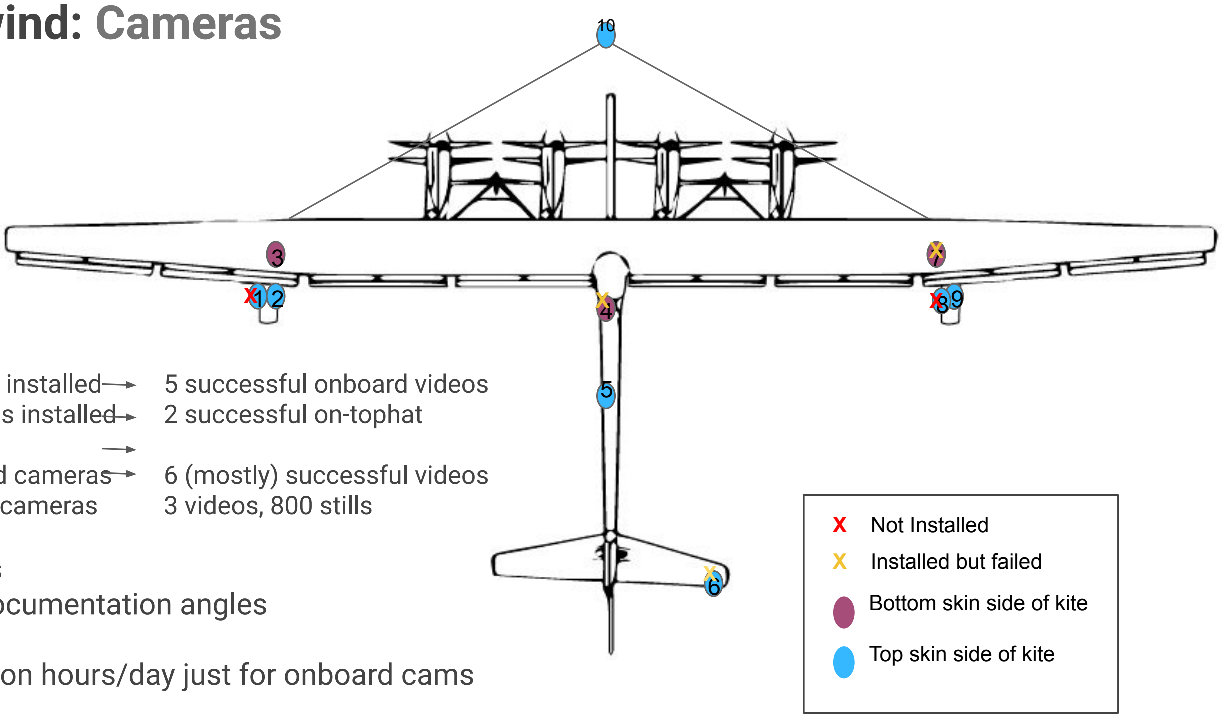
- Fair, but cleanup pending
- Adapt to multi-day+multi-operator
- Cameras are most time-consuming: distributed, need charging and data refresh

Overnight set-up

- Tiedown improvements
- Generators left on to collect data but led to damaged equipment

WAITING FOR WIND - morning						LDAP	Notes
Wing mechanical	**Wed 12/14**	**12/14**	**Tues 12/13**	**12/13**	**12/12**	**12/12**	
check for nests or water	X		X		X		
connect LV disconnect to weight	See I		X	mquick	🟥		12/14 still connected
Starboard lift, Top skin side							
Inspect STI prop and Spinner	X	breichle	X	breichle	X	breichle	
Inspect STO prop and Spinner	X	breichle	X	breichle	X	breichle	
Install and start STO, and star wing slamstick	X	breichle	X	breichle	X	jimmyhaley	
P1: Attach GoPro on top of fuselage facing pylons	x	breichle	x		x		
P2: Attach GoPro on starboard perch peg facing wingtip	x	breichle	x	breichle	See Note	breichle	battery only, no camera
P2: Attach GoPro on starboard perch peg facing fuselage	ee Note	breichle	x	breichle	See Note	breichle	12/14 no camera it is defective
Start all cameras, confirm red light is flashing	x	breichle	x	breichle	See Note	jimmyhaley	cameras not installed yet, not on
Starboart lift, Bottom skin side							
P2: Attach GoPro in starboard perch peg cavity facing bridle point	x	breichle	x	breichle	See Note	jimmyhaley	battery only, no camera
Inspect SBI Prop and Spinner	X	breichle	X	breichle	X	breichle	
Inspect SBO Prop and Spinner	X	breichle	X	breichle	X	breichle	
Start SBO prop Vlink	X	breichle	X	breichle	X	jimmyhaley	
Start STO prop Vlink	X	breichle	X	breichle	X	jimmyhaley	
install and start SBO slamstick	X	breichle	X	breichle	X	jimmyhaley	
remove tag line hoist rings (5/8" allen?)	X	breichle	X	breichle	X	jimmyhaley	
Port lift, Top skin side							
remove pitot cover, conduct pitot checks w/command center	X	allenwrench	X		🟥		
inspect PTI prop and spinner	X	allenwrench	X		X		
inspect PTO prop and spinner	X	allenwrench	X		X		
P1: Attach GoPro on port peg view of midwing tufts	x	allenwrench	x		x		
Start all cameras, confirm red light is flashing	🟥		x		x		
Port lift, Bottom skin side							
P0: Attach GoPro on tether termination facing down tether	x	allenwrench	x		x		
P3: Attach GoPro on bottom of fuselage facing bridles	x	allenwrench	x		x		
P1: Attach GoPro in port perch peg cavity facing bridle point	x	allenwrench	x		x		
Inspect PBI Prop, Spinner, and nacelle. Look for evidence of							

Wait-for-wind: Cameras



8 onboard cameras installed → 5 successful onboard videos
3 on-tophat cameras installed → 2 successful on-tophat videos
→
6 unmanned ground cameras → 6 (mostly) successful videos
4 personed ground cameras 3 videos, 800 stills

21 total cameras
17 successful documentation angles

W4W = ~16 person hours/day just for onboard cams

Wait-for-wind: Cameras

What worked

- Having enough camera people
- Processes for quickly installing cameras & handling media
- Equipment and checklist improvements
- Training entire team on gopros

Issues

- Setup time is long, maintenance is tedious
- Camera positions could be improved
- Battery life is being addressed both onboard and on the ground
- Long delay in Navy approval process (holiday)
- Messy transfer process for footage between ALM and CHL
    - Revisit server sync with Rooster
- **Determine new camera locations based on team feedback**

Wait-for-wind: ground cameras

203 youtube views — 18 minute flight summary

Wait-for-wind: onboard & tophat cameras

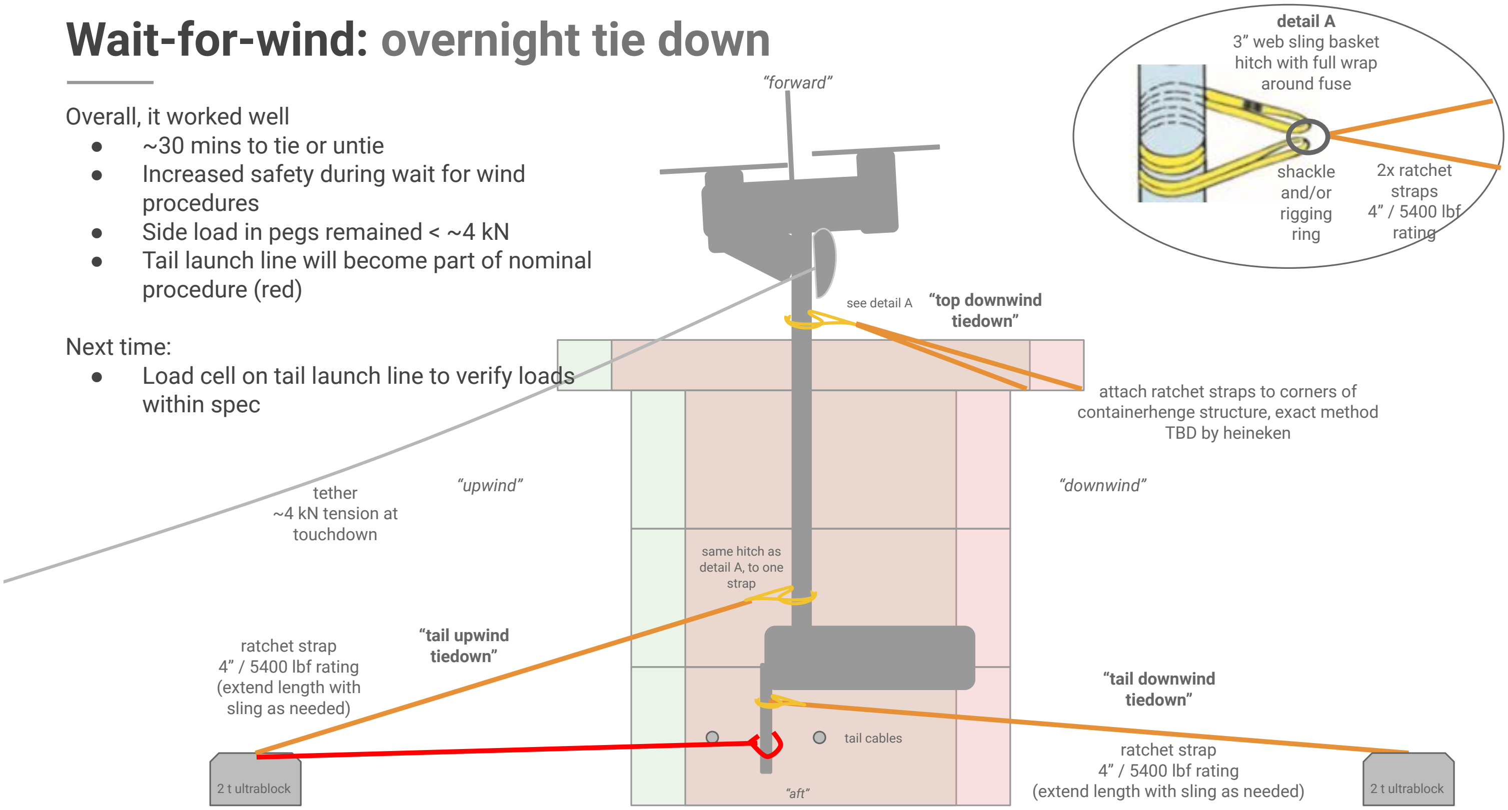
Wait-for-wind: overnight tie down

Overall, it worked well

- ~30 mins to tie or untie
- Increased safety during wait for wind procedures
- Side load in pegs remained < ~4 kN
- Tail launch line will become part of nominal procedure (red)

Next time:

- Load cell on tail launch line to verify loads within spec



"forward"

detail A
3" web sling basket hitch with full wrap around fuse

shackle and/or rigging ring

2x ratchet straps
4" / 5400 lbf rating

see detail A

"top downwind tiedown"

attach ratchet straps to corners of containerhenge structure, exact method TBD by heineken

"upwind"

"downwind"

tether
~4 kN tension at touchdown

same hitch as detail A, to one strap

ratchet strap
4" / 5400 lbf rating
(extend length with sling as needed)

"tail upwind tiedown"

"tail downwind tiedown"

tail cables

ratchet strap
4" / 5400 lbf rating
(extend length with sling as needed)

2 t ultrablock

2 t ultrablock

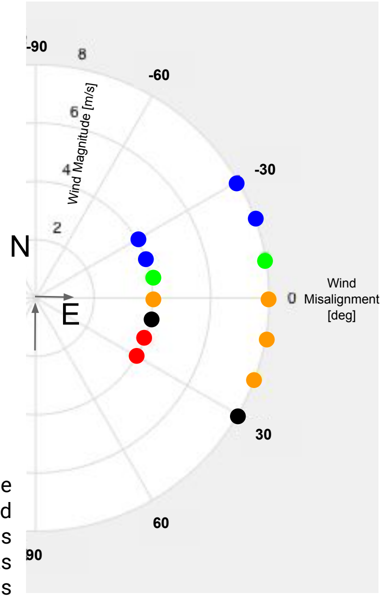
"aft"

Command center operations

- Several (cw-system) dryrun procedures not consistently documented
    - Pitot
    - Detwist
    - Loadcells
    - Servos
    - Tether release (b/33620965)
    - Motor spins (duration, speeds, throttle changes)
    - Long HITLs with motors? Can't get past HoverFullLength in dry run...
    - Command Center systems: GigE cameras, UPS
    - GS02
- Lost "Manual" Flight Plan, useful to throttle up and down with the joystick (b/33701895)
- What can we do in dry run that will reduce the risk of the crosswind phase of the flight?
- Command center flight conduct
    - Functional if not Optimal
    - Observation->execution is good
    - Overall situational awareness (SA) improved Post-RPX-01
    - Address decision making
    - Distribute workload/scan
    - Assess urgency of real-time decisions
    - **Action: Revisit CRM and Crew Coordination in Rehearsals, Consider CRM training**

Command center operations

- Inadvertent switch to HoverAccel
    - Large motion (10+ clicks) stabilized PilotHover->HoverFullLength.
    - Small motion (2-3 'clicks') HoverFullLength->HoverAccel (~5-7 mm @ top of stick)
    - Very easy to overshoot
    - **Action(s?): [internal ref], "Unload the Throttle" and b/33675261, "Determine joystick interface changes for next flight"**
    - **Proposed HoverAccel gate switch and command line to force accel**
- Update on safety/procedures/monitors during TransIn/Crosswind
    - Monitors show termination impact zone (AKA 'wedge of doom')
    - *Indicated* RPX-01/02 exposure time 0.0 sec
        - Termination landed well short of 'throw'
        - NW winds significantly worse for exposure
    - **b/33178471, "Command center safety/location in China Lake"**
    - **Action: "Is it safe?"** (Marathon Man, 1973)

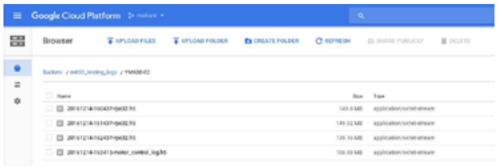


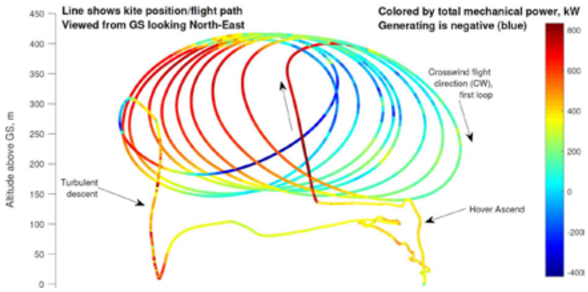
CC Exposure Time Variation w/Wind
Red: > 3s
Orange: > 2s
Green: > 0s
Blue: = 0s
Black: No Launch
Source: Simulation

Flight data

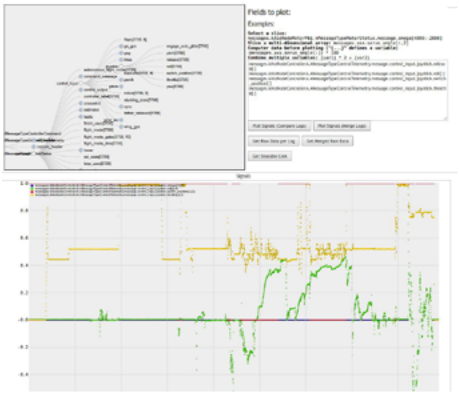
How is the broader team using flight data?

1. Download from Google Storage [internal ref]
   - 10 minutes, all telemetry, h5 files
   - Analysis in python or MATLAB





2. Use log plotter at [internal ref]
   - Plot a handful of variables on the web app
   - Concatenate a couple of logs
   - Download JSON files



3. Query all flight data: SQL tool for ColumnIO [internal ref]
4. Program checks with the log analyzer [internal ref]

Flight data

Scenarios and use cases

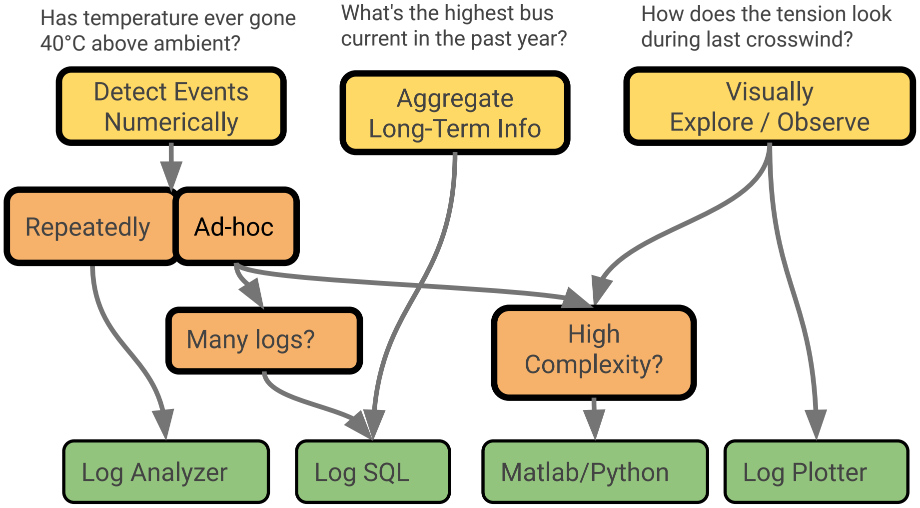
- Validate simulations
- Detect anomalies
- Check performance and operating conditions
- Forensics/Past patterns and trends

What may help:

- Publish a merged log
- Publish time 0 for all the plots.

Plan for a more comprehensive process

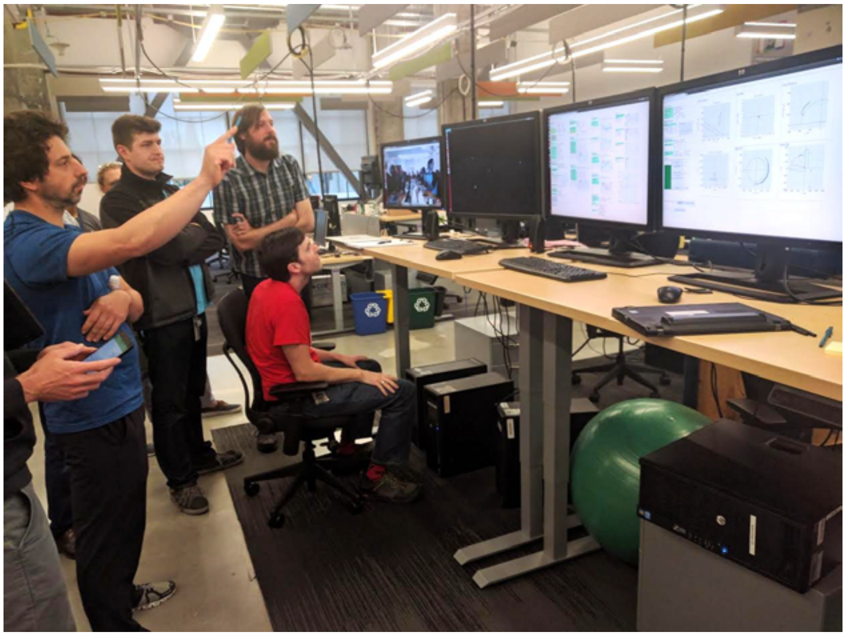
- Use buganizer to propose/dev analytical checks (need help from other teams, see buganizer hotlist)
- Increase analytics coverage of all telemetry fields
- Educate the usage of current tools, automate & improve



	Log Analyzer	Log SQL	Matlab/Python	Log Plotter
Cloud Service (No need to Download logs)	✓ Cloud Storage	✓ ColumnIO Database	🟥	✓ Cloud Storage
Export Data	🟥	✓ CSV	✓	✓ JSON
Aggregation	✓ Many Logs (OK speed)	✓ Many Logs (Fast)	▲ A few logs	▲ Up to tens of logs
Analysis Complexity	✓ Any Math	▲ Basic Math from SQL	✓ Any Math	▲ One-line Math (Numpy)

Flight data: monitors and remote viewing

- Monitors
  - Webmonitor performance was good
  - Balance continuous iteration with command center experience
  - Fix counter for crosswind loops
  - Address layout/indicator requests
    - detwist indicators
    - air density indicator
- Zephyr and RLS viewing
  - Good:
    - One crew at each site
    - Realtime commentary and Q/A was good!
  - In Progress:
    - Move RLS viewing to a room
  - Need:
    - Webcam + audio input for ALM-RLS communication.
    - A layout for a general audience



Loss of generator left ON overnight

Problem 1: Left the wing batteries connected overnight

- The batteries took over until they were almost depleted.
- By morning, the small backup battery was dead.

Solution:

- Disconnect the small battery (in software) when leaving the wing powered on the perch.

Problem 2: Wrong voltage input to the Rocket Box

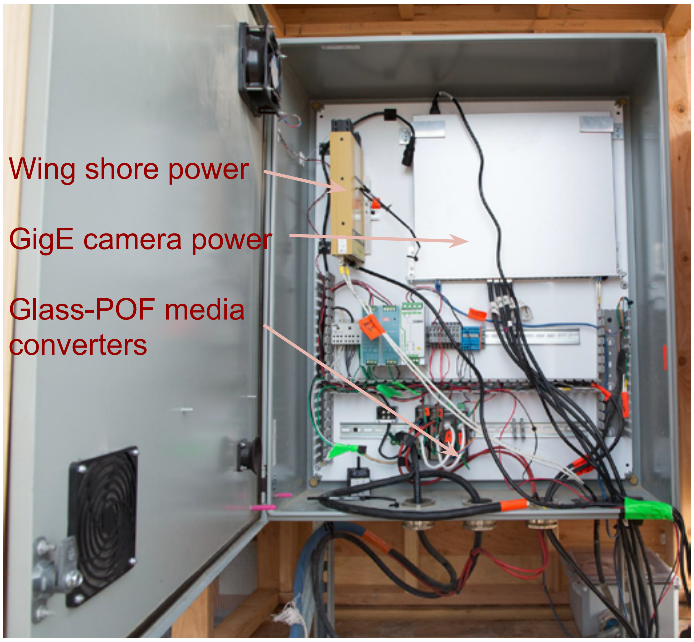
- 480V was provided instead of 240V, killing 1 Acopian, 1 Ubiquity switch and 2x 12V transformers.

Solution:

- Only use a medium Honda generator with expanded fuel tank to power the Rocket Box (240V only).

Lessons learned:

- Don't make "*improvements*" on a test day on something that works (Honda generator was working...)
- Spares in CL are essential, need to monitor the inventory.
- Need to have procedures to swap power generators that would include checking/probing voltages.



Rocket Box

Port net damage during launch

video “20161214 RPX-02 - Visualizing Airflow with Tufts“ on YouTube playlist
b/34198764

Problem:

- Rapid radial motion caused high energy impact into rear cable of net, breaking connector on inboard end of cable

Action pending full inspection of nets:

- Best case
    - Fittings are sacrificial and replaceable
- Worst case
    - Cables are damaged and stronger replacements must be sourced

RPX-03 flight objectives

- Correlate simulation
    - Crosswind tension discrepancy
    - Trans-in performance
    - Improve air speed measurements in crosswind and hover (wingtip pitot tube)
    - Mainplane aero measurements (ZOC box)
    - Thrust measurements to improve rotor tables

- Make more power
    - Gen4 props
    - Move bridle box
    - Smaller EoP box
    - Controller changes (flight path, etc)

- Improve flight characteristics → no pilot hover
    - Improve confidence in trans-out
    - Decouple pitch-roll
    - Active roll control
    - Avoid vortex ring state
    - Improved hover tension control
    - Squash yaw oscillations
    - Land on Containerhenge

Ground Station
RPX-02 Lessons Review

Jan 18, 2017

Executive summary

Overall a successful flight with no immediate concerns which would prevent the next flight

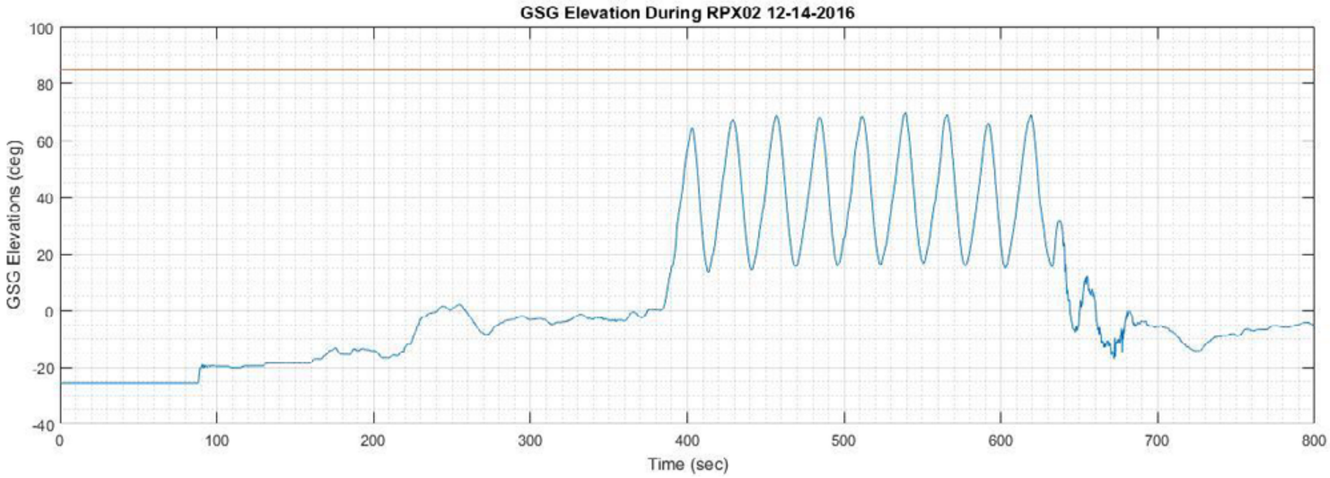
GSG Motion
- Nothing stands out as critically out of the ordinary
- Upcoming simulation correlation will help determine if the tether minimum bend radius is being encroached upon
- Higher levels of thrust help prevent reductions in tether tension, likely resulting in better than expected tether bending

Detwist
- Detwist torque considerably higher than anticipated, likely due to torque induced from the tether, shaft seals and rear main bearing
- Torque measurements suggest the servo will have enough torque to continually detwist until 140 kN and intermittently detwist until 190 kN

Top Hat Motion

Elevation

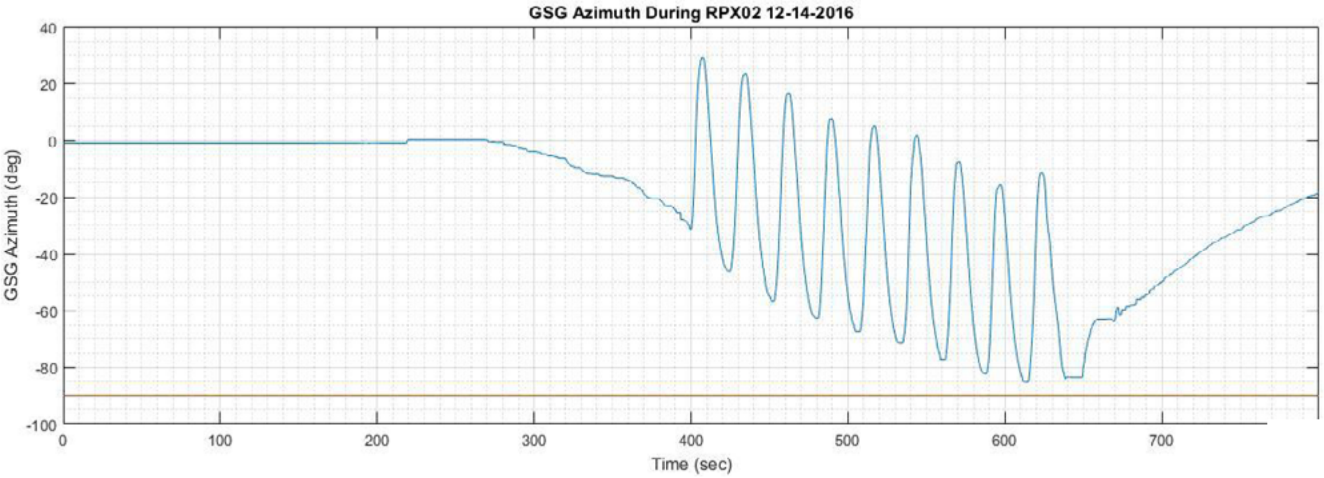
- Hard limit at 85° due to physical limitation of the Elevation Head range of motion
- Maximum angle achieved approximately 70°
- Motion in line with expectations - no concerns



Top Hat Motion

Azimuth

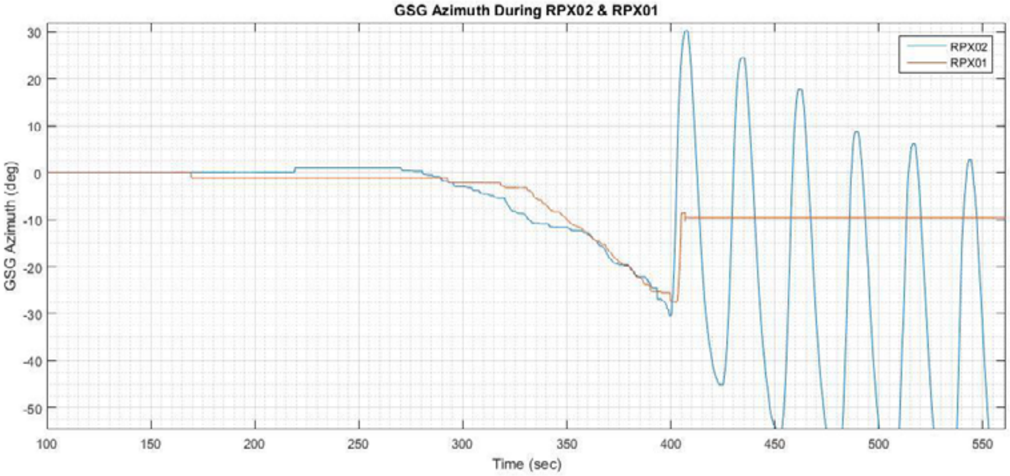
- Hard limit at -90° due to interference with the wind mast and cable tray
- Maximum azimuth motion was within 5° on its last loop, bug 34176608 initiated to prevent exceeding this and to investigate potential to open this window further - see video from last loop in “20161214 RPX-02 - Groundside Gimbal & Tether Attachment” on YouTube playlist



Top Hat Motion

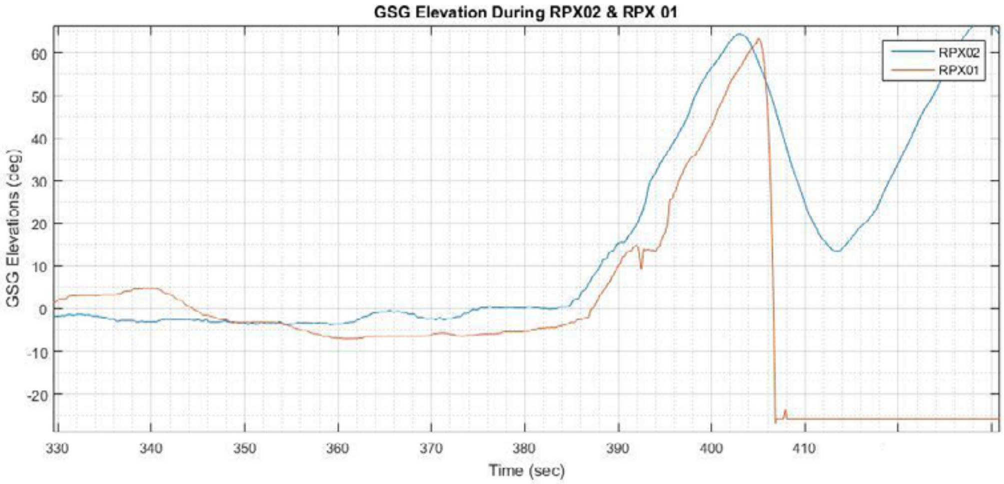
Dynamic Contribution to Tether Bending

- Controls group continuing efforts on correlating the flight simulation with test data (bug 342792263 found here)
  - Bend radius projections following the completion of this effort
- Azimuth slewing rate during RPX02 similar to RPX01
- YouTube playlist video “20161214 RPX-02 - Tether Dynamics“ from the BSR perspective shows nothing concerning during trans-in



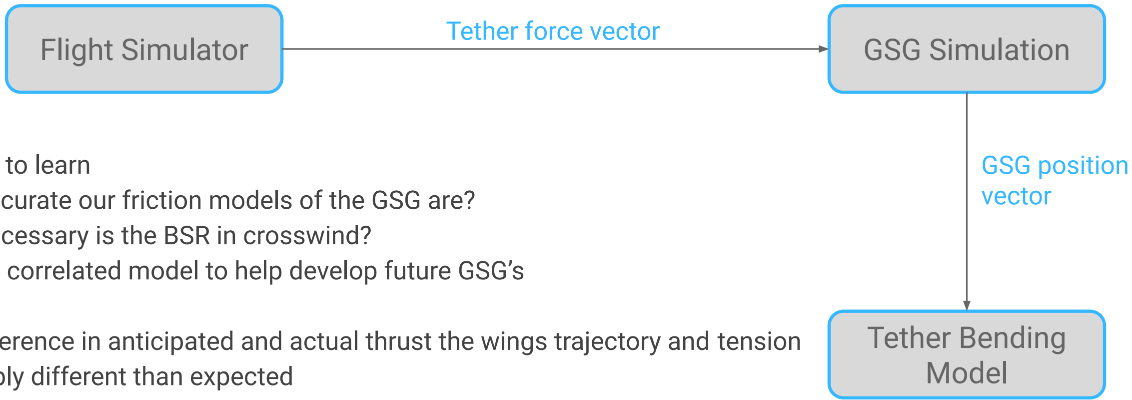
Top Hat Motion

- RPX02 elevation axis motion very similar to RPX01
  - Perturbation around 390 seconds due to decrease in tether tension
  - Less severe than previous simulation results due to greater than expected thrust
- YouTube playlist video “20161214 RPX-02 - Tether Dynamics“ from the BSR perspective shows nothing concerning during trans-in



What we are still trying to learn

GSG Dynamic Model Correlation



What we hope to learn

- How accurate our friction models of the GSG are?
- How necessary is the BSR in crosswind?
- Use the correlated model to help develop future GSG’s

Due to the difference in anticipated and actual thrust the wings trajectory and tension are considerably different than expected

- Hard to correlate the GSG simulation to recorded measurements (azimuth and elevation rotation) because input conditions are different
- Difficult to know how close to minimum bend the tether is - we are working on it….

Automated checks

Possible automated check/value reporting from a test flight:

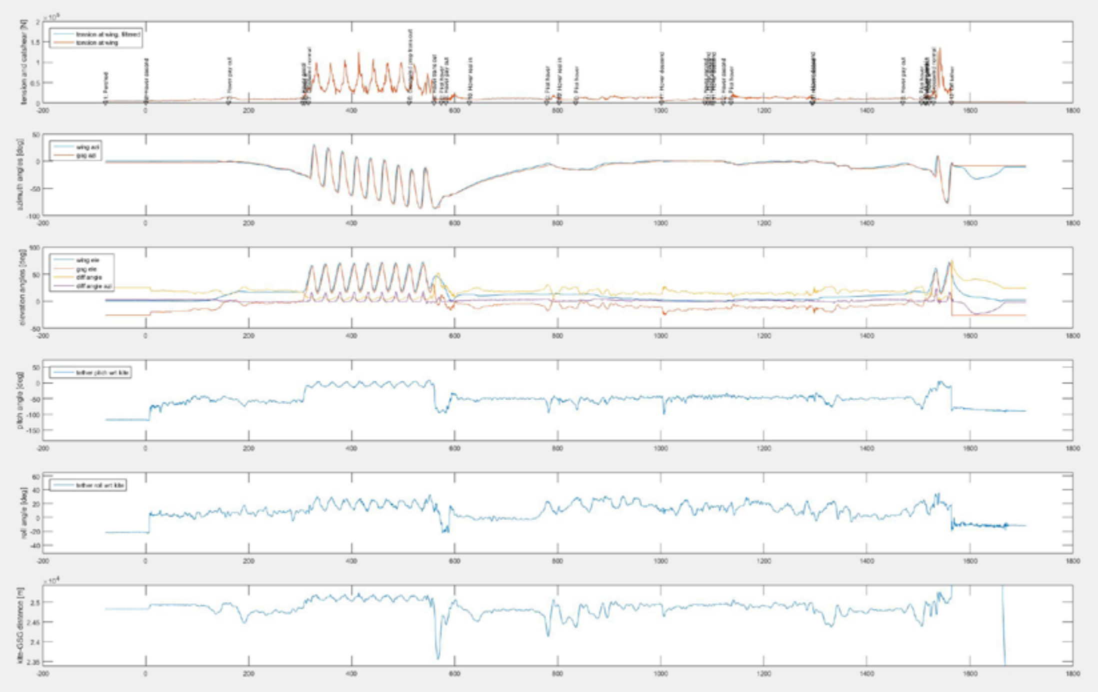
1. Maximum azimuth extent
2. Maximum elevation extent
3. Maximum detwist torque
4. Amplitude of detwist torque during crosswind

Tether
RPX-02 Flight Review

January 2017

Tether Summary

- Loads within design range, but higher than should have been w/ flight sim
- Thermals fine; may be issue in hotter weather and longer flight
- Plenty of dynamics to study more
- No strumming evidence

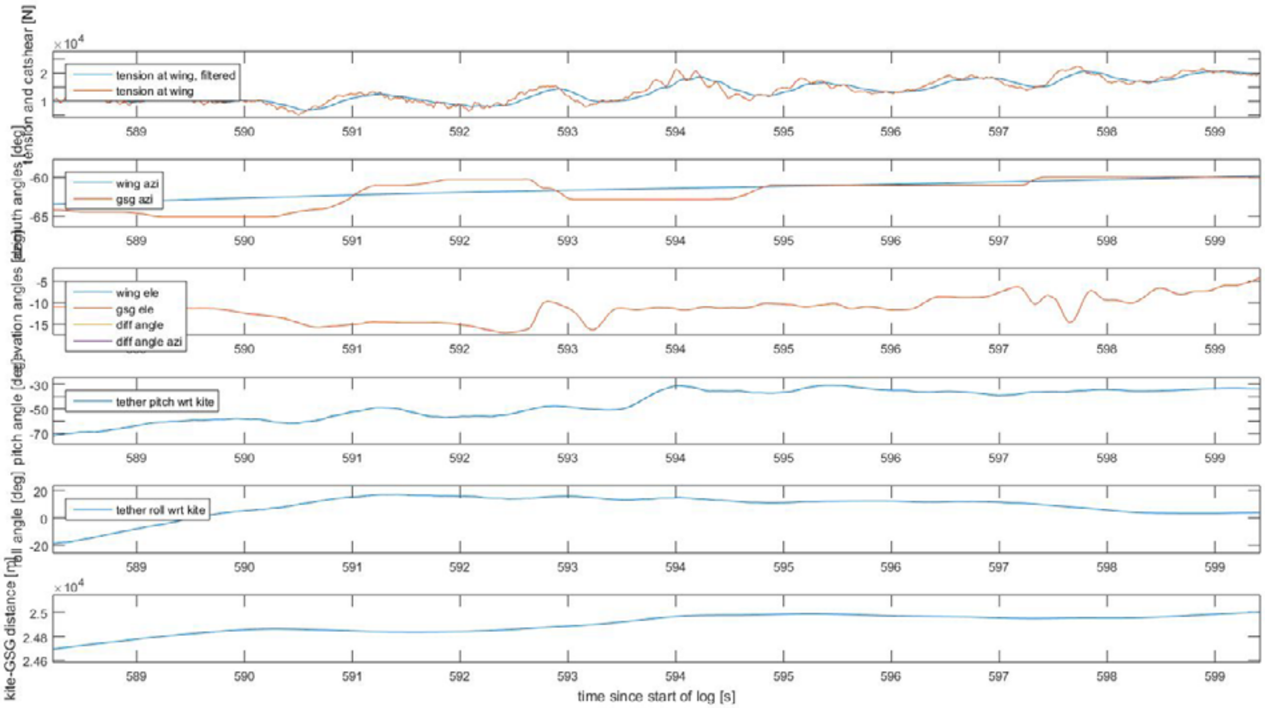


Tether hover dynamics

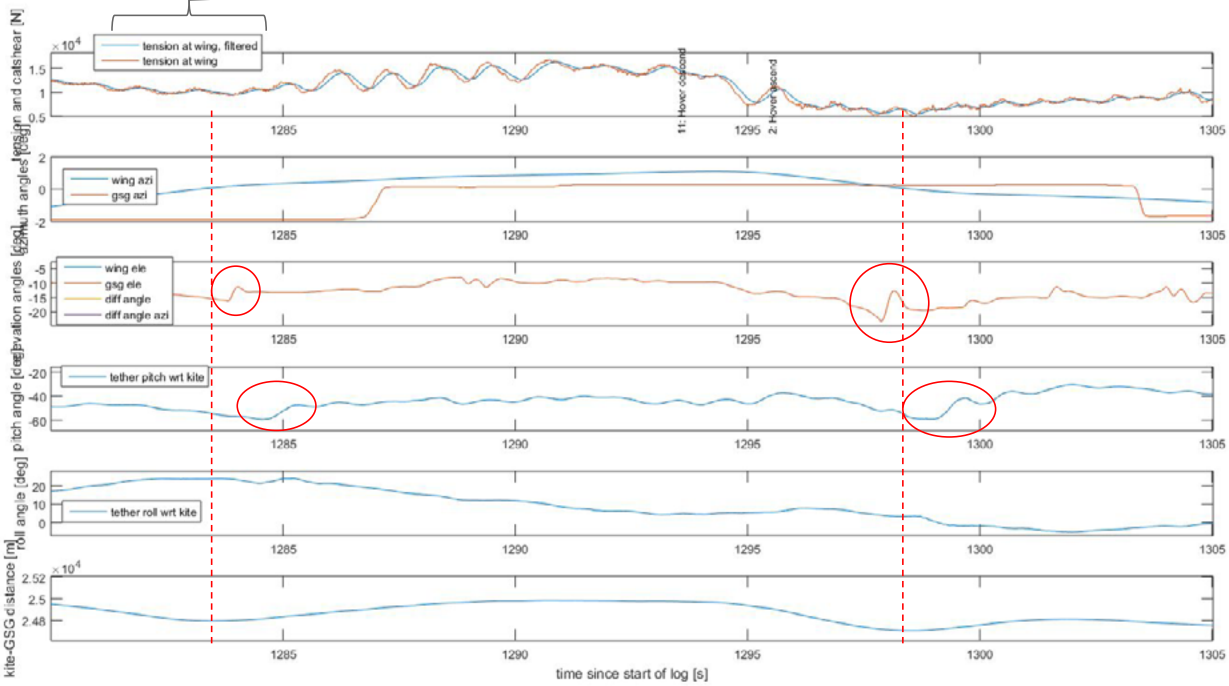
- Many waves that cause jerks at the GSG
  - “20161214 RPX-02 - Tether Dynamics” YouTube playlist video
    - 9:57 - VRS and recovery
  - “20161214 RPX-02 - Groundside Gimbal & Tether Attachment” YouTube playlist video
    - 9:57 - GSG view
    - 18:47 - following tail spike loss
    - 20:51&6 - ? (ground contact?)
    - 21:34 - ground contact and mode switch
- Wave speed at hover tensions (7-20 kN) predicts wave travel time of 3-5 s
- Still need to study what causes these jerks
  - Gust, mode transitions, ground contact, etc
- At high tensions, BSR less effective (most of length is straight)

Tether hover dynamics; RVS recovery

VRS and recovery (“tether view” vid), GSG view (“tophat” vid)

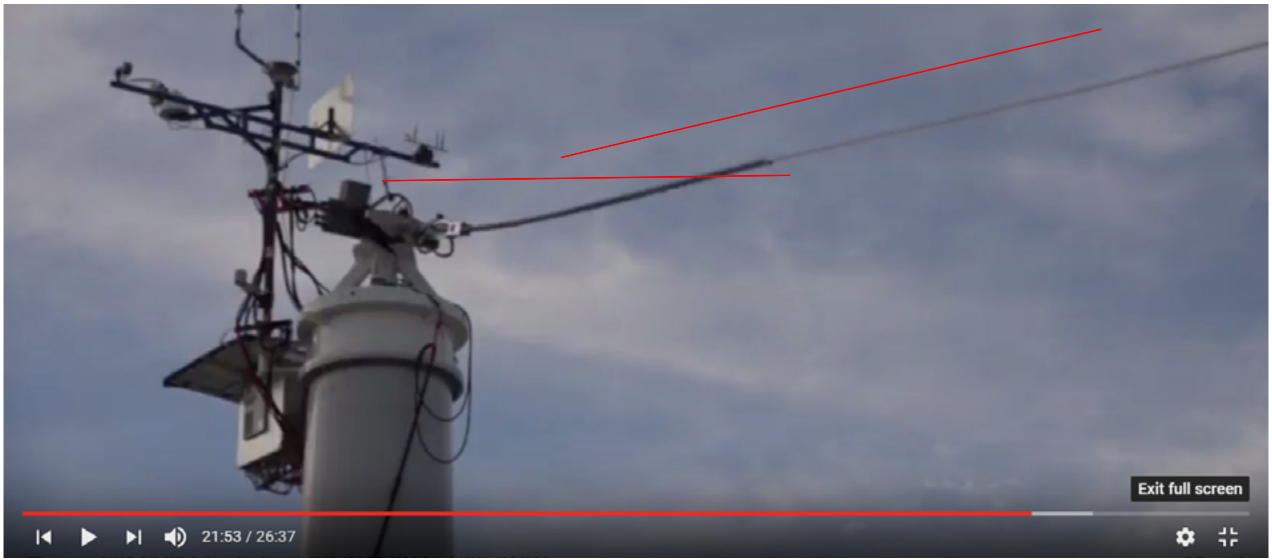


Tether hover dynamics; tether ground contact and re-lift-off



Tether hover dynamics

Ground contact and mode switch (21:50 “20161214 RPX-02 - Groundside Gimbal & Tether Attachment” video on YouTube playlist)



Tether visuals

- Very difficult to see from a distance, esp against sky

Twist and Torque induced by tension

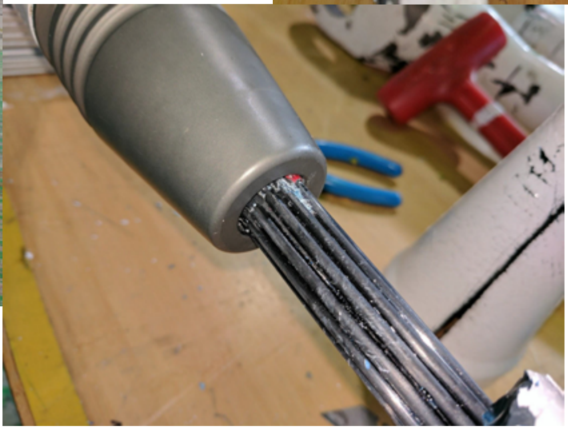
- We would normally expect about peak torque of ~13 Nm in the SW3 tether at 30 C and 140 kN, but with 20 RH twists it should be ~21 Nm.
- → almost double the torque

Tether termination seating

- Loud pops/thunks at the GSG as we trans-in
    - “20161214 RPX-02 - Groundside Gimbal & Tether Attachment” YouTube playlist video
        - 5:19, 25:34, 25:39
    - Likely from the tension being enough to overcome the friction in termination potting
    - On 2nd tran-in, a couple smaller pops a few seconds after the main pop
- Pops haven’t been as loud when testing short samples
- Wouldn’t have been able to notice these during proof loading
- Possible it was an additional factor in the tether break on RPX01?

Tether SW3-02 post flight inspection

- Post RPX-02 Inspection document
- At GS termination, nothing unusual/worrying



Tether strumming

- *No video or audio evidence of strumming in crosswind (yet)*

Tether tail contact @ trans out

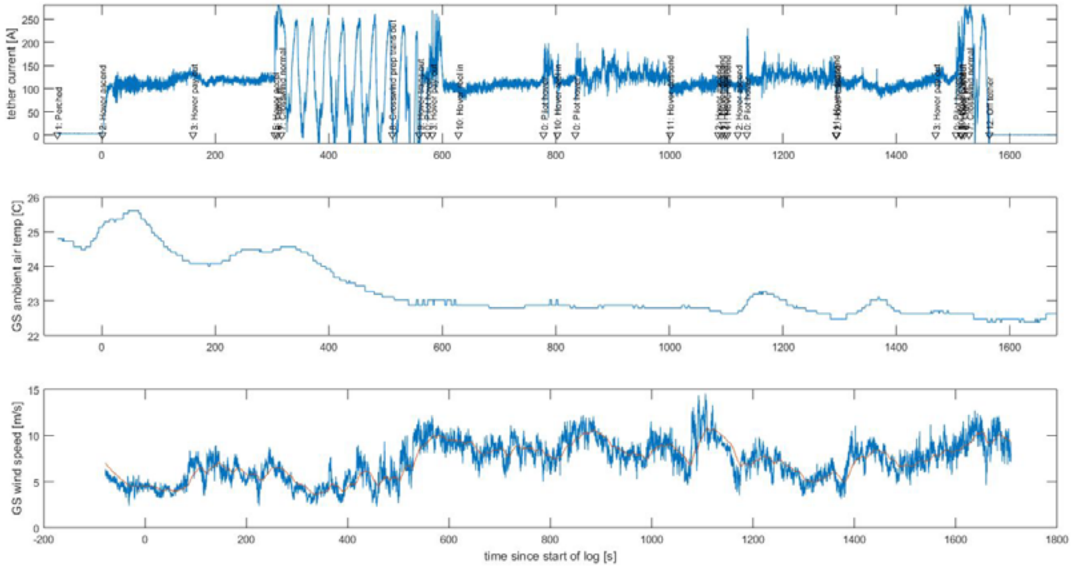
- *Bending in tether due to side contact force: would this be ok for solid tether?*
- *STBD bridle release mechanism impingement*

Bridles

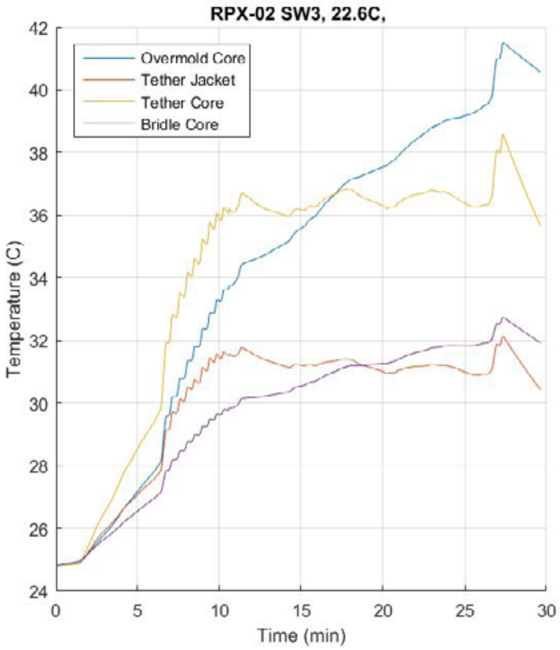
- Bridles and release seem to have worked as planned
- Release mechanism swung into wing, causing damage. Was a known risk that we had decided to fly with - working on adjustment for avoid in future flights.
- Pitch and roll range of motion: overall seem ok, except for trans-out

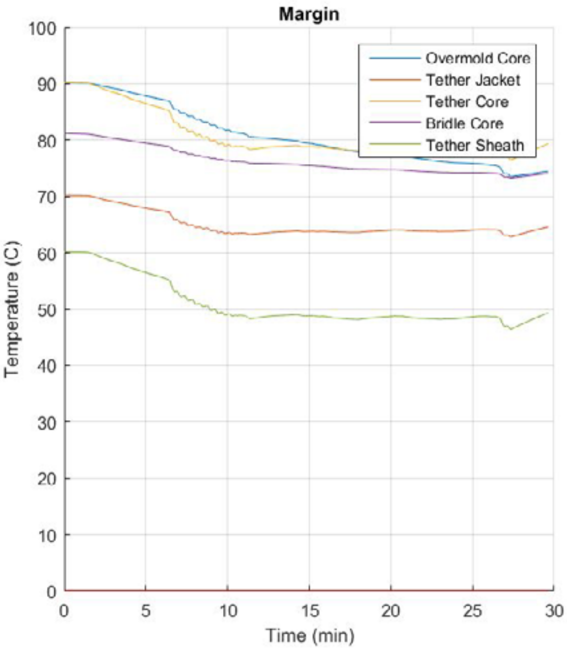
Tether thermal estimates

- Expected 155-180 A; had ~120 A in Hover, ~170 A in xwind

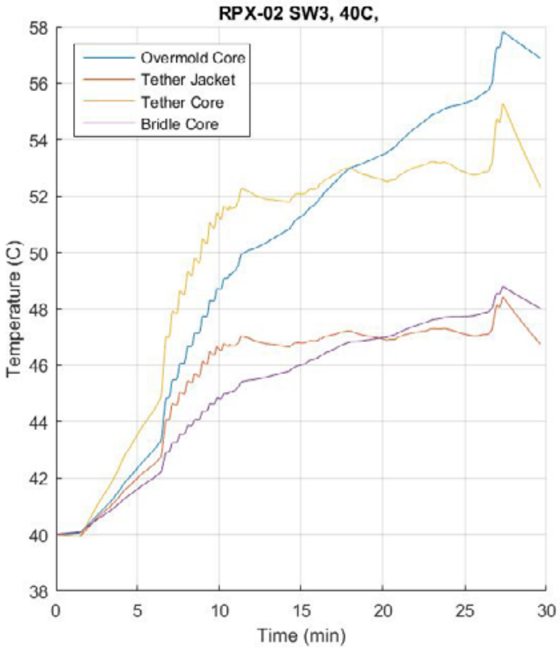


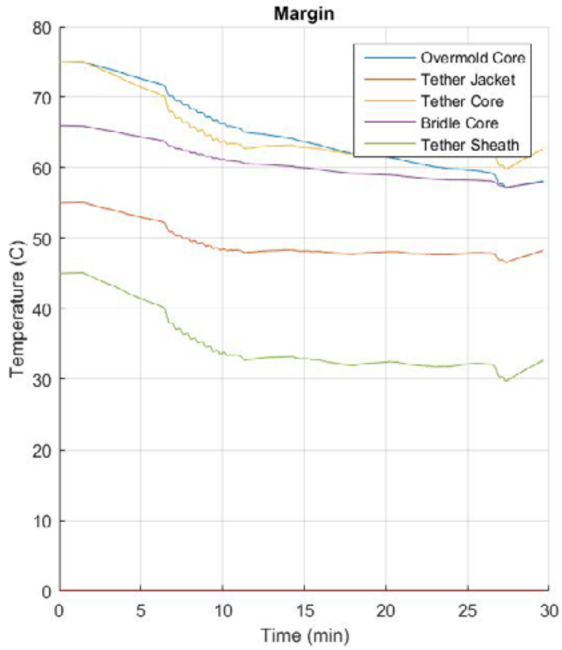
Tether thermal estimates





Tether thermal estimates (for 40C ambient)

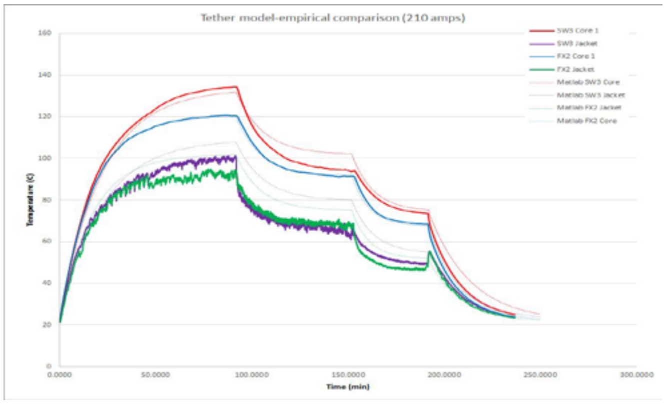


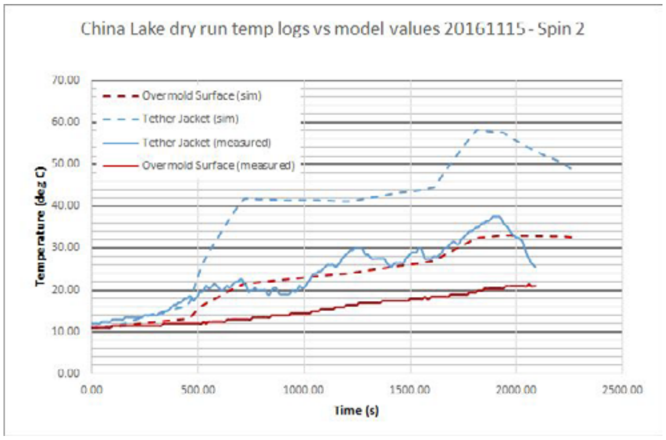


Thermal Model Comparison

Comparing the thermal model to bench test values shows reasonable fidelity (top).

Dry run data from China Lake shows large discrepancies (bottom), reasons currently unknown (possibly thermocouple placement). Fortunately the discrepancy is conservative



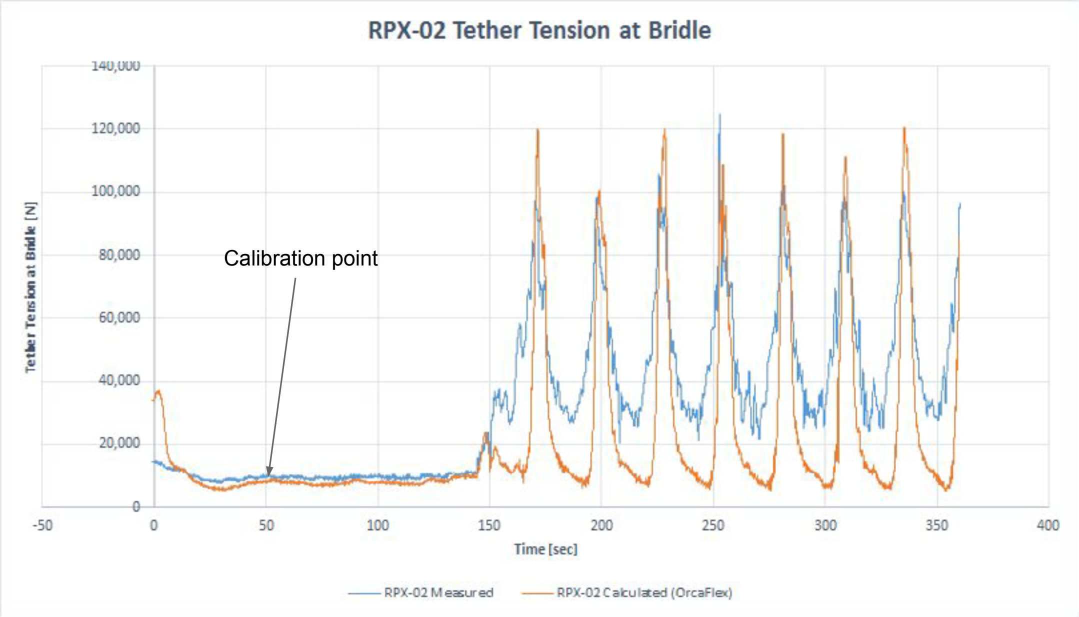


Tension comparison in Orcaflex

About OrcaFlex
- Commercially available dynamic analysis of offshore systems
- Extensively validated, industry-standard
- Rigid- and flexible-body vessel motions, finite element model of catenaries, risers, etc.
- Full definition of mooring lines (mass, drag, bending and torsional stiffness, many other properties

Tether Model
- Includes gimbal, BSR, tether (~200 nodes)
- Free to rotate at gimbal
- Kite position prescribed (from RPX-02 kite position time series)
- Time-stepping calculation of tether loads, position, stress, and many other responses

Tension comparison in Orcaflex



Next steps:
Improve gimbal model to reduce numerical noise

Re-run with higher drag coefficient
(1.2 → 1.3)

Detailed model of tether length (down to the centimeter)

Longer pre-analysis transient stage

What did we not present?

Things we looked at but did not present:

- Some tether catenary work

Things we would like to look at but haven't yet:

- Tether tension delta and shear from SIM
- Tether tension FFT in hover; explore root source of frequencies
- More tether dynamics and orcaflex
- Bridle details
- Overmold motion due to tether seating at high tension
- Pitch and roll range of motion limits

What do we want to learn next crosswind flight?

- Study tether thermals closer
    - have more confidence in the model as we approach summer
    - → use thermal camera at GSG, plugged into existing ethernet lines for monitoring at command center
- Test out improved tether visibility?
    - For PR, from FAA: “Alternating 150 foot bands of aviation orange and white”
- Dynamics validation?
    - Maybe with accelerometers near the GSG ?
- Tether tension discrepancy
    - ?

What can we automate?

- Tether tension limit checks, FFTs, loading rates
- GSG elevation motion and rate of motion - catching jerks
- Thermal model analysis

Kite Line-Angle Sensing

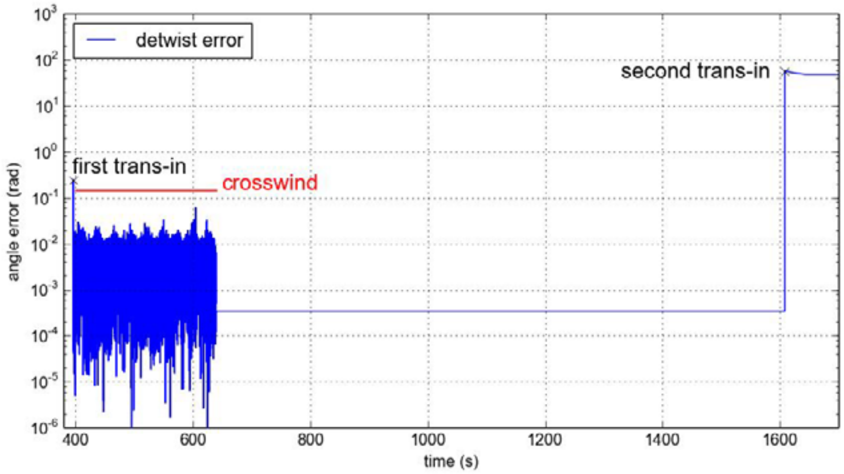
To-do: Project tension vector outward from kite, verify that it lands near GS.

Motivation: Verify tension direction estimate; estimate sheer forces at the GSG.

Not done yet.

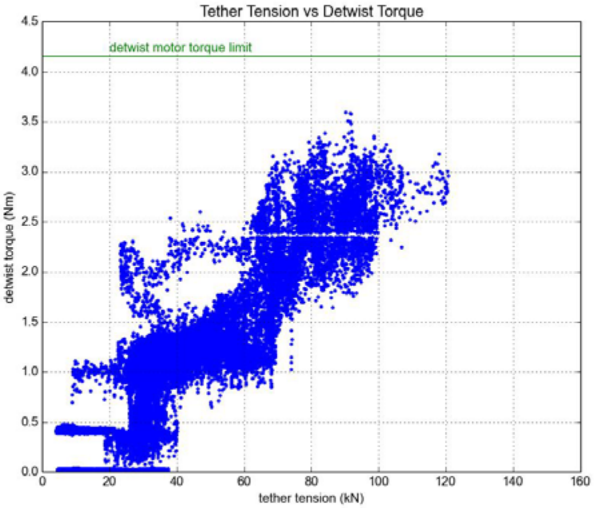
Detwist Performance

- Followed commanded angle during regular crosswind
- Errored out and disarmed upon second trans-in
  (expected because flight controller resets to a multi-turn angle of zero)
- First nonzero detwist command was -0.25 radians. This was larger than expected and did not cause an error, but larger discontinuities in the position command could be problematic. (Follow up with Controls.)



Detwist Torque

- High-load testing of detwist was skipped prior to RPX
- The torque required to rotate the detwist appears correlated with tether force
- At rated crosswind tensions the torque may exceed the gearbox limit of 4.16 Nm
- Mechanical solutions are being considered



MAKANI

RPX-07 Lessons Controls

November 30, 2017

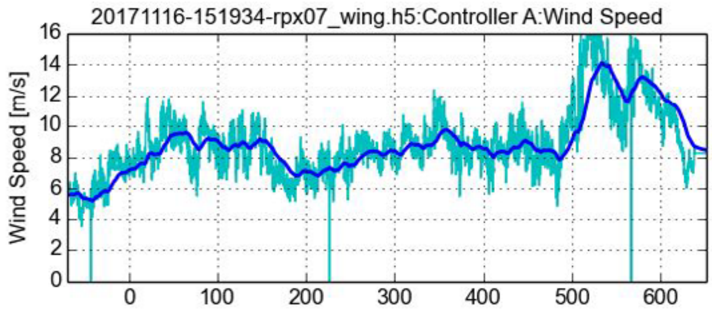
RPX-07 What was new? Changes since RPX-06.

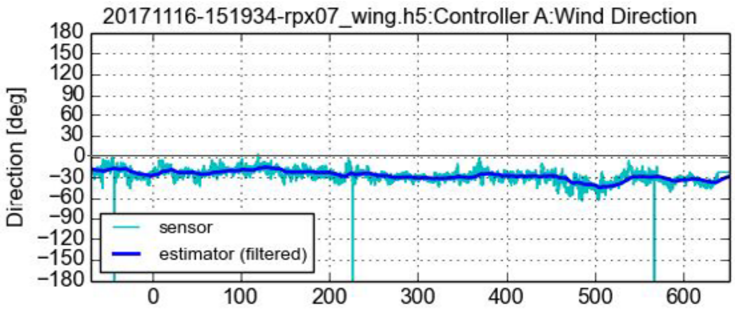
- Slats (with new aero database)
- Increased mass: ~118 kg
- Faster Slew Rates in Hover Modes
- Yaw Motor Steering in crosswind
- Updated crosswind roll feedforward command for the case: alpha = 5 deg, vel_cmd = 40 m/s

- We only flew one crosswind case, the baseline:
    - Alpha_cmd = 3 deg
    - Velocity_cmd = 40 m/s
- Loop radius decreased from 150m to 125m at the beginning of crosswind

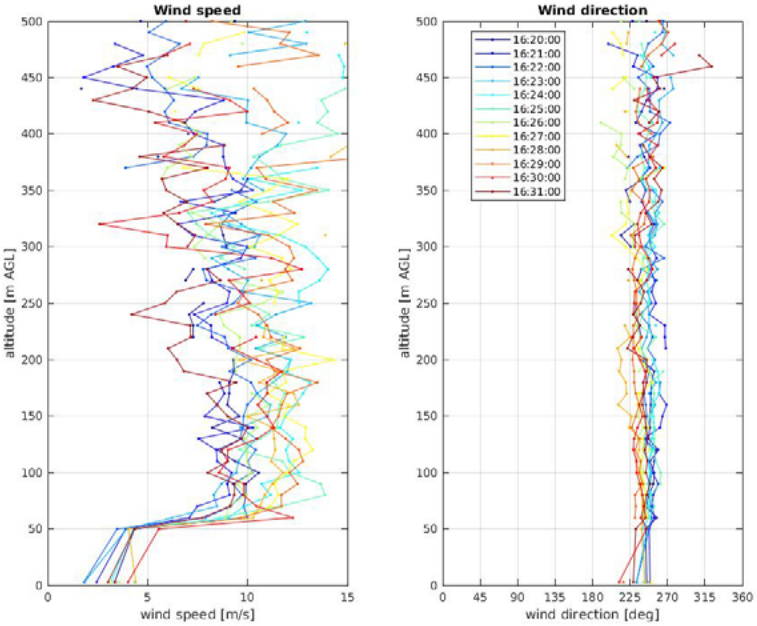
Flight Conditions Weather and Wind Nov 16, 2017 15:19

Temperature	22.5	°C
Pressure	92974	Pa
Humidity	30	%
∴ Density	1.092	kg / m³

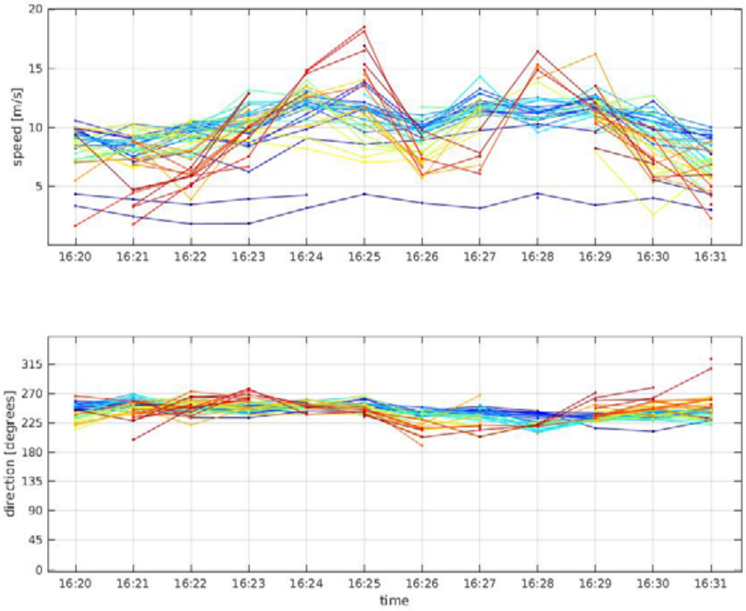




Flight Conditions SODAR data

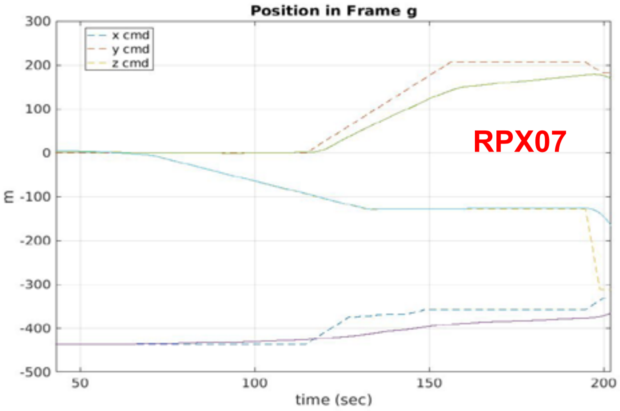


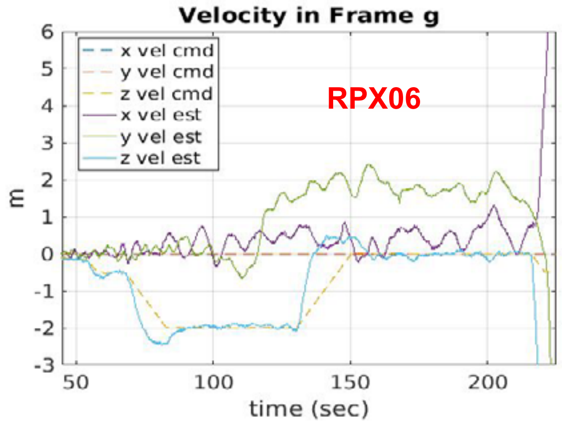
Flight Conditions SODAR data

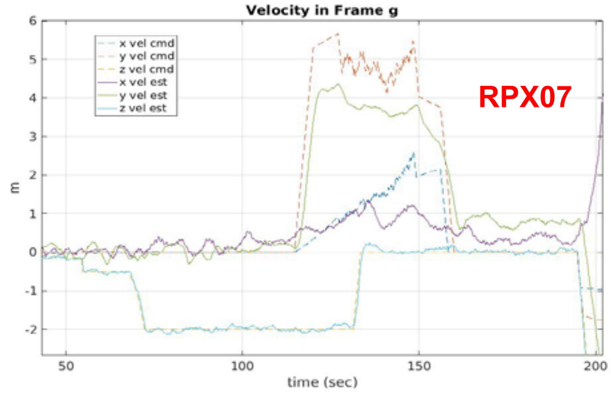


RPX-07 Hover Faster Slew Rates

- Kite performed as expected with this change
- Lateral velocity is faster
    - Max of around 4 m/s vs 2 m/s in RPX06
    - Only when cmd itself is slewing
    - TODO: Faster all the time

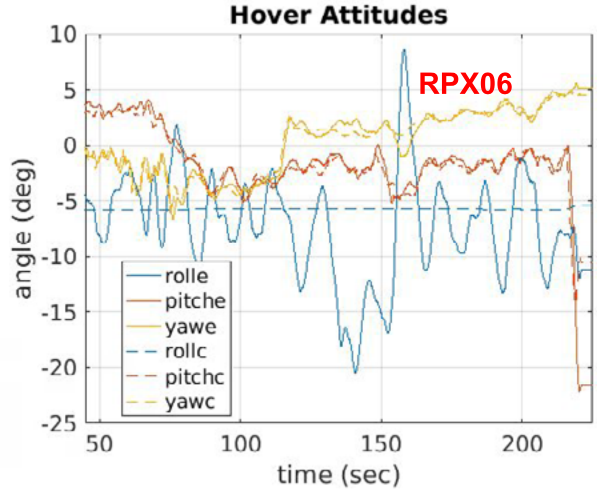


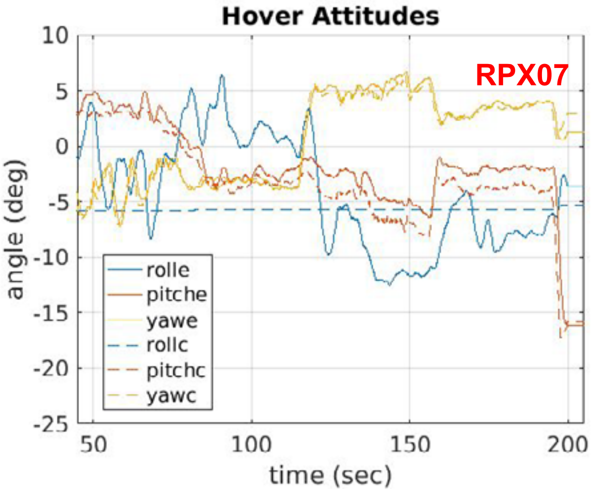




RPX-07 Hover Faster Slew Rates

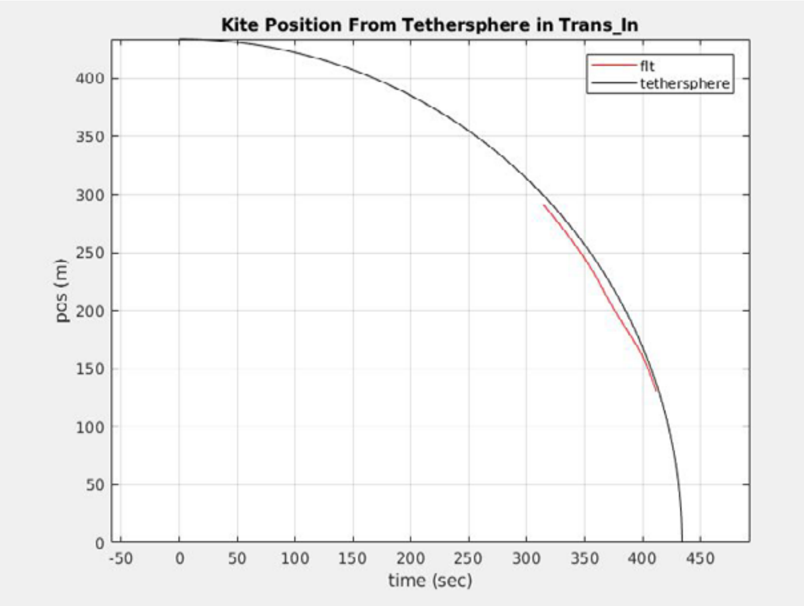
- Faster Slew Rates result in larger hover yaw attitudes





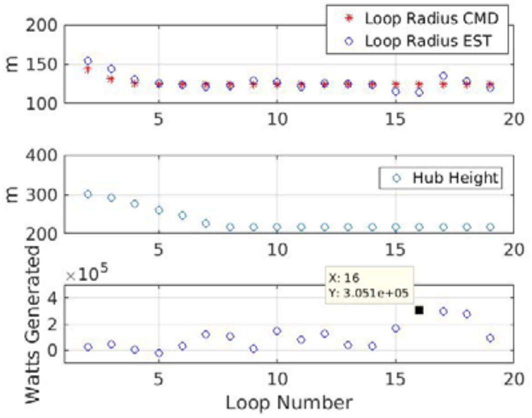
RPX-07 Trans-In

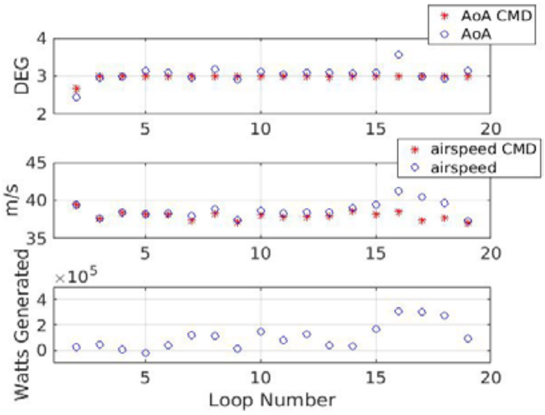
- Worked quite well.
- Stayed close to the tethersphere. similar to previous flights.
- Much better than the sim results



RPX-07 Crosswind Summary

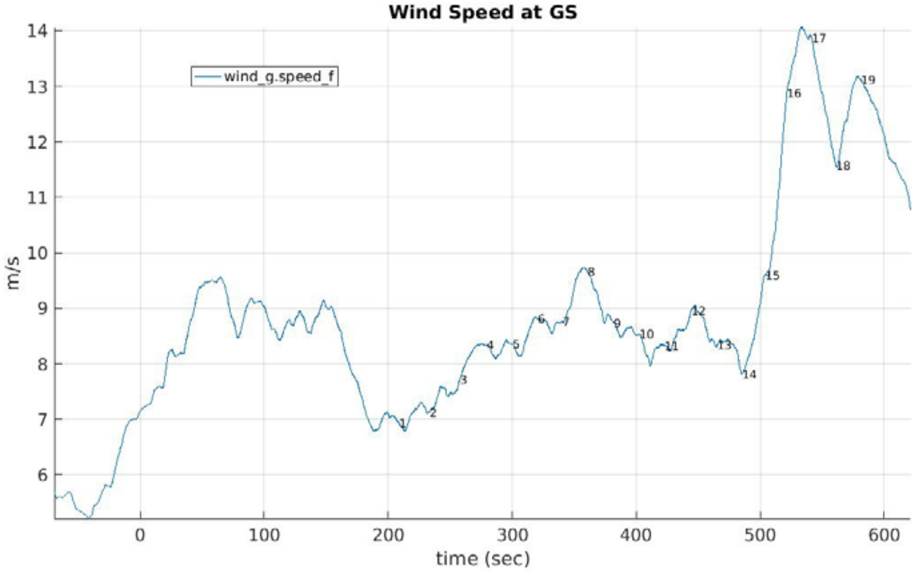
- WINDY! 8.5 m/s increasing to 13 m/s
- 19 loops including TransIn and the release
- Most loops flown at 125 m radius
    - Radius shrinks from 150m to 125m during first two loops
- alpha_cmd = 3 deg in the crosswind mode
- Mean airspeed cmd = 40 m/s
- Best avg: +305 kW at 10.8 m/s wind (at GS)
- Worst avg: -24 kW at 8.3 m/s wind (at GS)
- Best instantaneous: 805 kW (many times)
- Every loop except #5 was power positive
- Lots of control surface saturations
- Path tracking looks worse than RPX06
- Angle of attack and sideslip excursions persist
- Oscillating airspeed error caused swings in power required leading to generator failure.



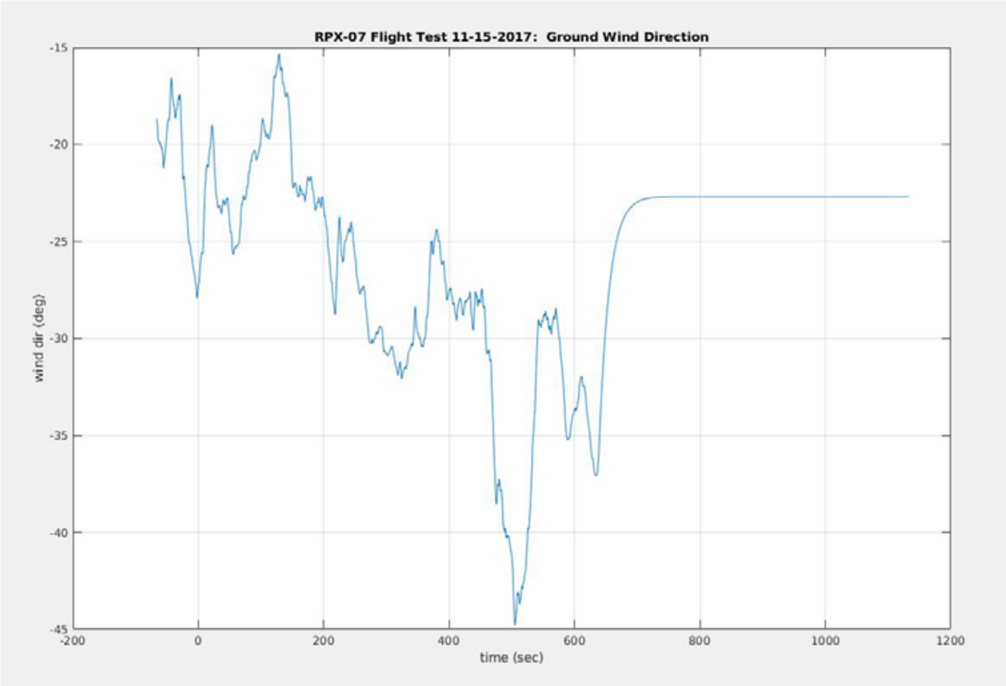


RPX-07 Wind

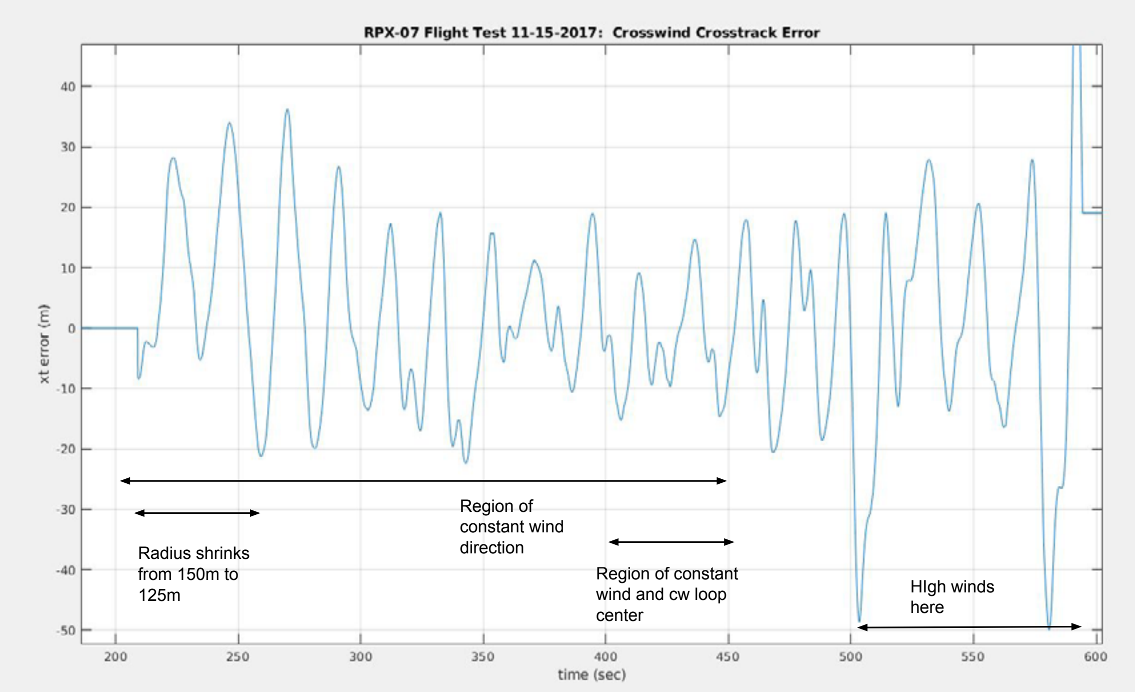
- Wind at GS increased dramatically after loop 13
- Beginning of each crosswind loop is marked



RPX-07 Ground Wind Direction



RPX-07 Crosswind Crosstrack Error



Radius shrinks from 150m to 125m

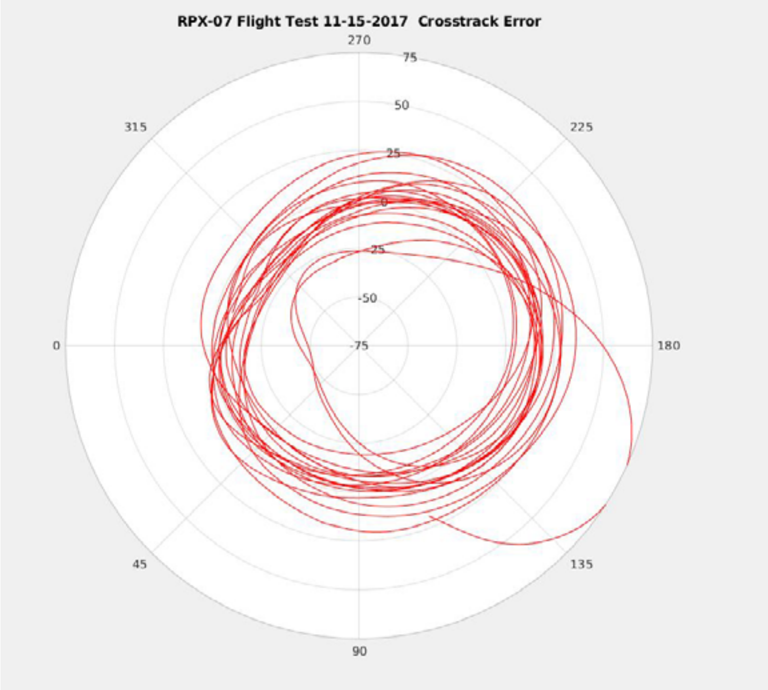
Region of constant wind direction

Region of constant wind and cw loop center

HIgh winds here

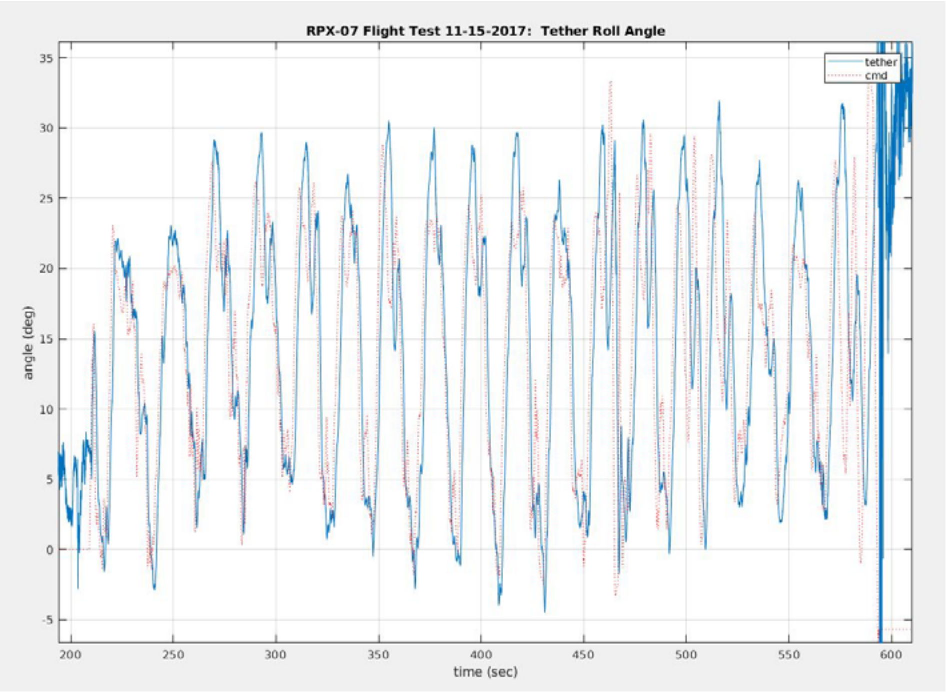
RPX-07 Crosswind Crosstrack Error

- Errors are outside the commanded radius on the downstroke
- Error are generally inside the commanded radius on the upstroke
- Some of this error is due to aileron saturation
- Some error is due to incorrect tether roll feedforward command (off-nominal operations)

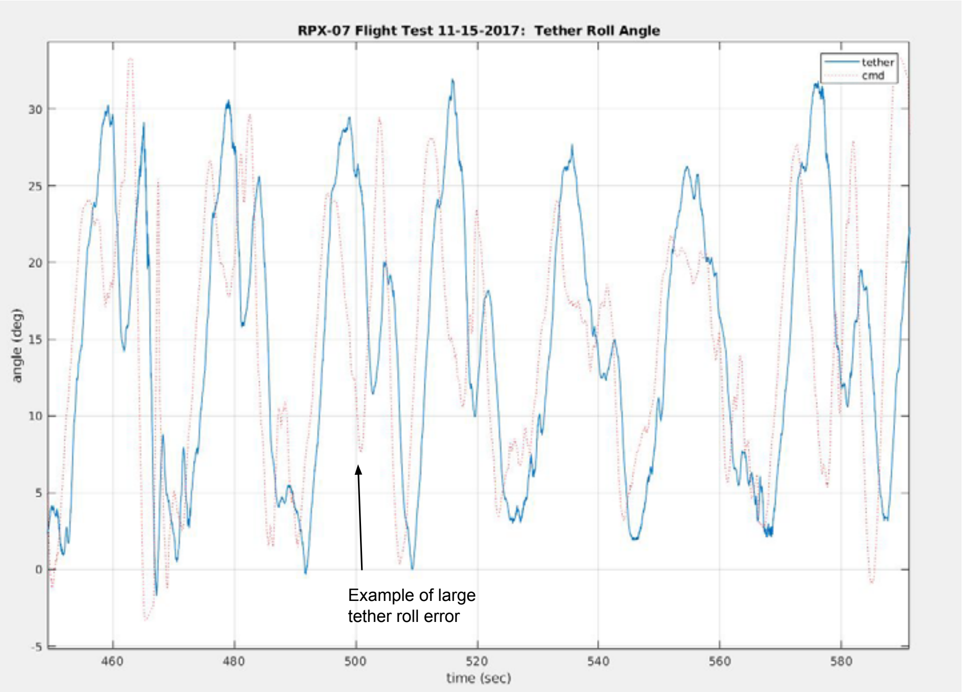


RPX-07 Crosswind Tether Roll

- The tether roll angles fairly well followed the commands until the wind increased at about 450 sec.
- The tether roll error was very large (20 deg) in the high wind regions.

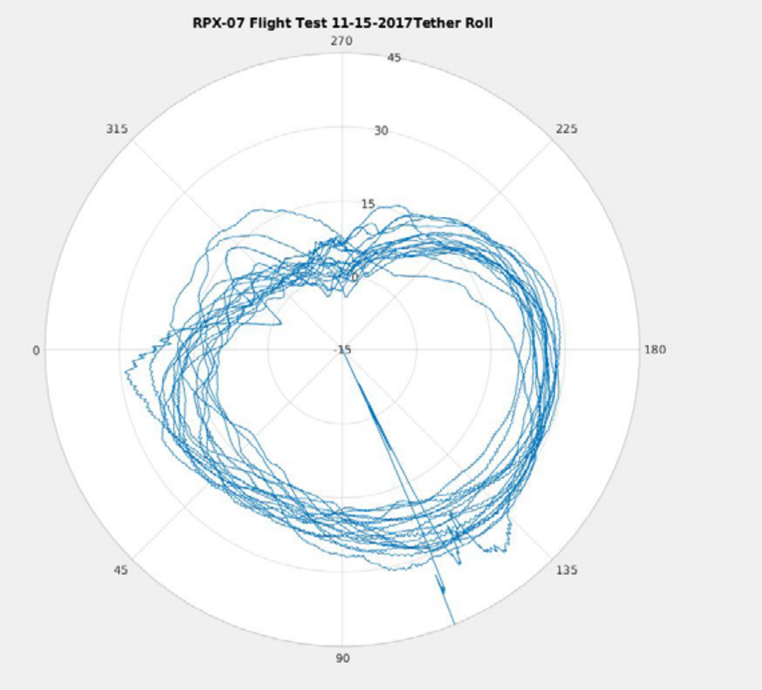


RPX-07 Crosswind Tether Roll (Expanded)

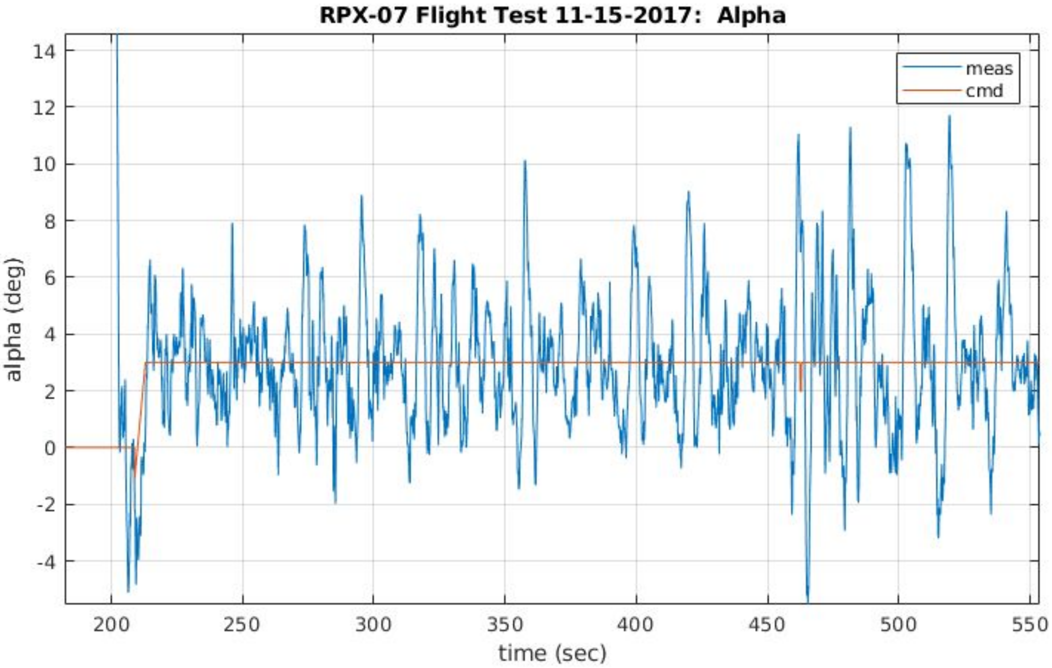


Example of large tether roll error

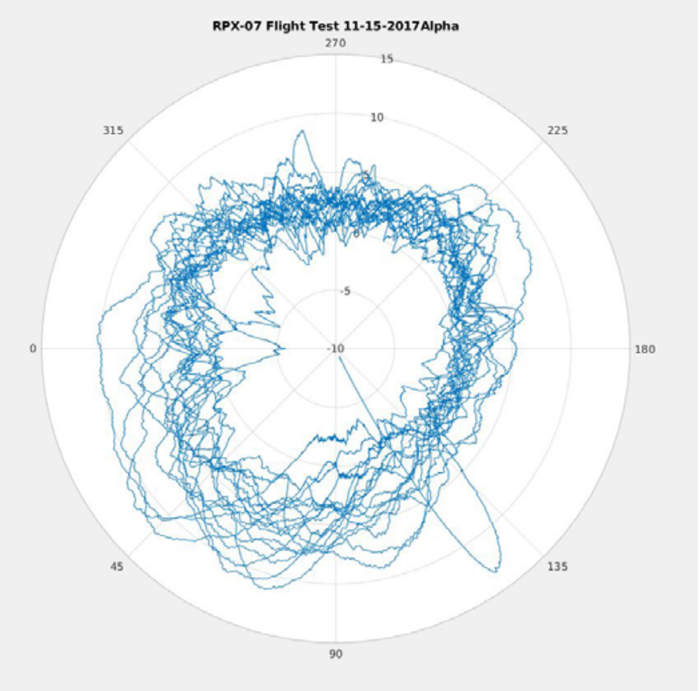
RPX-07 Crosswind Tether Roll



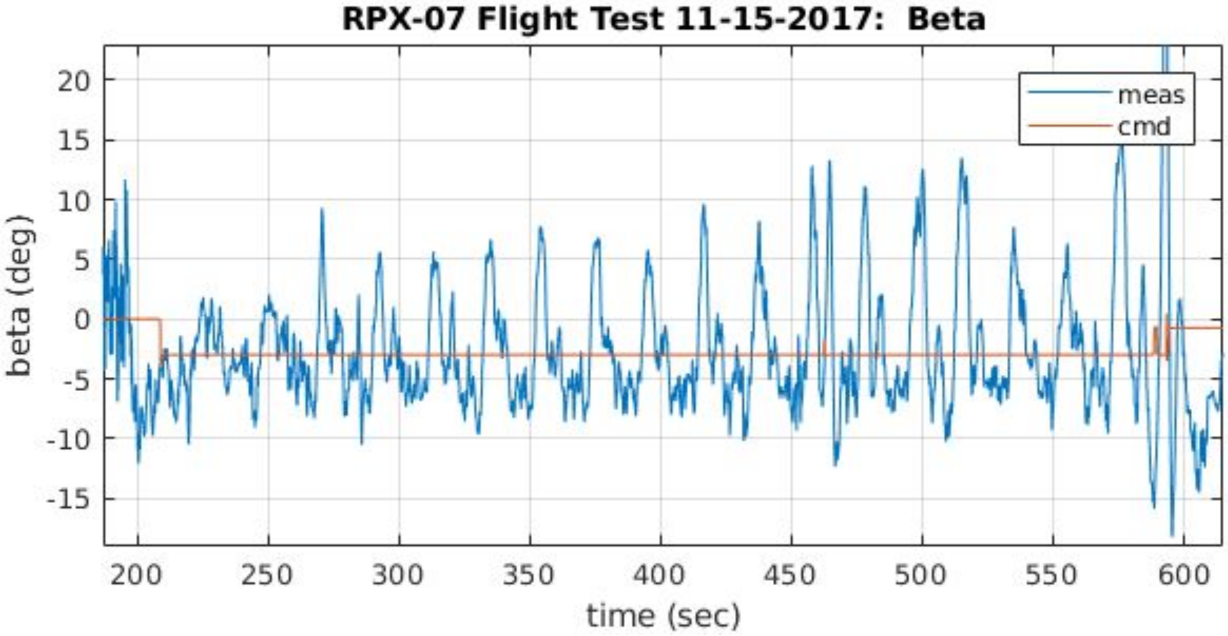
RPX-07 Crosswind Alpha vs time



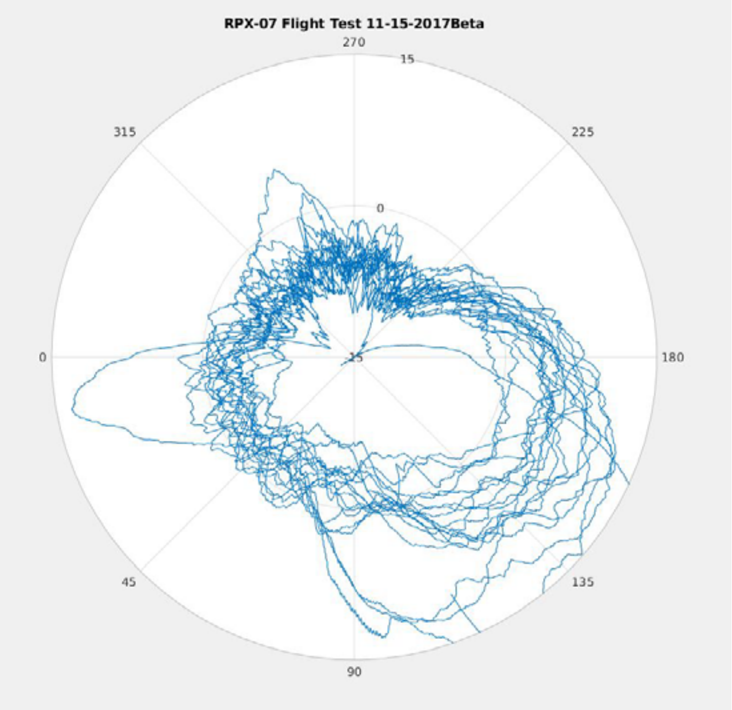
RPX-07 Crosswind Alpha Around the Loop



RPX-07 Crosswind Beta vs Time

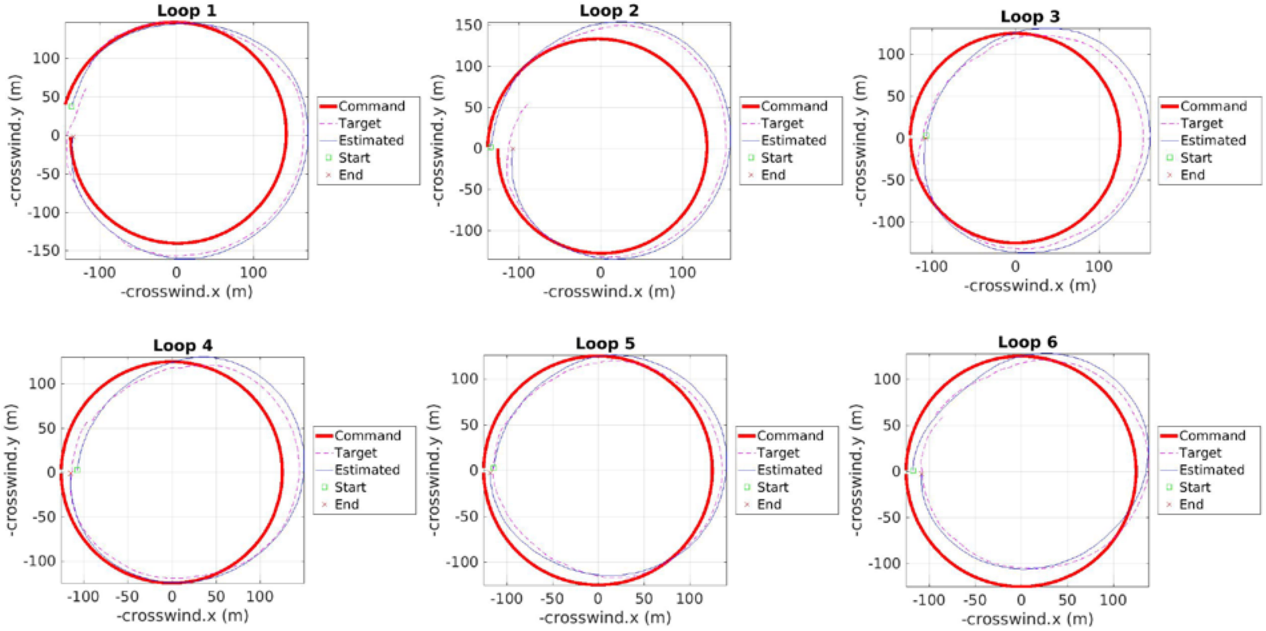


RPX-07 Crosswind Beta Around the Loop



RPX-07 Crosswind Path Tracking

- Some loops looked great, others not so much



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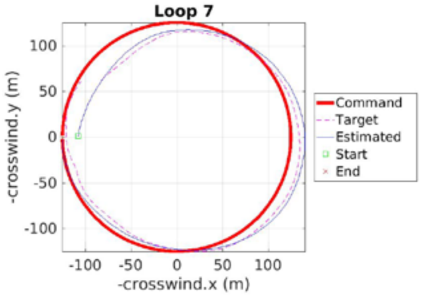
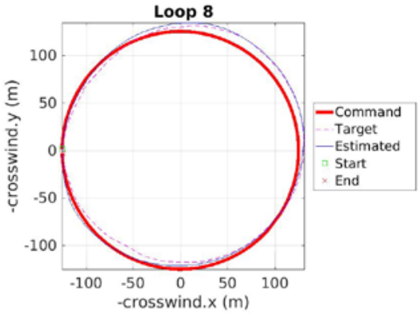
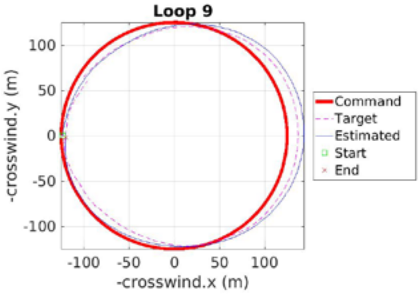
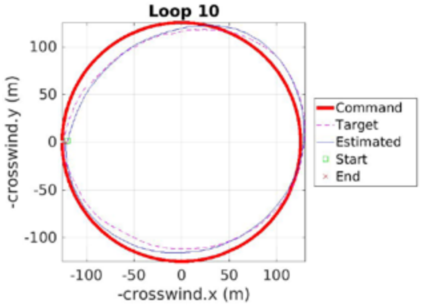
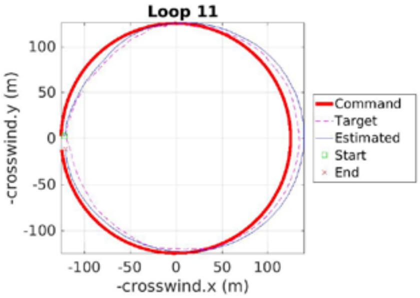
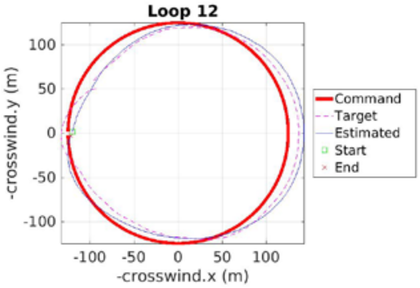






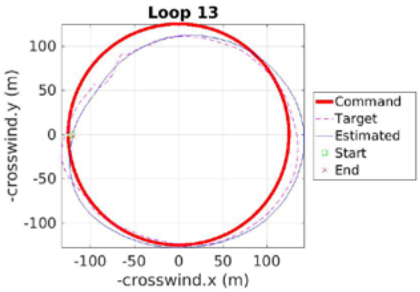


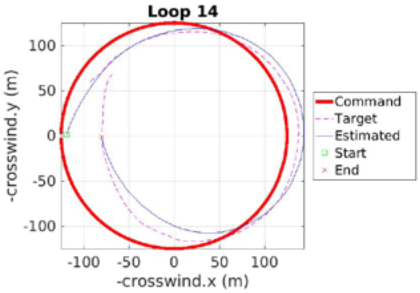


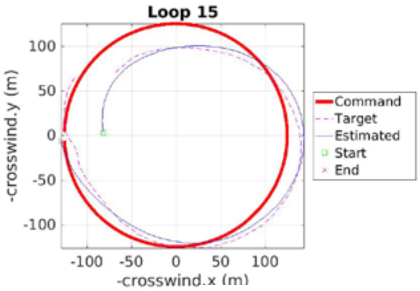


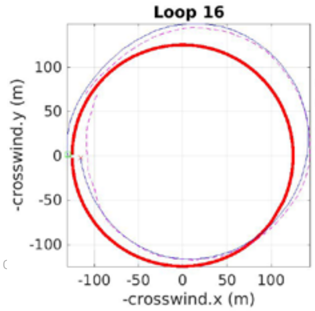
RPX-07 Crosswind Path Tracking

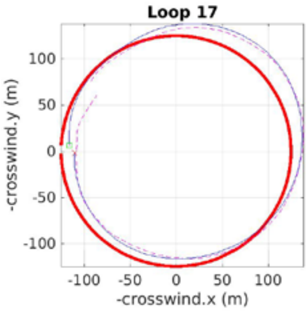
- Some loops looked great, others not so much

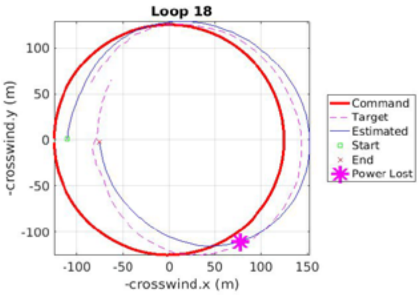


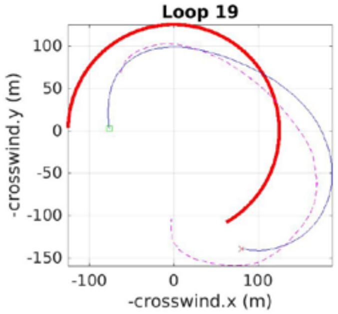






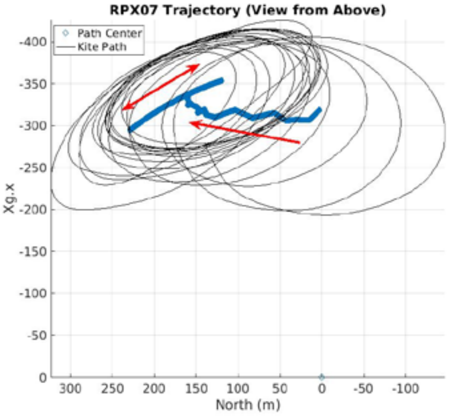


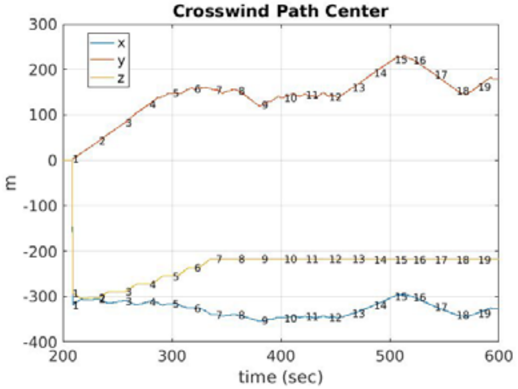


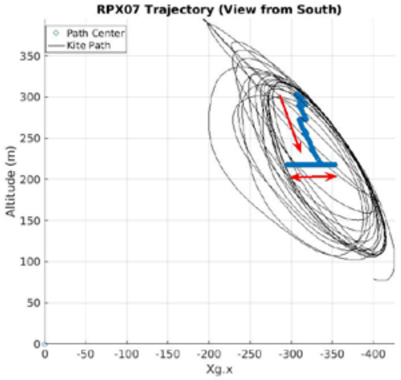


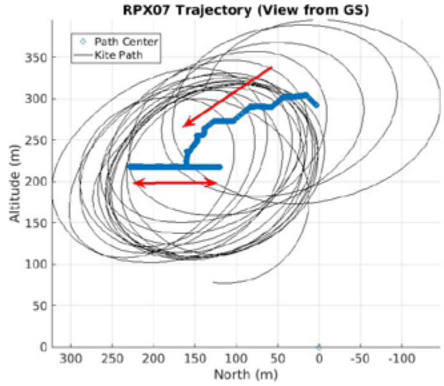
RPX-07 Crosswind Path Center Slewing

- Crosswind circle plots tell a deceptive story.
- The crosswind plane moves in order to track the wind.
- Max travel per loop: about 40 m laterally, 25 m vertically



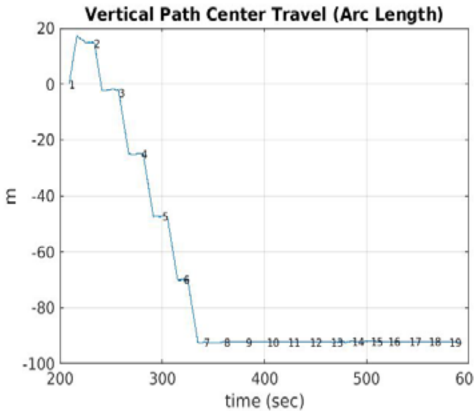


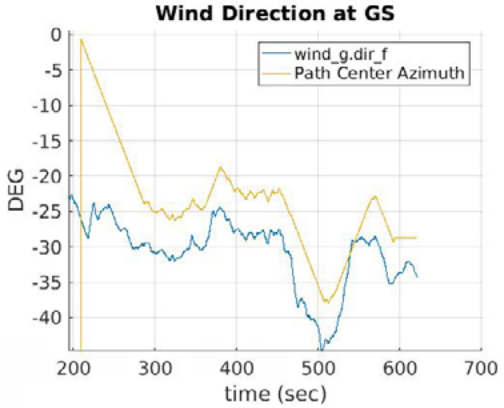


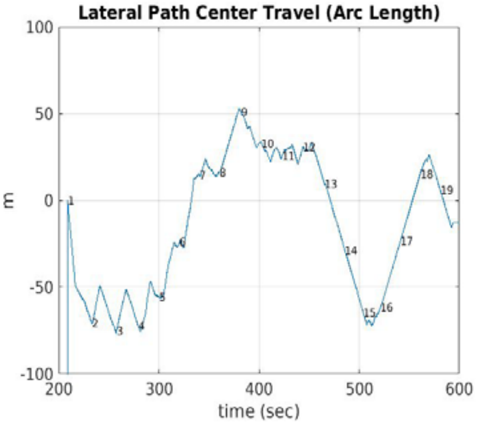


RPX-07 Crosswind Path Center Slewing

- Vertical position moves at the beginning of each loop, then plateaus. After loop 7 it is constant.
- Lateral position moves for every loop except 10, 11, 12.
- The azimuth of the path center tracks the azimuth of the wind
  - This is by design
  - Consider slowing the max slew rate
- Our "worst" loops are those where the path center changes direction (15, 18 especially)

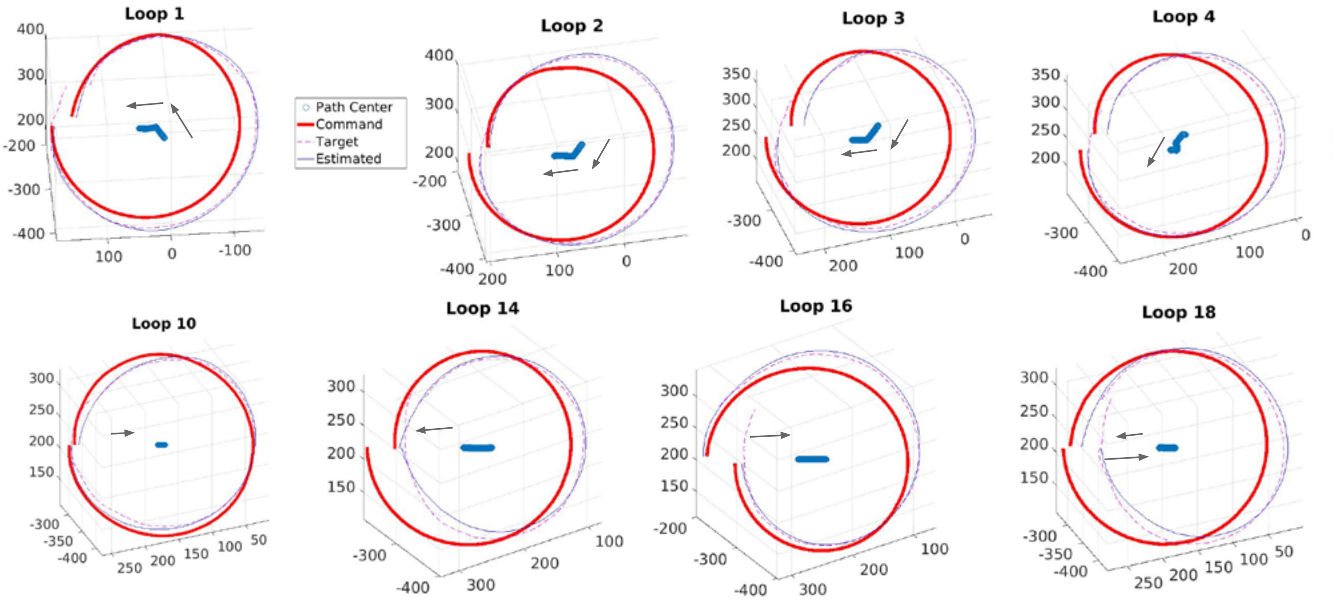






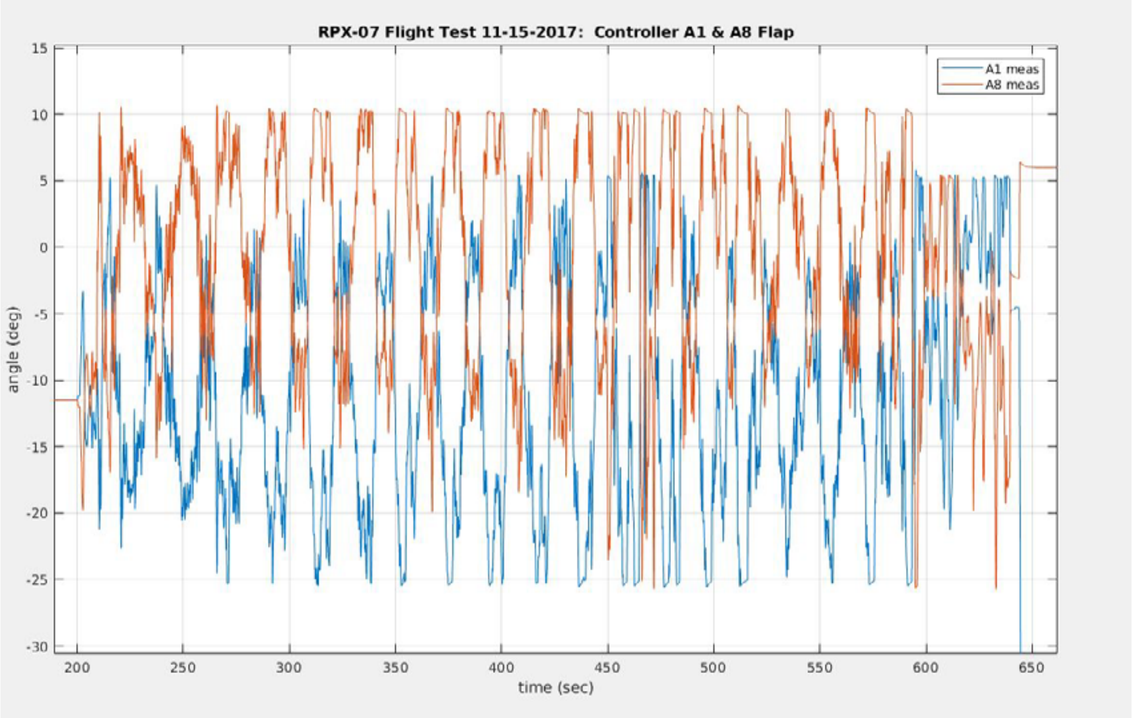
RPX-07 Crosswind What The Loop Commands Really Look Like

This shows the actual commanded path as seen from the ground station looking up the center of the cone.



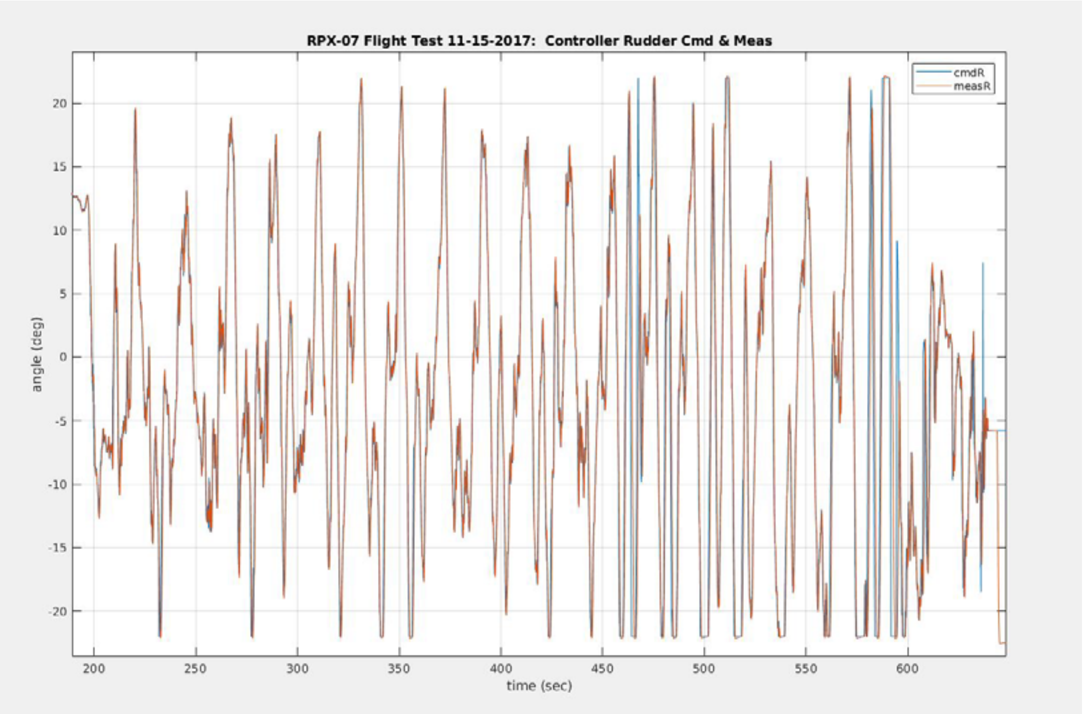
RPX-07 Crosswind Ailerons

- The right outer aileron saturated on most loops.

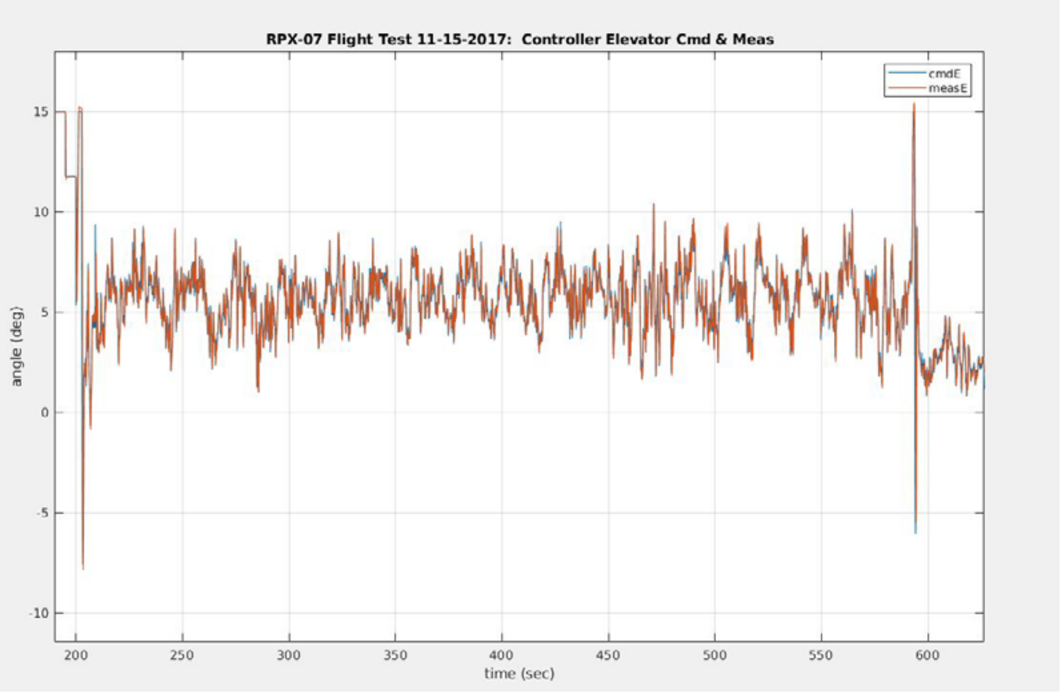


RPX-07 Crosswind Rudder

- The rudder began saturating when the wind increased around 450 sec.



RPX-07 Crosswind Elevator

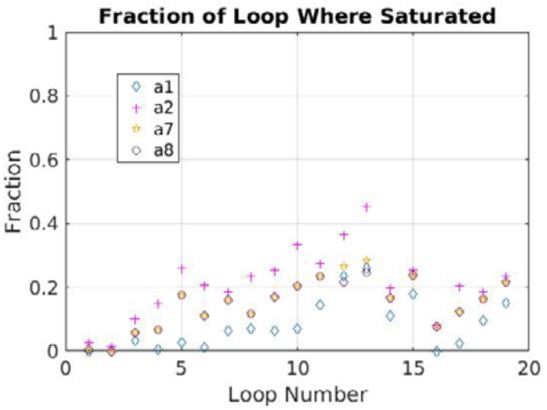


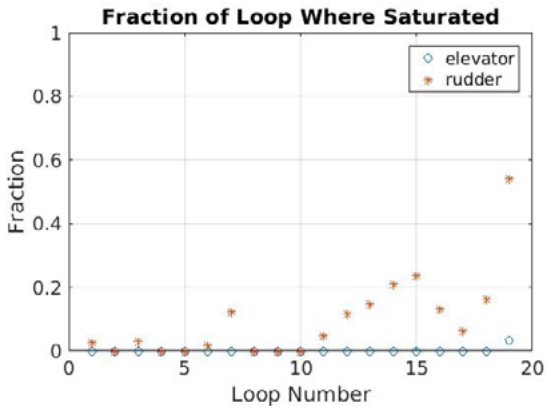
RPX-07 Crosswind Actuator Saturations

- The kite regularly saturates its ailerons (high and low)
- Rudder saturations are more frequent later in the flight at higher wind
    - Motor steering is helping the rudder
    - It would otherwise be worse
- Elevator only saturates on Loop 19 just before we release

Fraction of time spent saturated during all of crosswind flight:

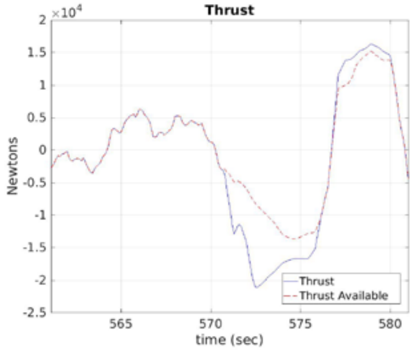
a1	7.8%
a2	20.7%
a7	14.4%
a8	13.9%
elevator	0.1%
rudder	8.5%

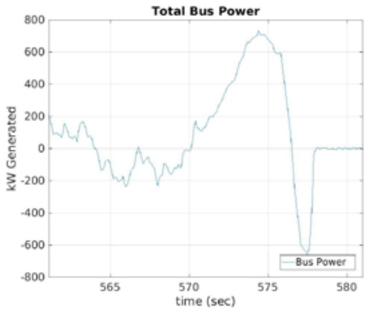


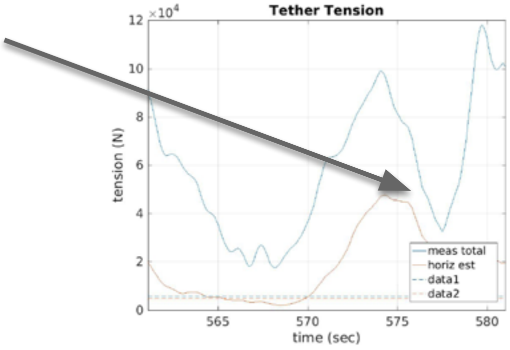


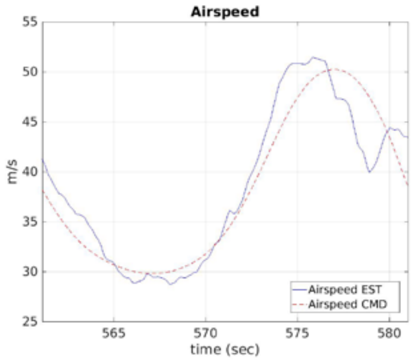
RPX-07 Crosswind What Happened on Loop 18

- We made the ground power station angry because
- We requested huge swings in thrust because
- Our airspeed error swung from + to - to + quickly because
- We flew a poor loop during which we saw
    - Big sideslip followed by
    - Drop in alpha
    - Drop in tether tension



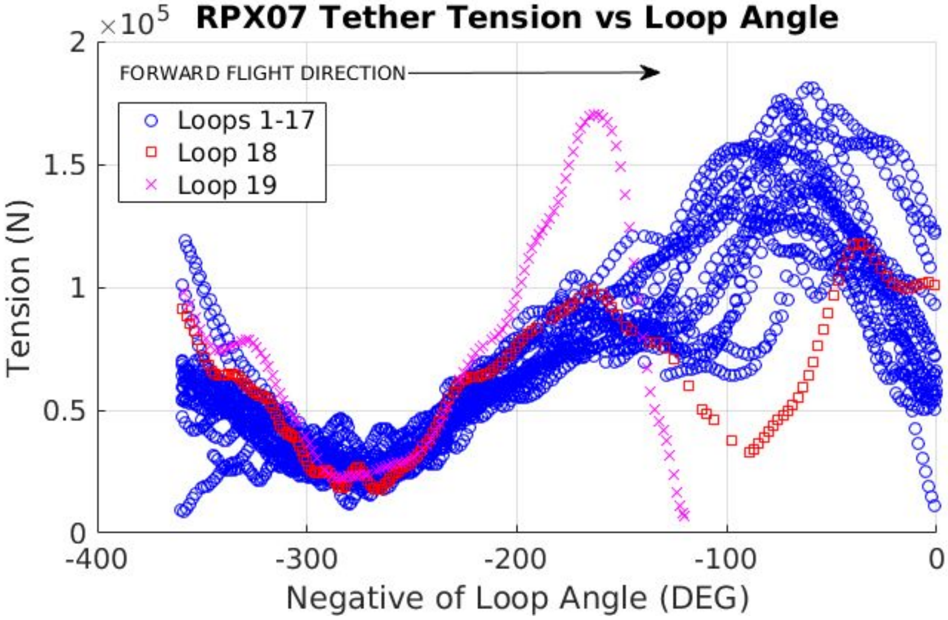






RPX-07 Crosswind What Happened on Loop 18

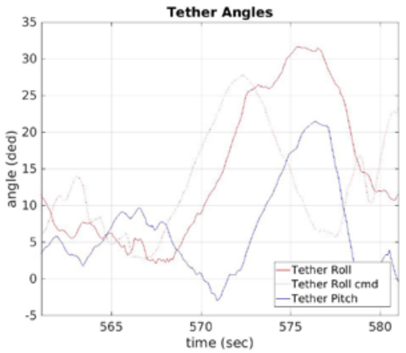
- The tension event on loop 18 was “unique” in that it was the worst example of something that only sometimes happens
- These low tensions on the downstroke have large tether pitch angle changes associated

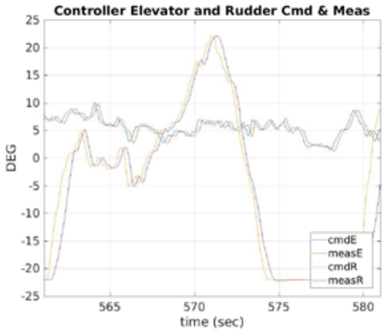


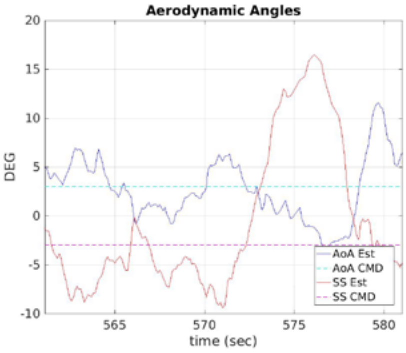
RPX-07 Crosswind What Happened on Loop 18

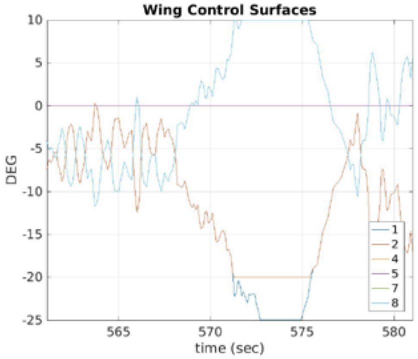
- Really bad aileron saturations on this loop
- Leads to large tether_roll errors
- We also saturated the rudder very badly
- Leads to large beta (during which alpha drops)
- Followed by large alpha (this is a theme)

Path center slew changed direction during this loop (max rate on both sides of the change)

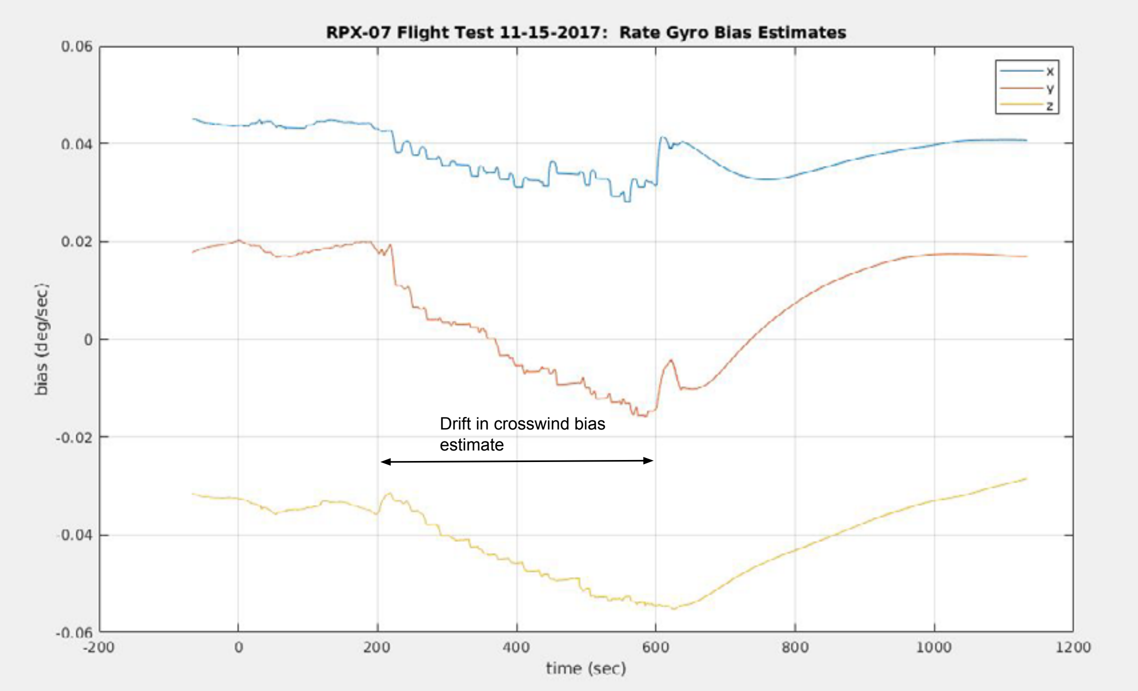






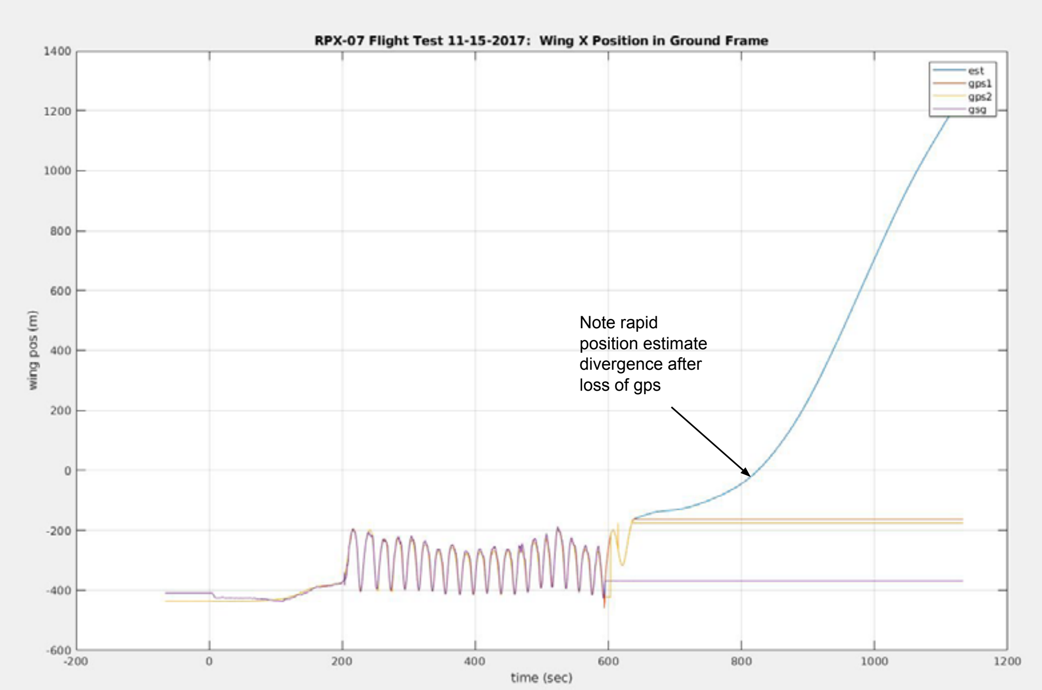


RPX-07 Full Flight: Gyro Bias Estimates



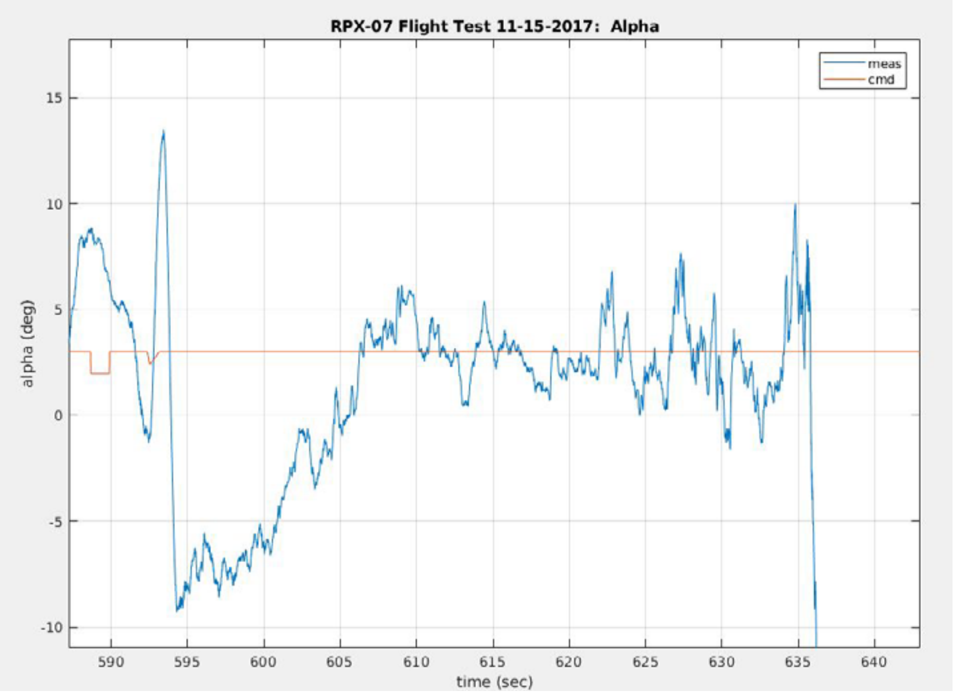
Drift in crosswind bias estimate

RPX-07 Full Flight: X Position Estimates

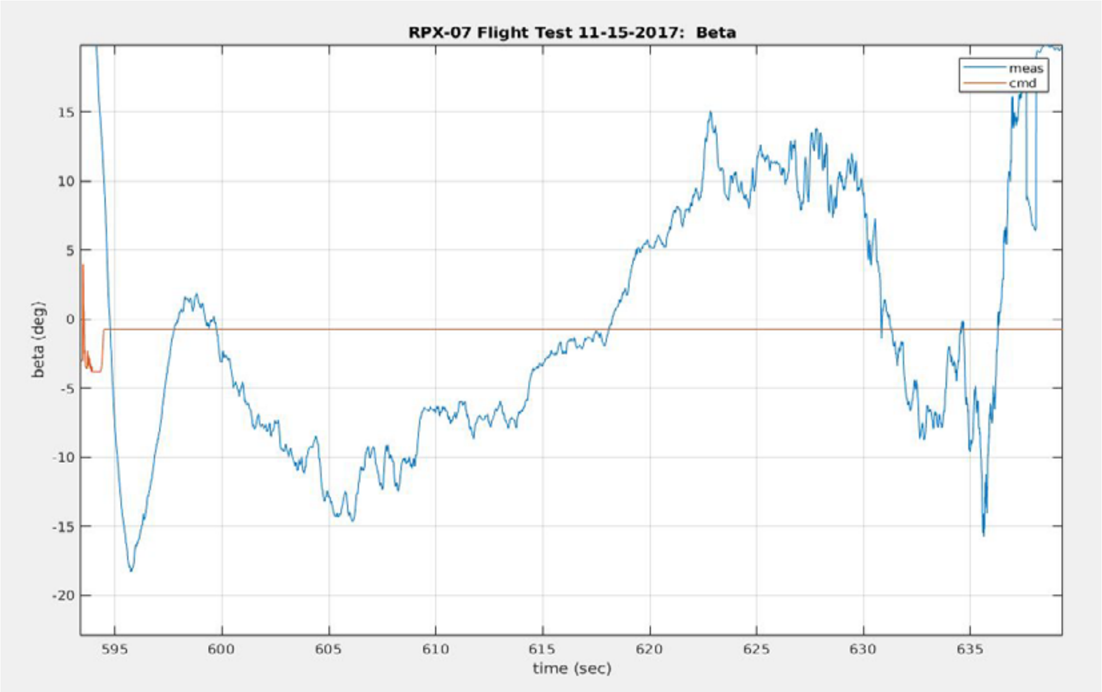


Note rapid position estimate divergence after loss of gps

RPX-07 Glide to Landing: Alpha



RPX-07 Glide to Landing: Beta

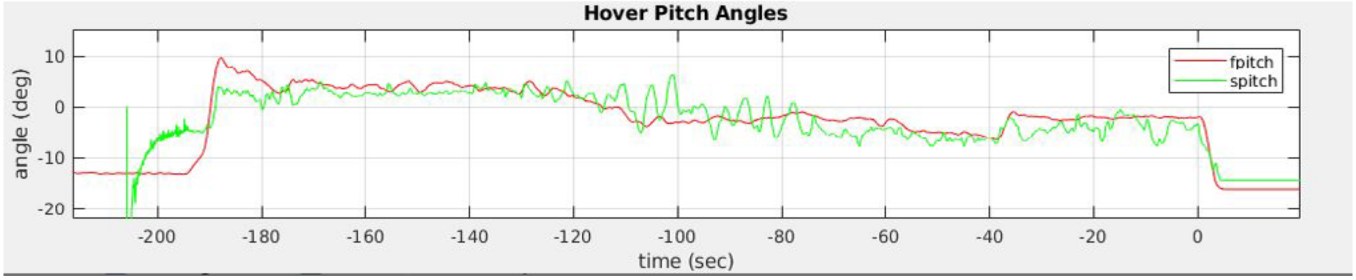


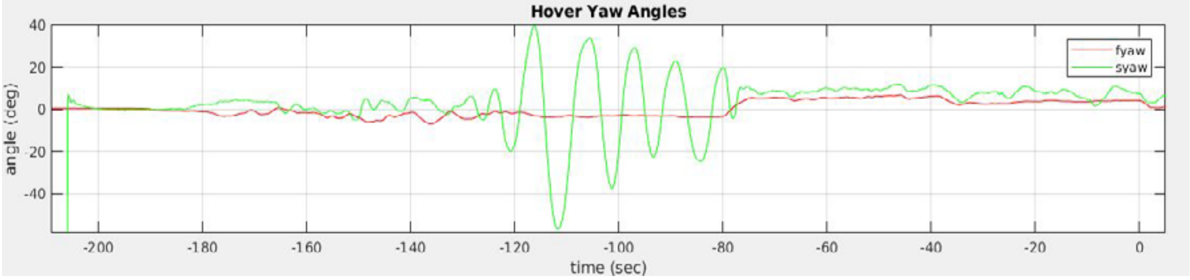
Lessons Learned

- Increased lateral velocity of kite in hover seems benign.
- The slewing of the crosswind plane to track wind azimuth contributes to our poor path tracking.
- Airspeed errors can create unacceptable thrust commands when we fly poorly.
- The rudder and yaw motor torque were working together in sync (not fighting each other)
- The basic crosswind controller was stable in the linear portions of the flight where the control surfaces were not saturated.
- The reduced rudder yaw torque authority predictions seem to be reasonable.
- Adaptive tether roll feed-forward (and beta?) commands will improve path tracking.
- Need to “fly better” in regions of varying winds and crosswind loop center commands.
    - How do we quantify “fly better”?
    - What are our limits to “flying better”?

Lessons Learned Part 2

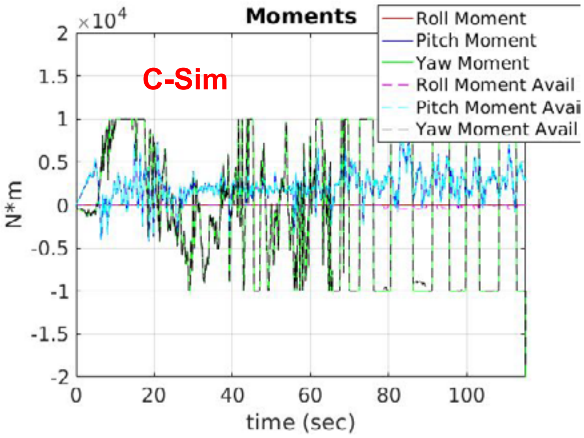
RPX-07 Hover Pitch and Yaw Angles: Flight vs. Sim

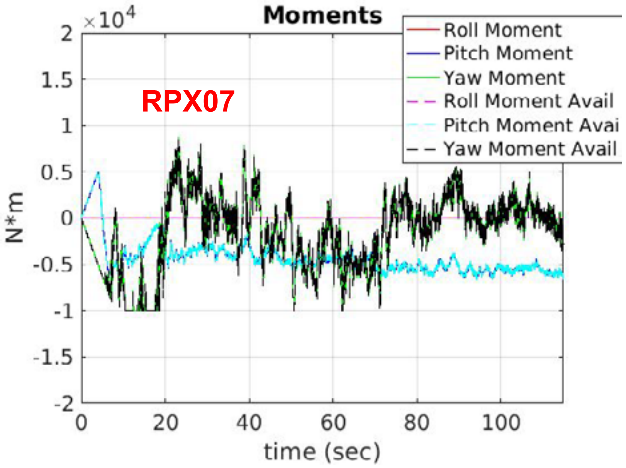




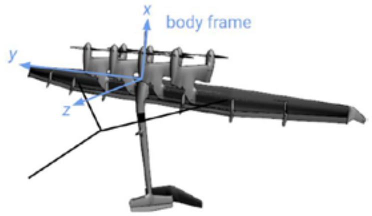
RPX-07 Hover Ascend

- Sim has rotor yaw moment saturations leading to limit cycle oscillations
- Not seen during flight test
- Incorrect prediction of total aerodynamic moments on the kite in hover
  - Notice the wrong sign on the pitching moment

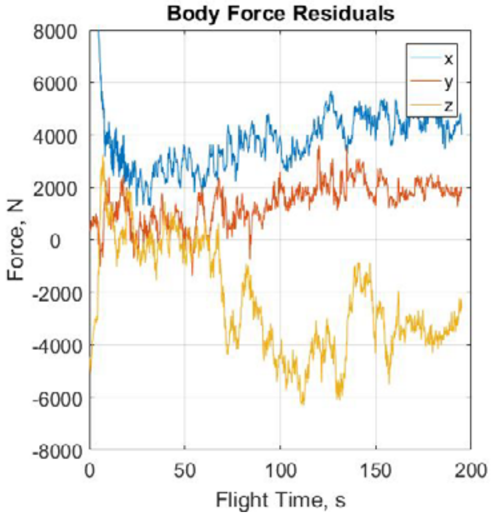


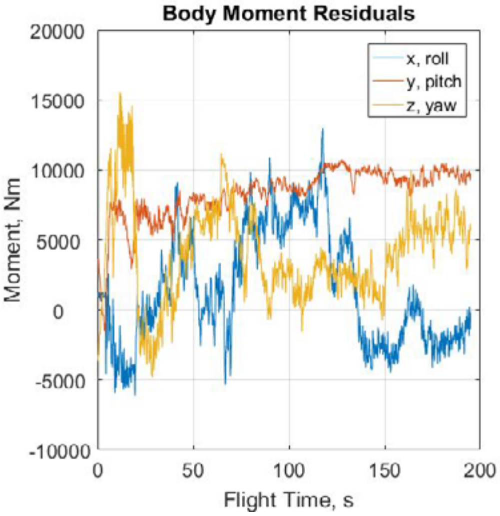


RPX-07 Hover Ascend & Hover Full Length

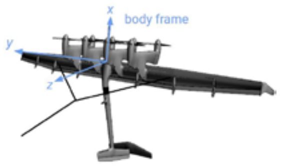


- Residuals = what we think the models (or measurements) are missing
- We have unaccounted for:
    - Pitch-back moment (+y)
    - Upwards X force (-weight, +rotor thrust, -tether tension)
    - Backwards Z force (+kite drag, -tether tension)

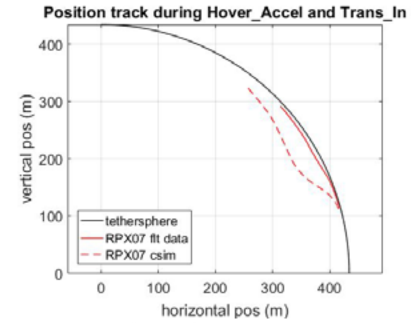

Body Force Residuals

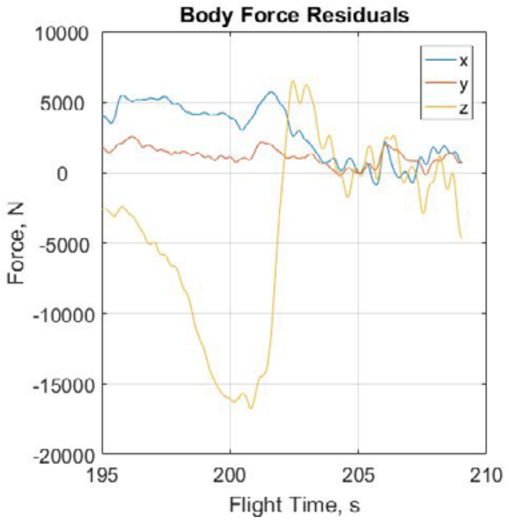

Body Moment Residuals

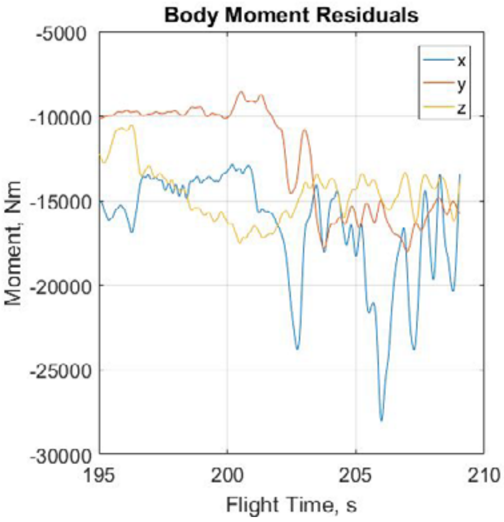
RPX-07 Hover Accel & Trans In

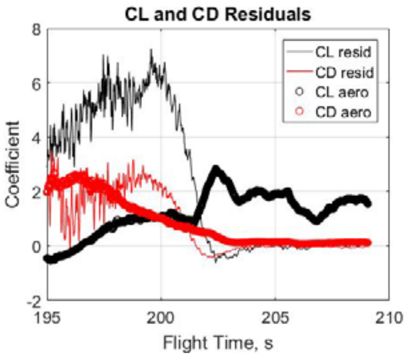


- At start of Hover Accel, same residuals as at the end of hover
- Then, large -Z force residual develops (missing a large force pinning us to the sphere)
    - This cannot come from excess rotor thrust, due to geometry
    - Airspeed estimate at the peak is approx 12 m/s
- At the peak, aero models predict CL = 1
    - Missing lift force is equivalent to an extra +6 CL


Position track during Hover_Accel and Trans_In


Body Force Residuals

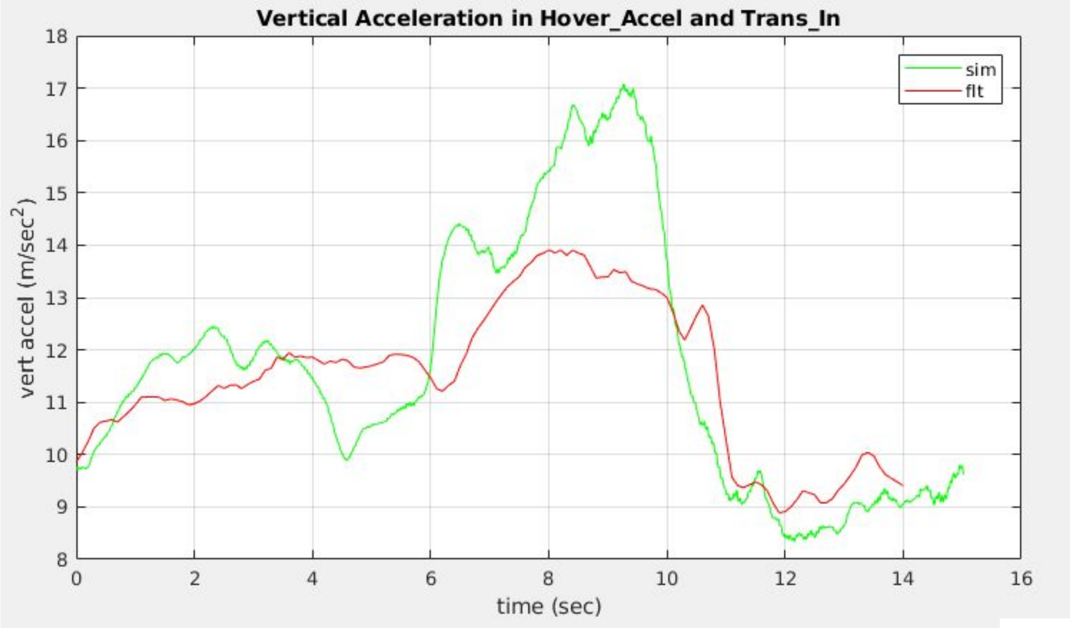

Body Moment Residuals


CL and CD Residuals

RPX-07 Hover Accel Vertical Acceleration

The vertical accel is greater in the sim than in flight.

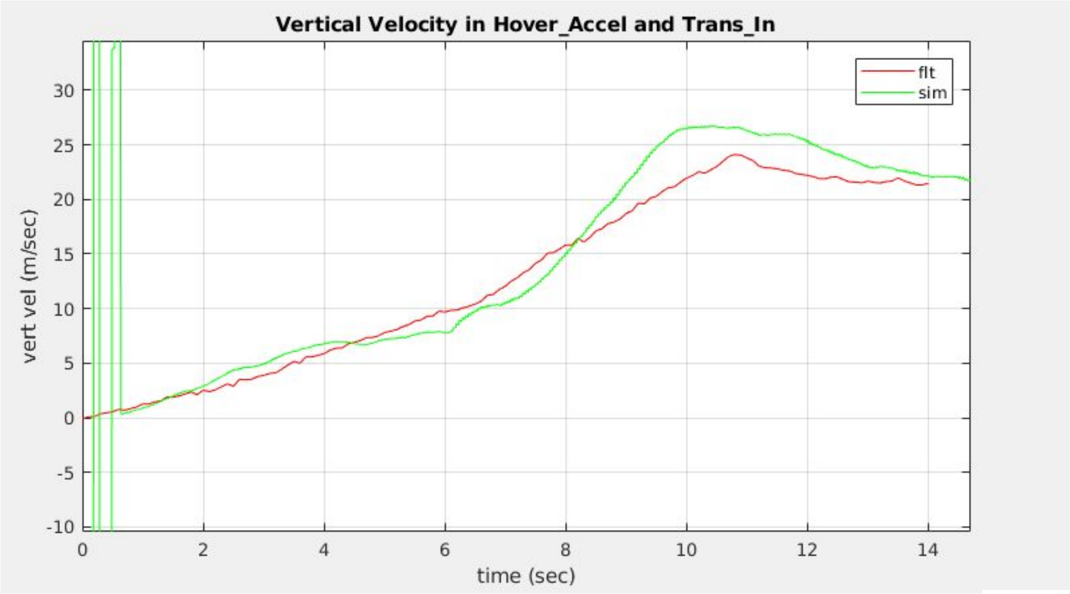
The opposite was true in rpx-02.



RPX-07 Hover Accel Mode: Vertical Velocity

The vertical accel is greater in the sim than in flight.

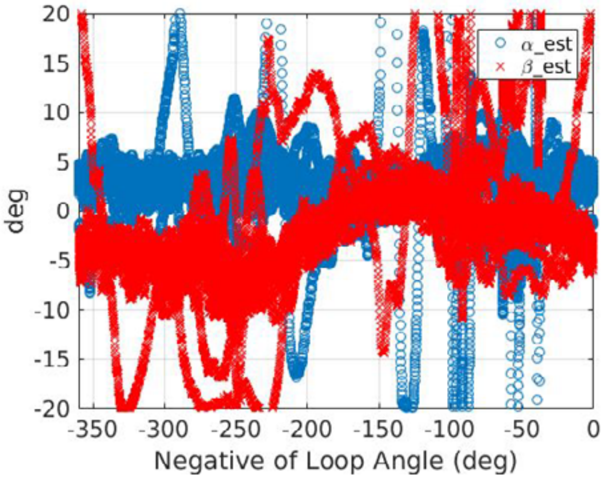
The opposite was true in rpx-02.



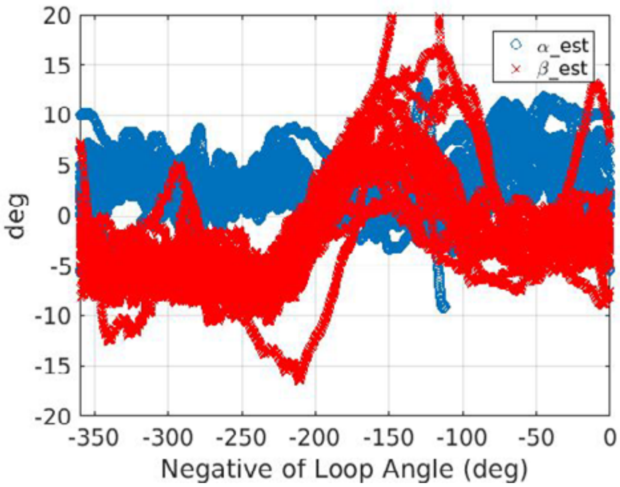
RPX-07 Crosswind Aerodynamic Angles vs Loop Angle

- The general trend of beta excursions around the loop is predicted
- Sim underpredicts the size of the once per loop swing from - to +

C-Sim

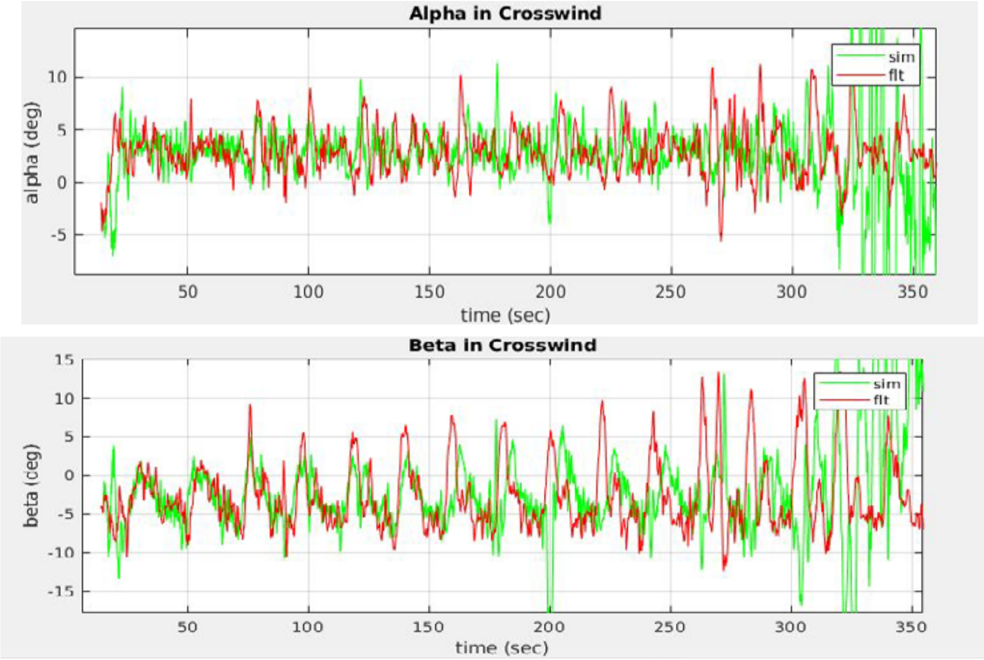


RPX07



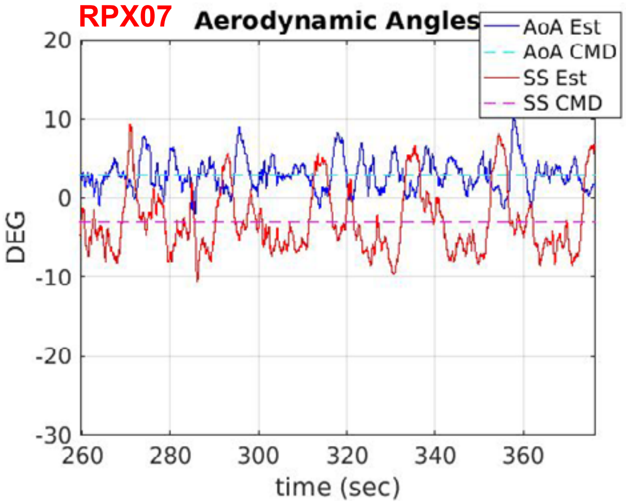
RPX-07 Crosswind Aerodynamic Angles vs Time

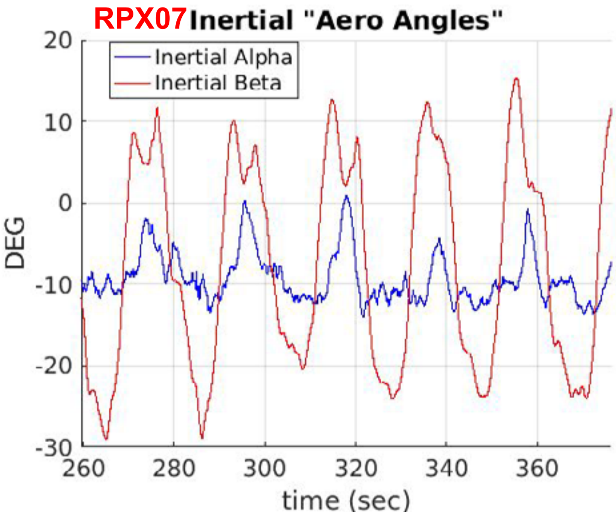
The alpha and beta excursions are between sim and flight are similar, but the flight values are generally larger.



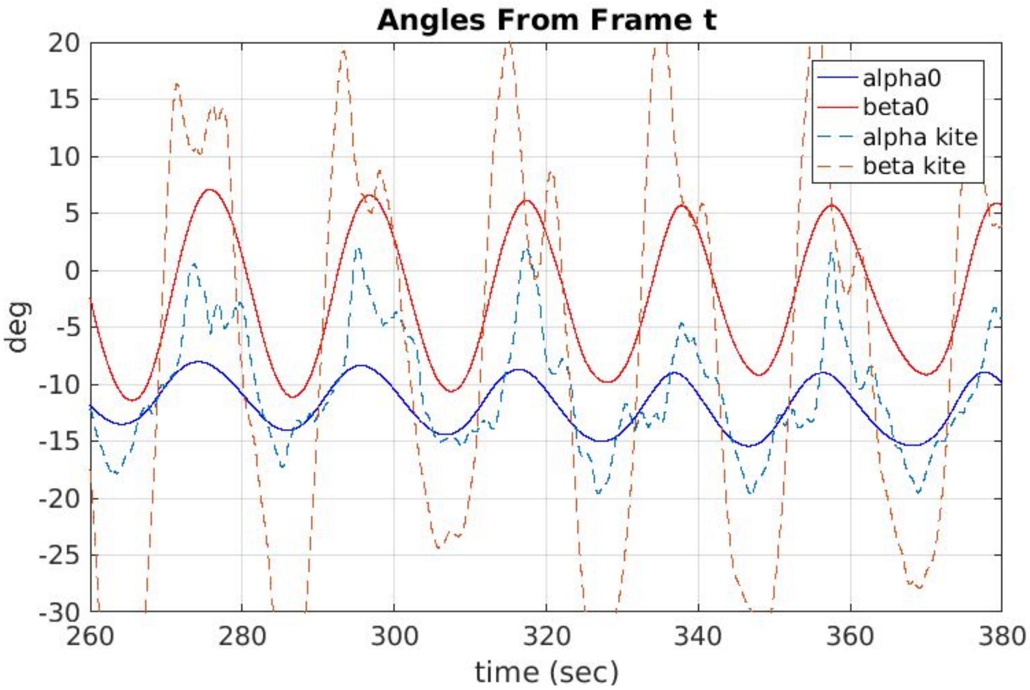
RPX-07 Crosswind Aero Angles Reminder

- There is a lot of inertial kite motion happening already
    - Rotations AND Translations both contribute to alpha & beta





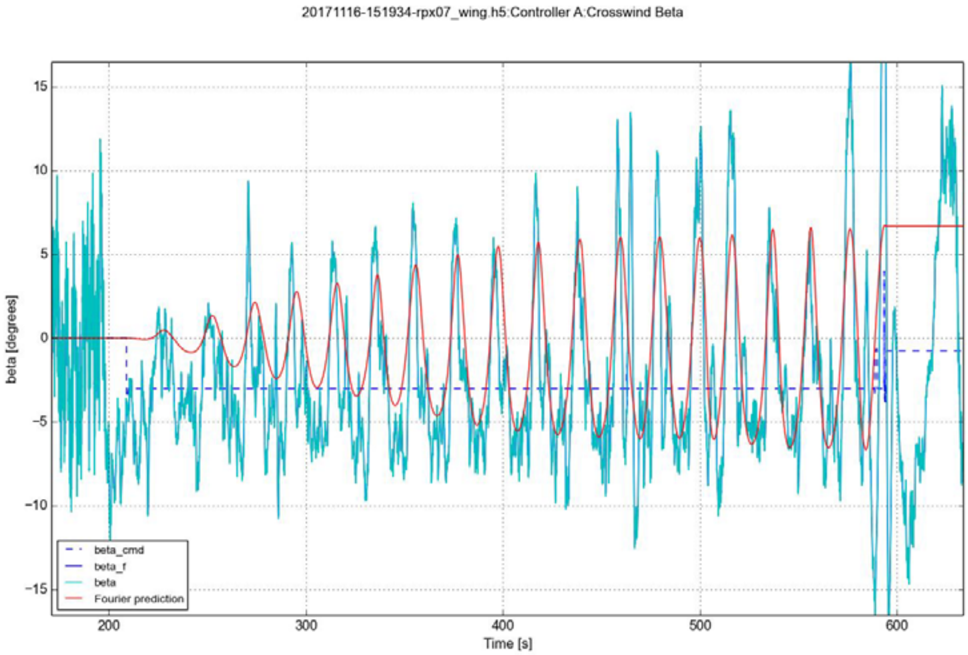
RPX-07 Motion Away From the Crosswind Circle



alpha0 & beta0 are motions away from the circle tangent required to fly exactly zero aerodynamic alpha and beta

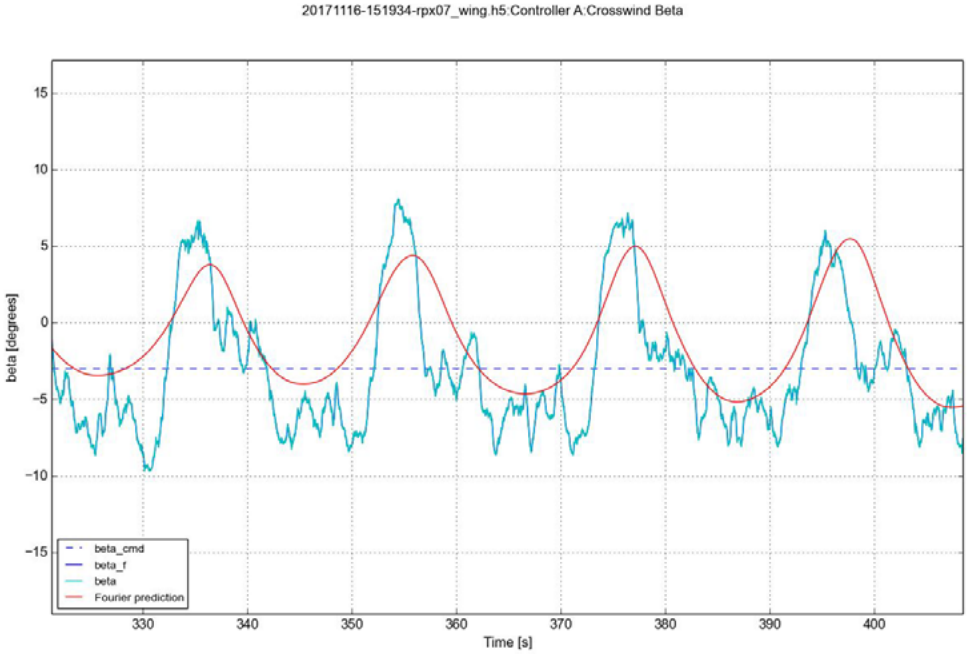
alpha kite and beta kite are euler angles representing the kite motion away from the circle tangent (how the kite's nose actually points in space)

RPX-07 Crosswind Aerodynamic Angles Beta



Online estimator fits Fourier coefficients to the beta excursions.

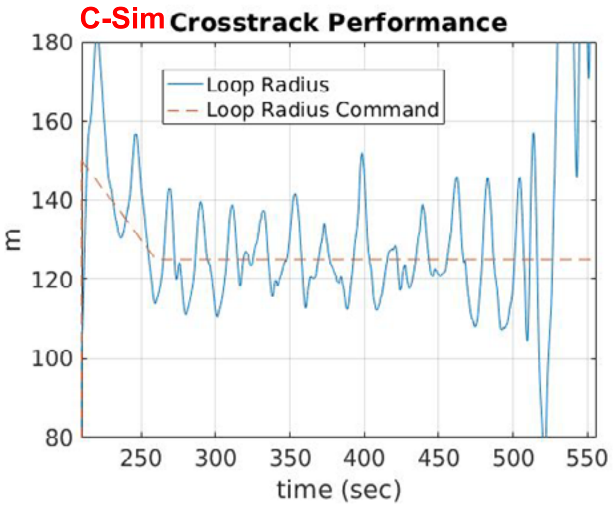
RPX-07 Crosswind Aerodynamic Angles Beta

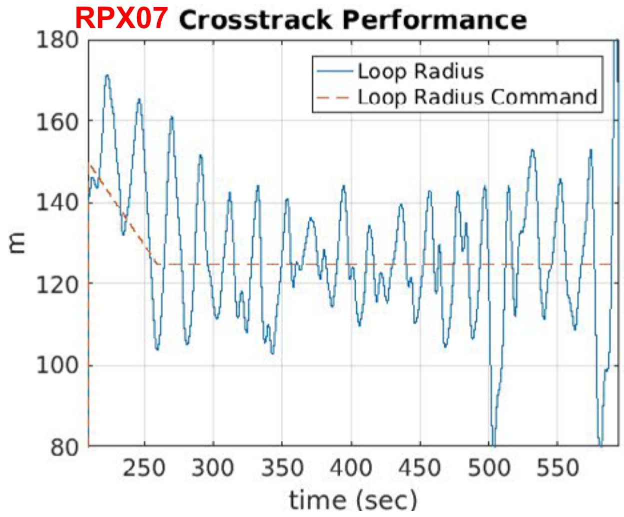


But the fit doesn't look so great in the flight data.

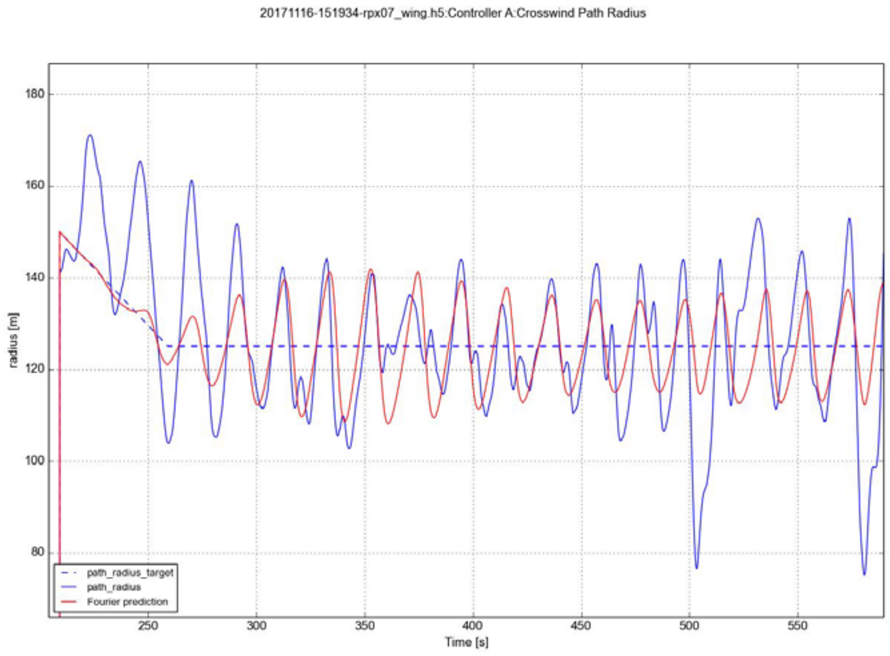
RPX-07 Crosswind Crosstrack Performance

- Crosstrack performance is slightly worse in flight than in sim
- Note that the C-sim crashes and so has a shorter x axis for this flight mode





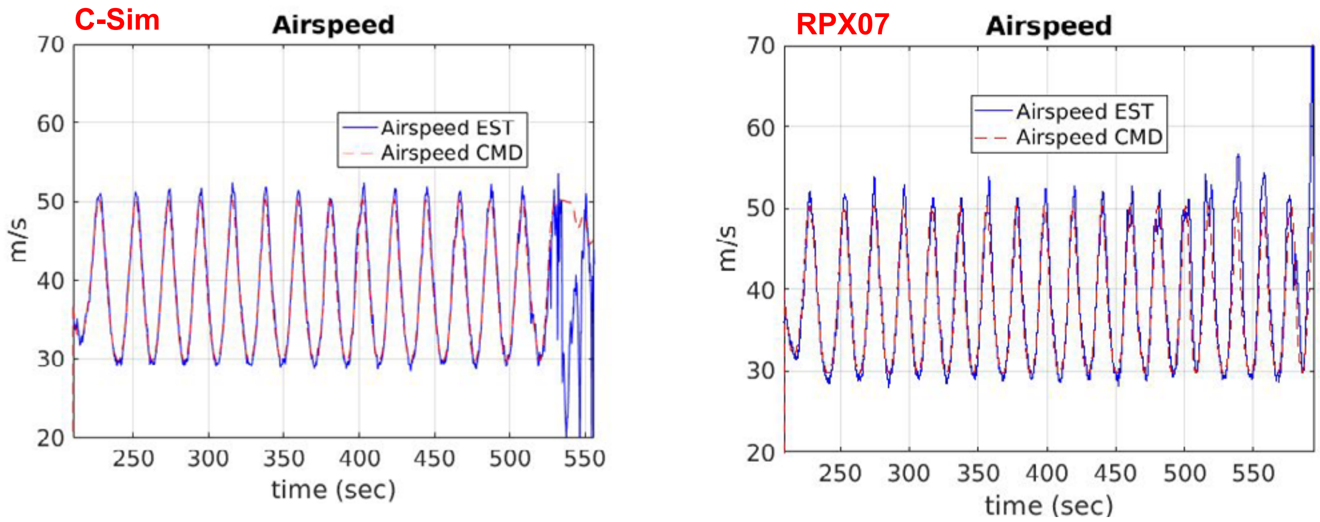
RPX-07 Crosswind Crosstrack Performance



Online Fourier fit to cross-track error.

RPX-07 Crosswind Airspeed Performance

- Airspeed performance is slightly worse in flight than in sim



RPX-07 Lessons Learned

- Sim hover is worse than flight
    - Yaw moment limit cycle

RPX-07 Lessons Learned Notes and Action Items

1. Add collapsed bridle model to the sim
2. Look at beta driving loss of lift (decreasing alpha)
3. Around 570-575 sec, look at dr, tether yaw command. yaw motor cmd to see what is happening
4. Look at long-term rate gyro bias estimates, esp. in cw
5. Redo hover Euler angle plot with correct time (chart 40)
6. Match sim/flt in hover for rpx-04 - 06
7. Why to trans-in from high hover? Look at tran-in-ing from low hover for high winds. Then use kite lift to power into cw mode.
8. How does sim vs. flight tension compare?
9. Look at huge increases in sim cndr, cnda, etc. to see if alpha, beta excursions get much better. Could also reduce the inertias.
10. Look at sim vs flight bridle moments on the kite.
11. Estimate roll error from catenary dynamics.
12. Compare rpx-06 to -07 for: alpha, beta, dr, da, loop radius, crosstrack error, velocity error, etc., winds
13. Look at sim vs. flight test at start of trans-in. Looks like they don't start at the same horizontal positions. Why not?

Fixes for next flight

1. Smooth out motor thrust commands (first-order filter + rate limit)
2. Make circle center slews for wind changes smarter to integrate with kite position around the circle.
3. Change int_aileron, int_rudder telemetry points to int_tether_roll_error and int_beta_error

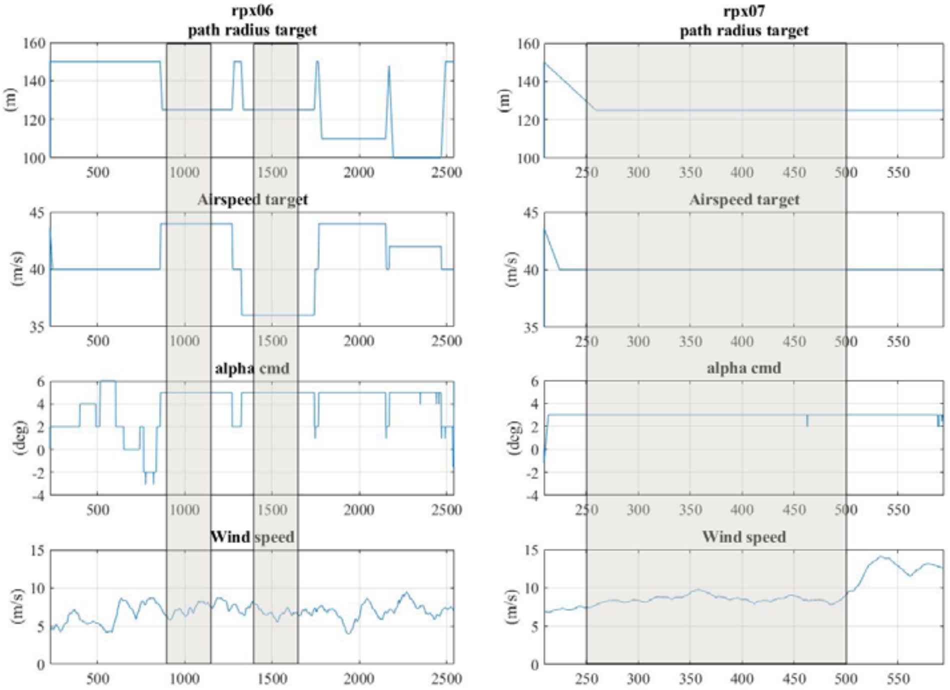
MAKANI

Comparison RPX-06 vs. RPX-07

14 December 2017

Test Configs

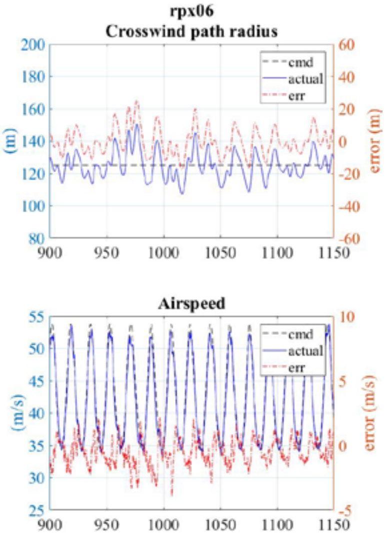
- We did not fly a same combination of R_target, V_target and alpha_target in rpx-06 as we did in rpx-07.
  → focus on a comparison at same R_target: rpx06a and rpx06b vs. rpx07 (250 seconds each).
- The difference in alpha_target (5 deg. vs. 3 deg.) should have no significant effect on flight quality (aero is linear for both angles).
- The difference in V_target could have an effect on flight quality.
- The wind speed was approximately 2 to 3 m/s higher in rpx07 than in rpx06a and rpx06b.



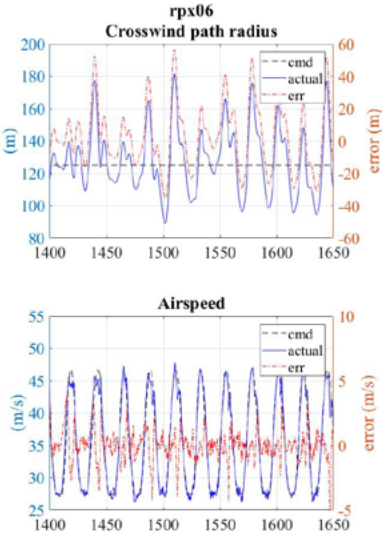
rpx06a rpx06b rpx07

Path and Airspeed Control

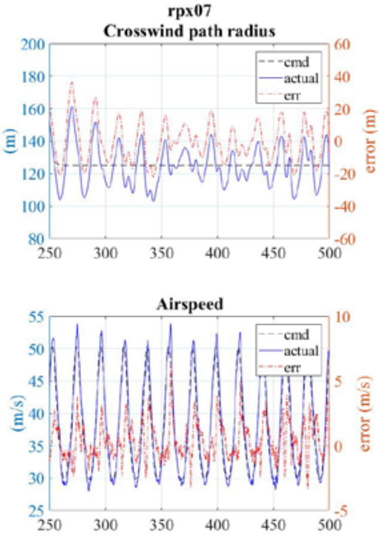
- After the transient from the first two loops, the x-track error in rpx07 was similar to rpx06a: +/- 20 m.
- The airspeed error in rpx07 was significantly larger than any of the two rpx06 cases.
- See next slide for zoom and details



rpx06a
(V_target = 44 m/s)



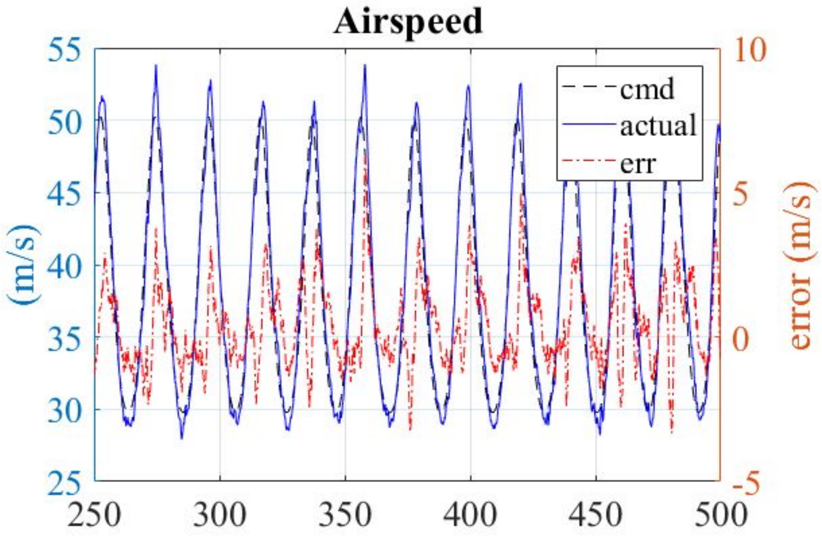
rpx06b
(V_target = 36 m/s)



rpx07
(V_target = 40 m/s)

Path and Airspeed Control

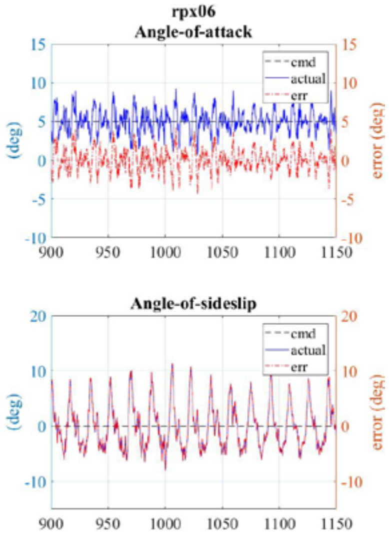
- The airspeed error during RPX07 was +/- 3 m/s with a few peaks at +5 m/s.
- The max airspeed error occurred close to the bottom of the loop.



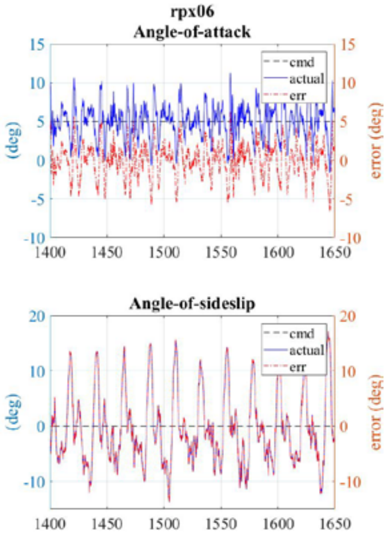
rpx07
(V_target = 40 m/s)

Aero Angles Control

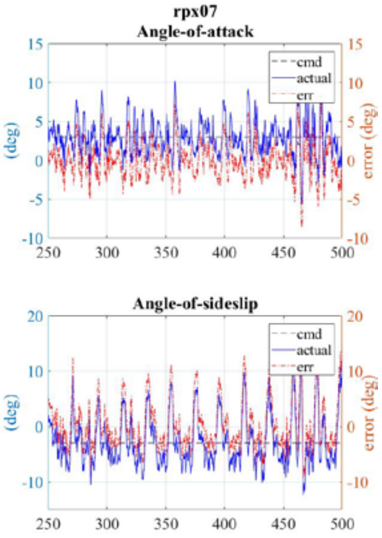
- The **sideslip excursions** during RPX07 were similar to RPX06a (**-5 / +10 deg.**) and less than during RPX06b.
- The **angle-of-attack excursions** during RPX07 were worse than RPX06a and on a par with RPX06b.
- The higher angle-of-attack excursions at lower airspeeds suggests that the excursions are not due to a lack of passive stability (stability decreases with airspeed)



rpx06a
(V_target = 44 m/s)



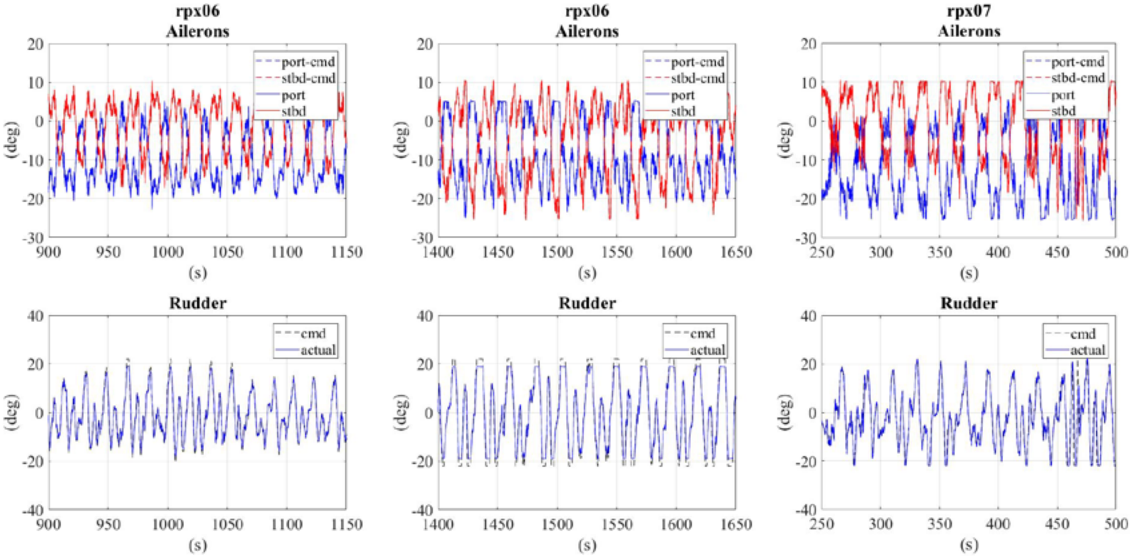
rpx06b
(V_target = 36 m/s)



rpx07
(V_target = 40 m/s)

Ailerons and Rudder Control

- The rudder was saturated in a similar way between RPX06a and RPX07. The rudder saturated a lot more during rpx06b.
- The ailerons saturated a lot more during RPX07 than RPX06 a or b.



rpx06a
(V_target = 44 m/s)

rpx06b
(V_target = 36 m/s)

rpx07
(V_target = 40 m/s)

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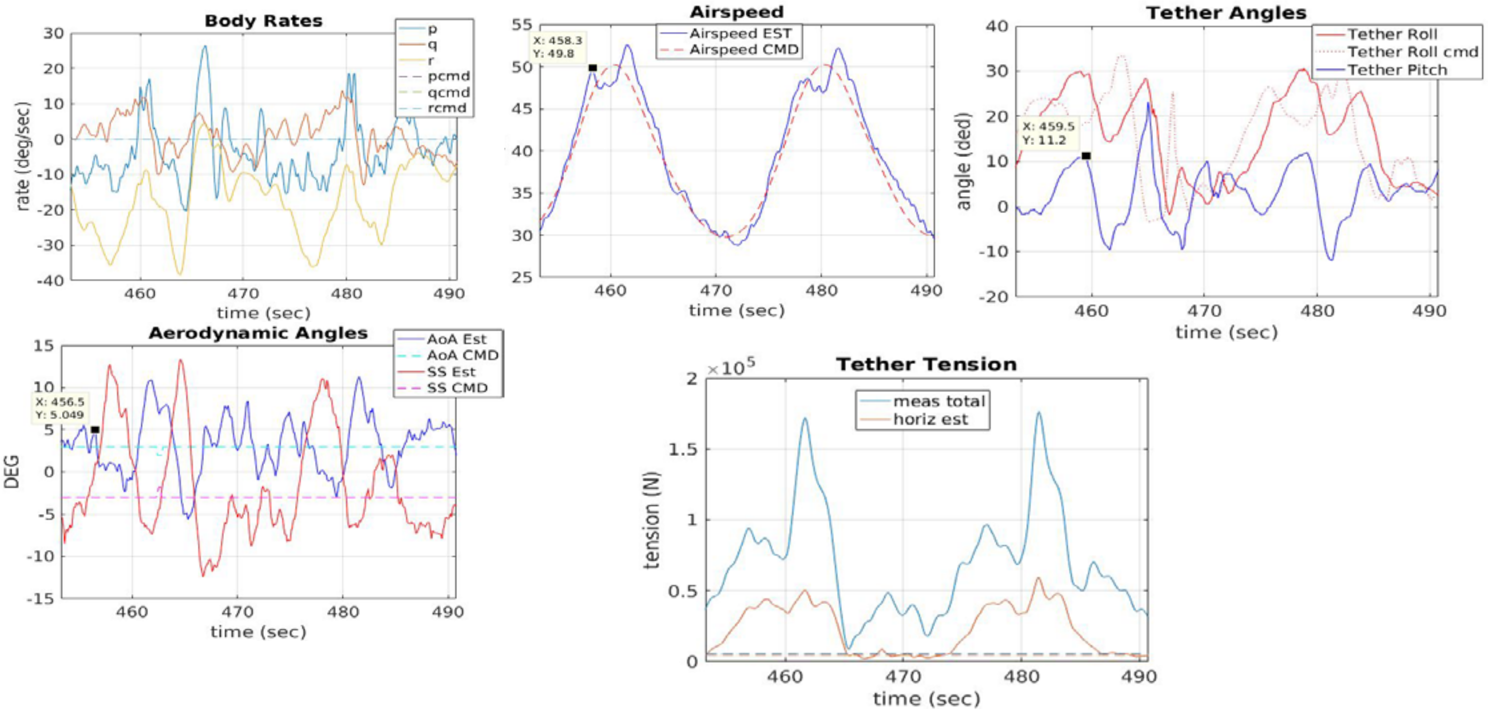
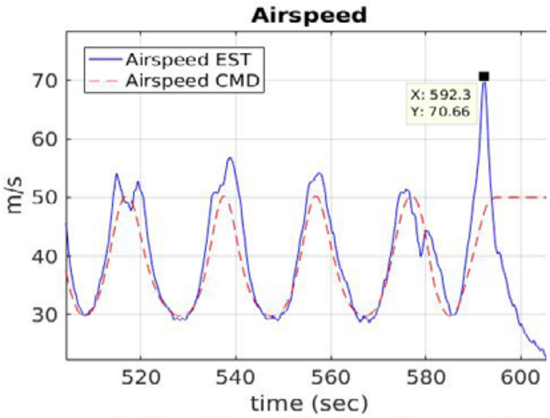
Appendix / Deep Dives

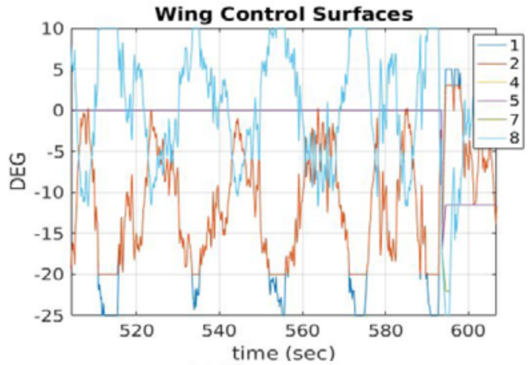
RPX-07 Notes.

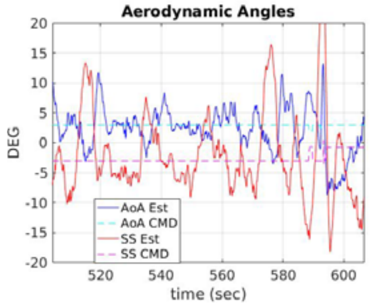
- what do other groups want us to discuss
    - rudder
    - ailerons
    - motor steering
    - commands to power system
    - add power system dynamic model to sim?
    - alpha command to control airspeed, in addition to props
    - push to get things done by control team prior to the flight and how did that work?
    - Should we fly a low-wind flight test to examine the aero and flight dynamics?
    - actuator slew rates

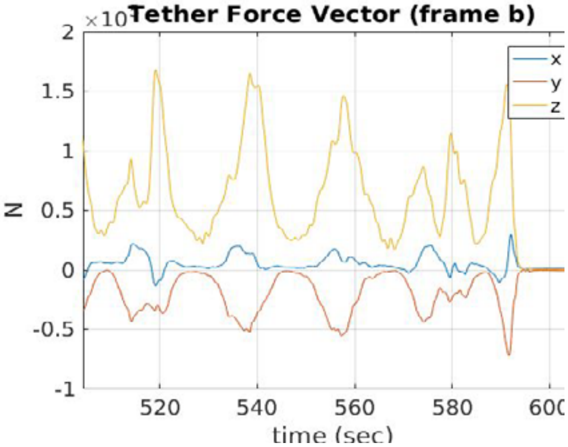


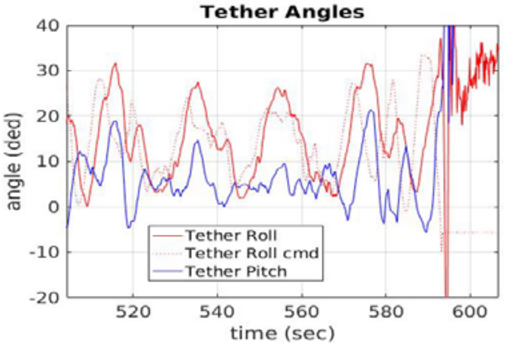
RPX-07 Notes.

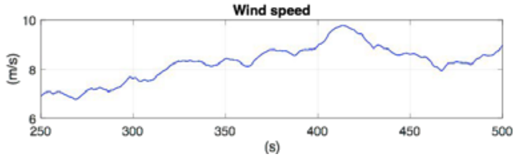

Airspeed
Airspeed EST
Airspeed CMD
X: 592.3
Y: 70.66
m/s
70
60
50
40
30
520
540
560
580
600
time (sec)

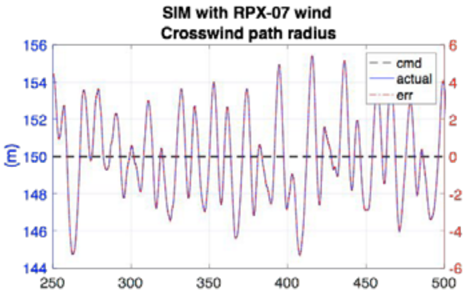

Wing Control Surfaces
1
2
4
5
7
8
DEG
10
5
0
-5
-10
-15
-20
-25
520
540
560
580
600
time (sec)

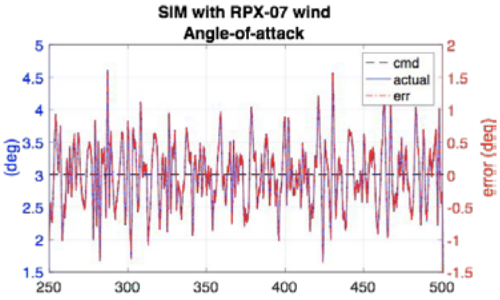

Aerodynamic Angles
AoA Est
AoA CMD
SS Est
SS CMD
DEG
20
15
10
5
0
-5
-10
-15
-20
520
540
560
580
600
time (sec)

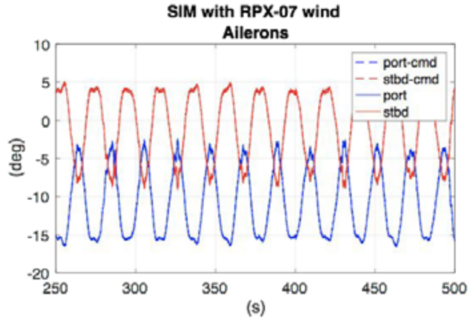

×10
Tether Force Vector (frame b)
x
y
z
N
2
1.5
1
0.5
0
-0.5
-1
520
540
560
580
600
time (sec)

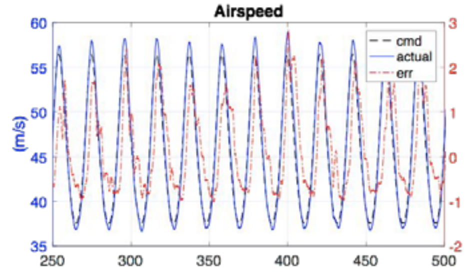

Tether Angles
Tether Roll
Tether Roll cmd
Tether Pitch
angle (ded)
40
30
20
10
0
-10
-20
520
540
560
580
600
time (sec)

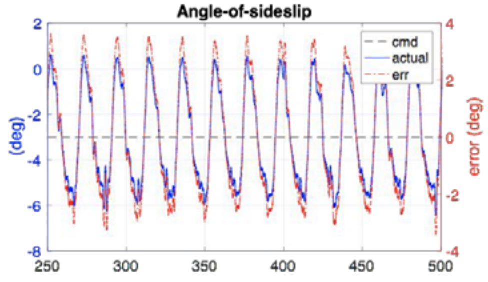

Wind speed
(m/s)
10
8
6
250
300
350
400
450
500
(s)

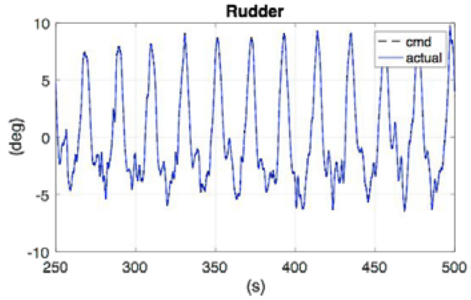

SIM with RPX-07 wind
Crosswind path radius
cmd
actual
err
(m)
error (m)
156
154
152
150
148
146
144
6
4
2
0
-2
-4
-6
250
300
350
400
450
500


SIM with RPX-07 wind
Angle-of-attack
cmd
actual
err
(deg)
error (deg)
5
4.5
4
3.5
3
2.5
2
1.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
250
300
350
400
450
500


SIM with RPX-07 wind
Ailerons
port-cmd
stbd-cmd
port
stbd
(deg)
10
5
0
-5
-10
-15
-20
250
300
350
400
450
500
(s)


Airspeed
cmd
actual
err
(m/s)
error (m/s)
60
55
50
45
40
35
3
2
1
0
-1
-2
250
300
350
400
450
500


Angle-of-sideslip
cmd
actual
err
(deg)
error (deg)
2
0
-2
-4
-6
-8
4
2
0
-2
-4
250
300
350
400
450
500


Rudder
cmd
actual
(deg)
10
5
0
-5
-10
250
300
350
400
450
500
(s)

Flight Testing
RPX-07 Lessons Review

RPX-07 Outline

Outline

- Flight summary
- Objectives
- W4W
    - Wind
    - CC & flight conduct
    - Cameras
- Crash management
- RPX-08 flight objectives
- RPX-08 preliminary schedule

Summary

- Thurs, 11/16, wind 10-14m/s
- Launched at 6:11pm in ~ 6m/s wind
- Flew ~17 loops
- Generated more power than we have before
- MV failure → poor flight quality → ABORT

Flight Objectives, Summary

- Fly 2 hours of crosswind in wind > 8m/s
  a. Return to flight with SN3, including the above system upgrades
  b. Safely land on the perch
- Fly test cases per RPX-07 Flight Controls Plan
  a. General test cadence
    i. 10 loops in baseline case
    ii. Assess stability of baseline without motor steering
    iii. Alpha sweep, from 2 deg to 12 deg (without motor steering if stable)
      1. 10 loops each
      2. Target min altitude of 120m
    iv. 10 min power points at highest predicted generation test cases
      1. Airspeed command binned by wind speed
      2. Highest stable alpha
      3. With whichever gains look better
      4. Target min altitude of 100 m

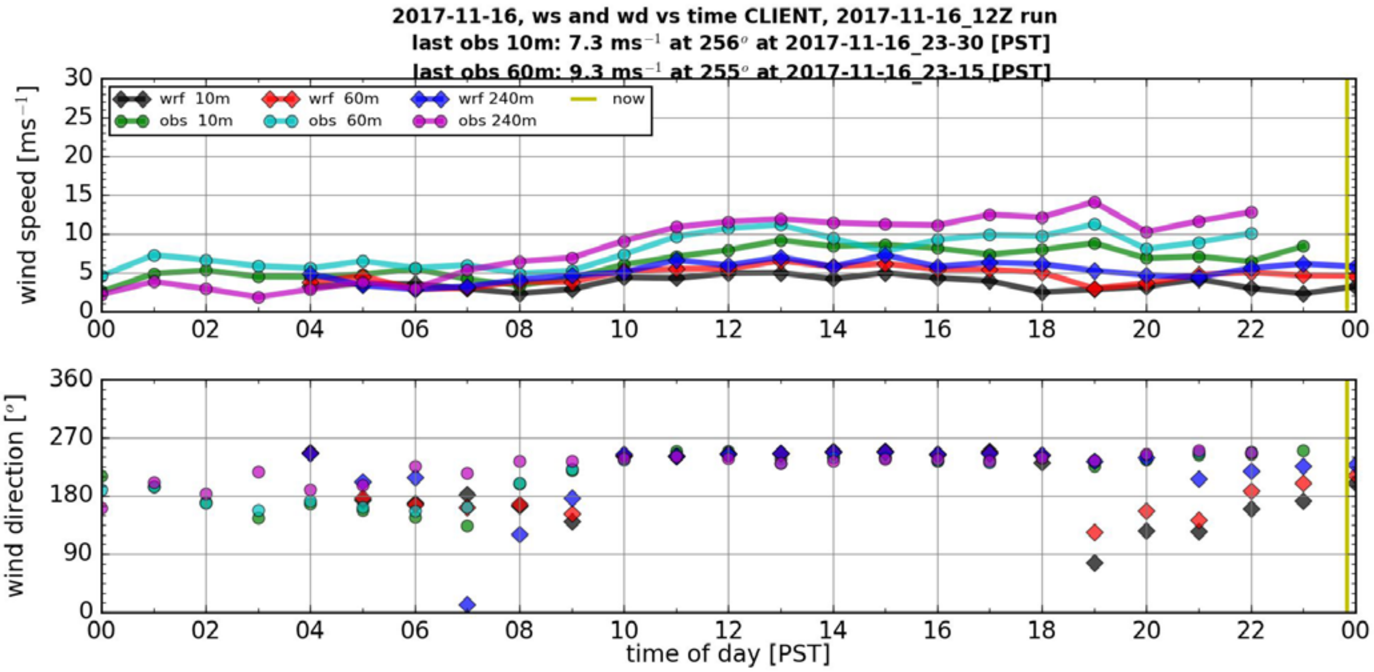
Flight Objectives, Summary

- Collect data that will be used to:
    a. Quantify aerodynamic improvements from slats and fairings
        i. Mainplane pressure data
        ii. Tuft videos
        iii. Flight performance
    b. Investigate known discrepancies between the sim and flight performance:
        i. Crosswind tension
        ii. Rudder effectiveness
        iii. Trans-in
        iv. Large pitch moments in hover
    c. Inform tether & bridle fairing design
        i. Measure angle of attack of three different fairing sections
        ii. Collect video of bridle fairings
- Collect video from numerous ground and onboard cams [internal ref: RPX camera positions doc]
- Find unknown crosswind-related issues

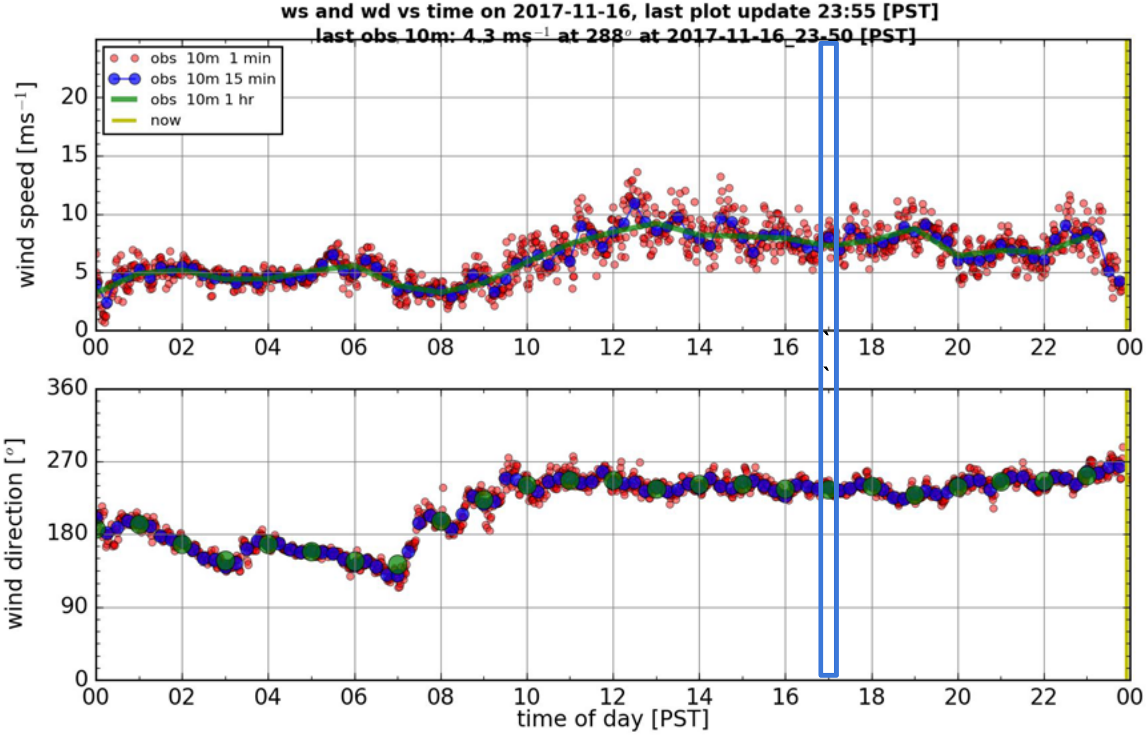
W4W

- Marginal forecast, but lots to do. Call was go to CL and get ready
    a. Mon: FCU swap
    b. Tues: code freeze, finish dry run
    c. Wed: W4W began
    d. Thurs: RPX-07

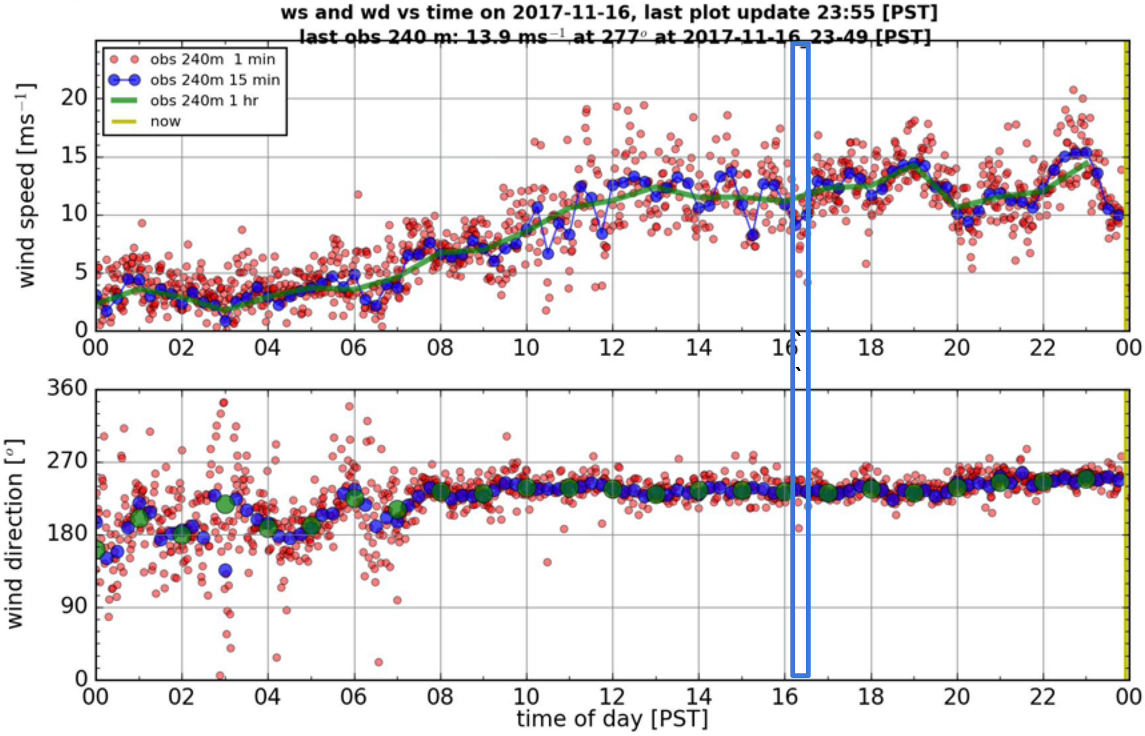
Day-of wind



Day-of wind



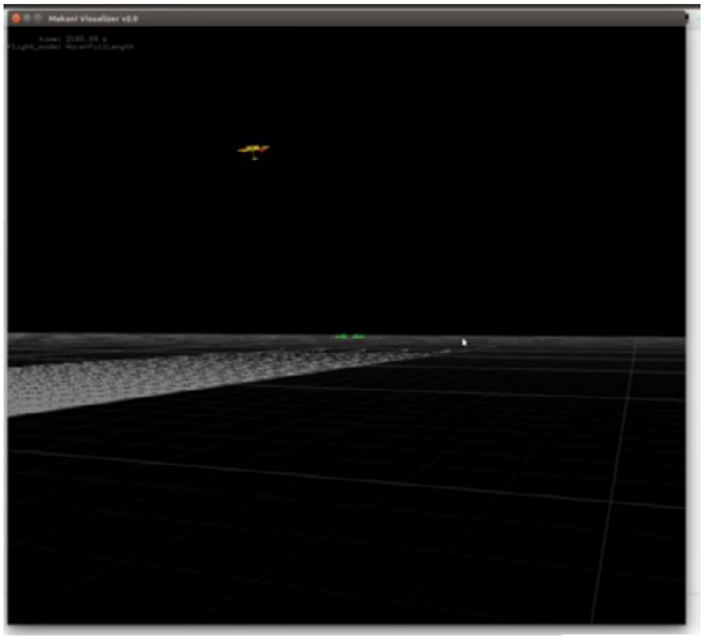
Day-of wind



CC & flight conduct

- What worked
    - TD and pilot swap - all things considered, successful
    - Comprehensive morning rehearsal
    - Alameda & RLS on call during rehearsal, pre-flight checks

- What could be better
    - Pilot situational awareness during glide
        - Wind direction indicator
        - Targets for alpha, airspeed on touchdown
        - Visual beta feedback



Attitude Management

The Good

- No people or hardware were harmed during salvage
- Everyone stayed calm, followed checklists
- People took initiative and kept themselves busy
  - Designating task leads on 2nd day worked well
  - Alameda provided good support on recovery
    - Power team on Satcon data recovery
    - Ops team fast-tracked Navy approval

The Bad

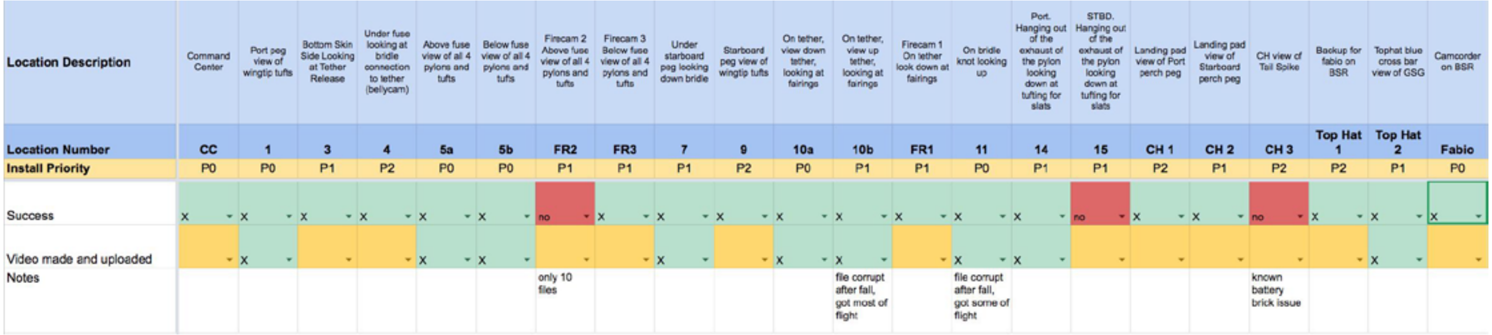
- Kite was at risk of falling, and we didn't maximize our time to mitigate this biggest risk before sunset
- Everyone stayed calm, followed checklists
  - *Checklists could have been better*
- People took initiative and kept themselves busy
  - *Sometimes to detriment of overall operation*

The Ugly

- No clearly defined leader on evening of landing
- Need to kit additional stabilization/salvage supplies
  - Kite stabilization rigging, weights, dunnage, ladders, light plants, talk-to-kite kit, etc.

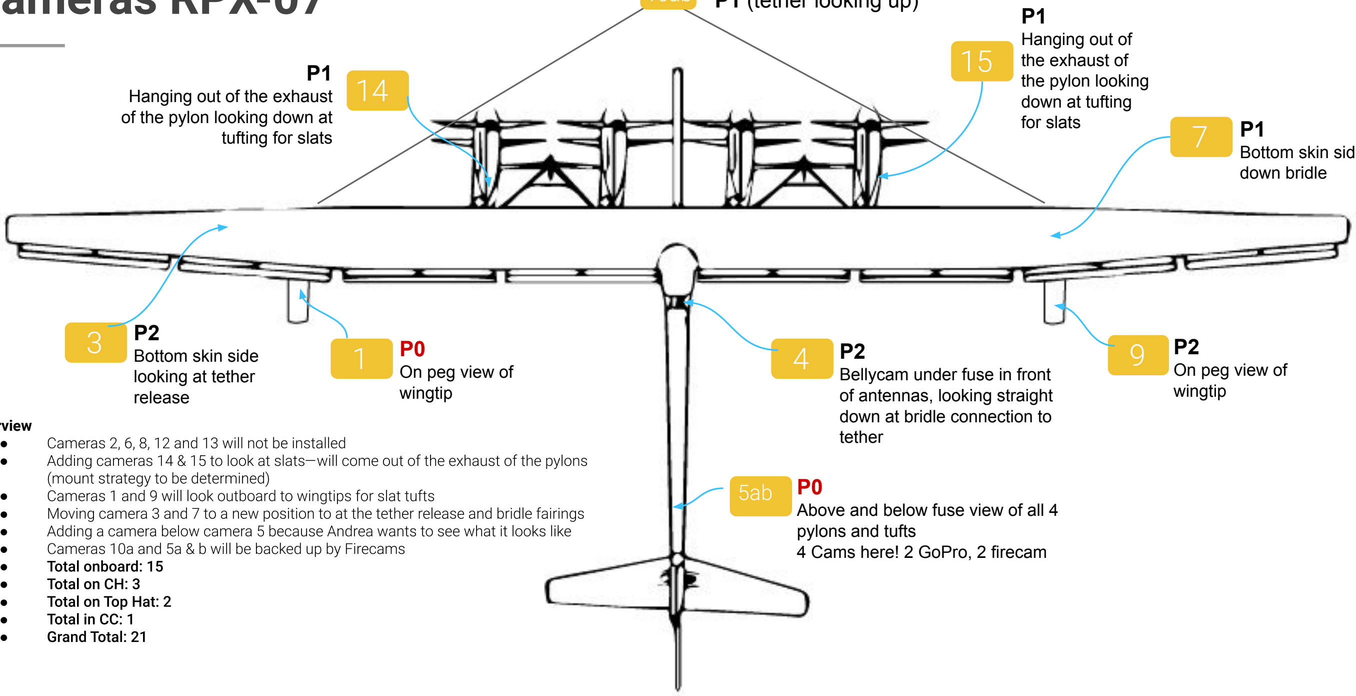
[internal ref: Test Day Notes]

Onboard Cameras - 95% Successful



Location Description	Command Center	Port peg view of wingtip tufts	Bottom Skin Side Looking at Tether Release	Under fuse looking at bridle connection to tether (bellycam)	Above fuse view of all 4 pylons and tufts	Below fuse view of all 4 pylons and tufts	Firecam 2 Above fuse view of all 4 pylons and tufts	Firecam 3 Below fuse view of all 4 pylons and tufts	Under starboard peg looking down bridle	Starboard peg view of wingtip tufts	On tether, view down tether, looking at fairings	On tether, view up tether, looking at fairings	Firecam 1 On tether look down at fairings	On bridle knot looking up	Port. Hanging out of the exhaust of the pylon looking down at tufting for slats	STBD. Hanging out of the exhaust of the pylon looking down at tufting for slats	Landing pad view of Port perch peg	Landing pad view of Starboard perch peg	CH view of Tail Spike	Backup for fabio on BSR	Tophat blue cross bar view of GSG	Camcorder on BSR
Location Number	**CC**	**1**	**3**	**4**	**5a**	**5b**	**FR2**	**FR3**	**7**	**9**	**10a**	**10b**	**FR1**	**11**	**14**	**15**	**CH 1**	**CH 2**	**CH 3**	**Top Hat 1**	**Top Hat 2**	**Fabio**
Install Priority	P0	P0	P1	P2	P0	P0	P1	P1	P1	P2	P0	P1	P1	P0	P1	P1	P2	P1	P2	P2	P1	P0
Success	x	x	x	x	x	x	no	x	x	x	x	x	x	x	x	no	x	x	no	x	x	x
Video made and uploaded		x			x	x			x		x	x		x	x						x	
Notes							only 10 files					file corrupt after fall, got most of flight		file corrupt after fall, got some of flight					known battery brick issue			

Proposed & Installed GoPro Cameras RPX-07



11 **P0** (bridle knot looking up)
10ab **P0** (tether looking down) Plus firecam
P1 (tether looking up)

14 **P1**
Hanging out of the exhaust of the pylon looking down at tufting for slats

15 **P1**
Hanging out of the exhaust of the pylon looking down at tufting for slats

7 **P1**
Bottom skin side looking down bridle

3 **P2**
Bottom skin side looking at tether release

1 **P0**
On peg view of wingtip

4 **P2**
Bellycam under fuse in front of antennas, looking straight down at bridle connection to tether

9 **P2**
On peg view of wingtip

5ab **P0**
Above and below fuse view of all 4 pylons and tufts
4 Cams here! 2 GoPro, 2 firecam

Overview

- Cameras 2, 6, 8, 12 and 13 will not be installed
- Adding cameras 14 & 15 to look at slats—will come out of the exhaust of the pylons (mount strategy to be determined)
- Cameras 1 and 9 will look outboard to wingtips for slat tufts
- Moving camera 3 and 7 to a new position to at the tether release and bridle fairings
- Adding a camera below camera 5 because Andrea wants to see what it looks like
- Cameras 10a and 5a & b will be backed up by Firecams
- **Total onboard: 15**
- **Total on CH: 3**
- **Total on Top Hat: 2**
- **Total in CC: 1**
- **Grand Total: 21**

Onboard Cameras

What worked:

- Low ambient temperature
- Firecams for reliability and duration
- Two cameras at every P0 location
- Checklists and communication improvement, training, 3 lifts!

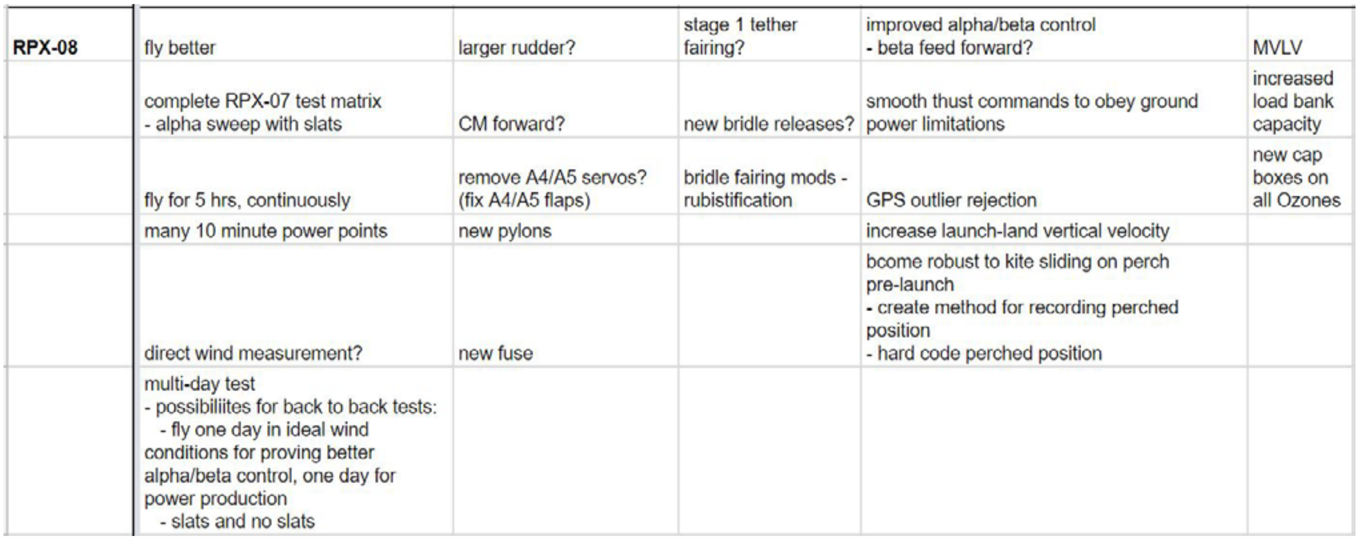
Immediate actions for RPX-08:

- Encourage team to reduce number of onboard cameras
- Share sample footage in rough form on Drive while working to sync for youtube playlist and data overlay

Ongoing long-term actions:

- Work with team to identify key camera locations for permanent installation
  - Test LV bus to power cameras on SN3
- Long-term: integrate cameras into airframe and controls with help from team

Upcoming flight objectives

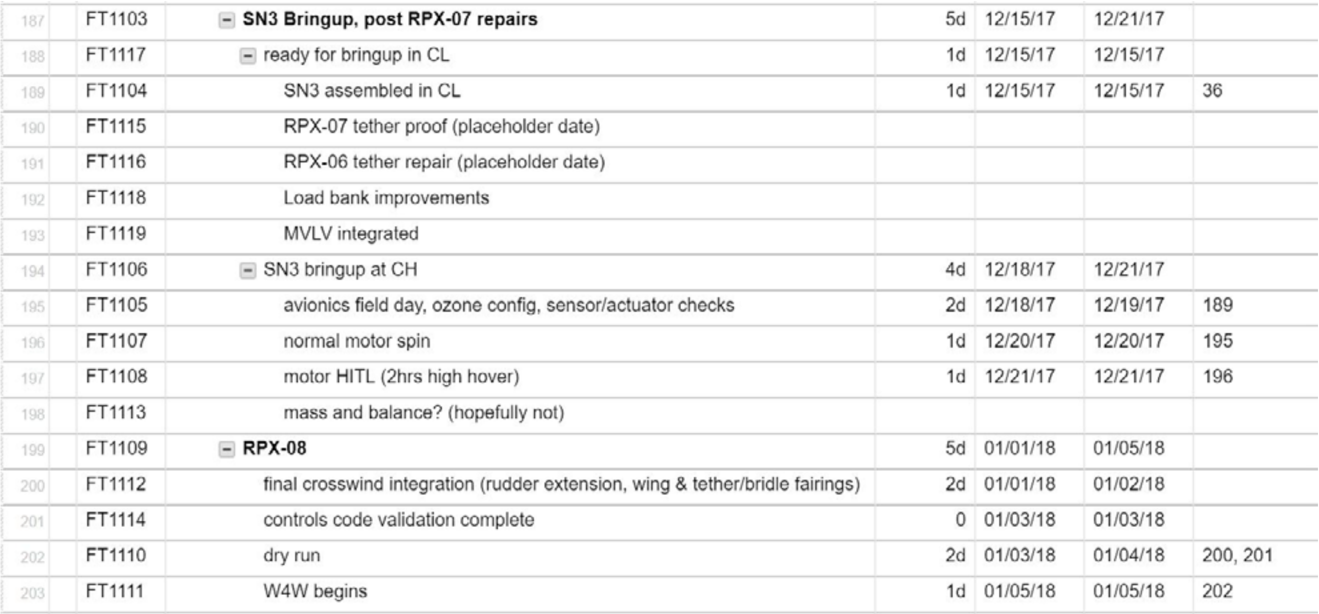


RPX-08	fly better	larger rudder?	stage 1 tether fairing?	improved alpha/beta control - beta feed forward?	MVLV
	complete RPX-07 test matrix - alpha sweep with slats	CM forward?	new bridle releases?	smooth thust commands to obey ground power limitations	increased load bank capacity
	fly for 5 hrs, continuously	remove A4/A5 servos? (fix A4/A5 flaps)	bridle fairing mods - rubistification	GPS outlier rejection	new cap boxes on all Ozones
	many 10 minute power points	new pylons		increase launch-land vertical velocity	
	direct wind measurement?	new fuse		bcome robust to kite sliding on perch pre-launch - create method for recording perched position - hard code perched position	
	multi-day test - possibiliites for back to back tests: - fly one day in ideal wind conditions for proving better alpha/beta control, one day for power production - slats and no slats				

This is very much a first pass, and will be informed by the lessons learned from each team.

Live objectives sheet

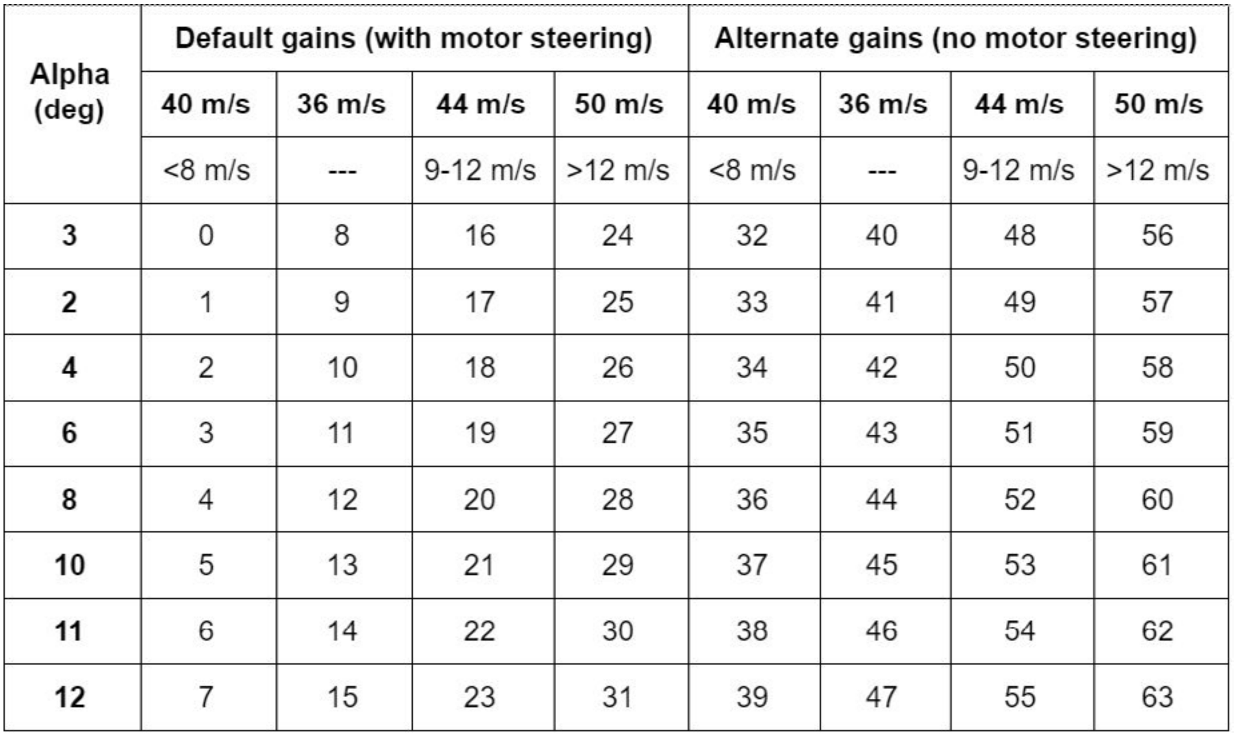
Preliminary schedule



187	FT1103	⊟ **SN3 Bringup, post RPX-07 repairs**	5d	12/15/17	12/21/17	
188	FT1117	⊟ ready for bringup in CL	1d	12/15/17	12/15/17	
189	FT1104	SN3 assembled in CL	1d	12/15/17	12/15/17	36
190	FT1115	RPX-07 tether proof (placeholder date)				
191	FT1116	RPX-06 tether repair (placeholder date)				
192	FT1118	Load bank improvements				
193	FT1119	MVLV integrated				
194	FT1106	⊟ SN3 bringup at CH	4d	12/18/17	12/21/17	
195	FT1105	avionics field day, ozone config, sensor/actuator checks	2d	12/18/17	12/19/17	189
196	FT1107	normal motor spin	1d	12/20/17	12/20/17	195
197	FT1108	motor HITL (2hrs high hover)	1d	12/21/17	12/21/17	196
198	FT1113	mass and balance? (hopefully not)				
199	FT1109	⊟ **RPX-08**	5d	01/01/18	01/05/18	
200	FT1112	final crosswind integration (rudder extension, wing & tether/bridle fairings)	2d	01/01/18	01/02/18	
201	FT1114	controls code validation complete	0	01/03/18	01/03/18	
202	FT1110	dry run	2d	01/03/18	01/04/18	200, 201
203	FT1111	W4W begins	1d	01/05/18	01/05/18	202

CL Testing SmartSheet

RPX-07 Test Cases

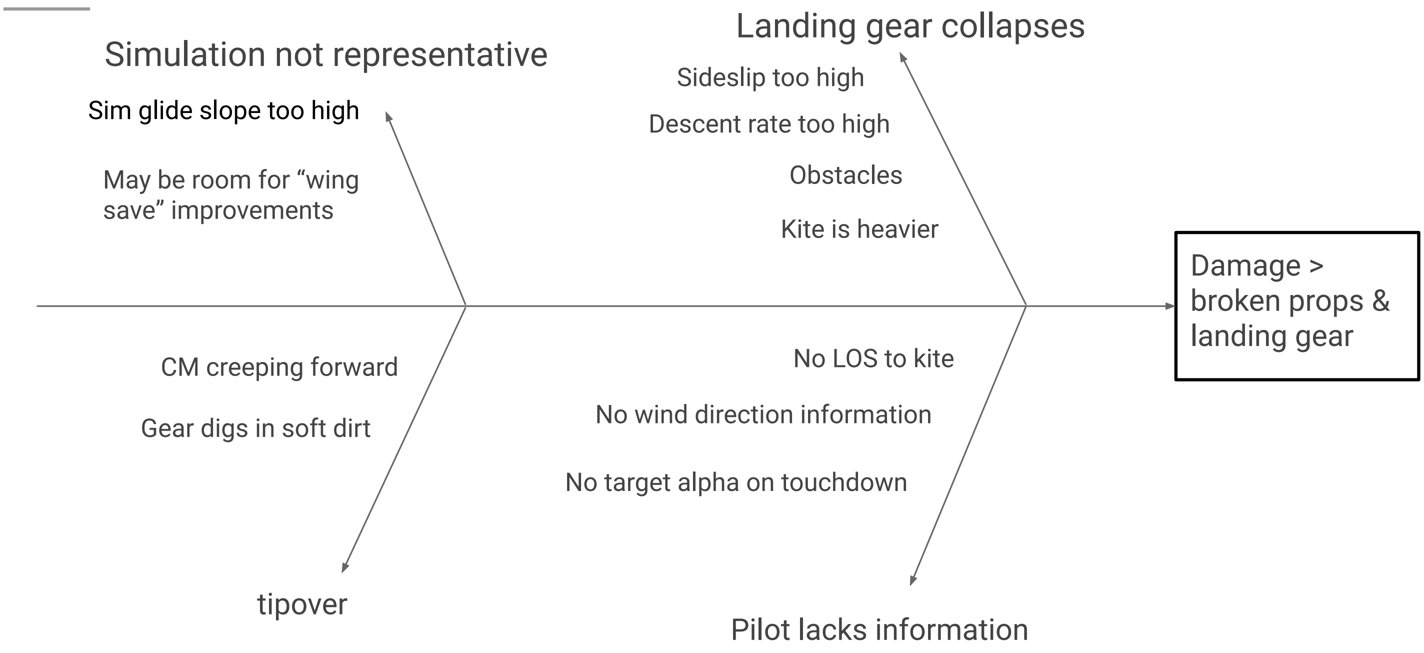


Alpha (deg)	Default gains (with motor steering)				Alternate gains (no motor steering)			
	40 m/s	**36 m/s**	**44 m/s**	**50 m/s**	**40 m/s**	**36 m/s**	**44 m/s**	**50 m/s**
	<8 m/s	---	9-12 m/s	>12 m/s	<8 m/s	---	9-12 m/s	>12 m/s
3	0	8	16	24	32	40	48	56
2	1	9	17	25	33	41	49	57
4	2	10	18	26	34	42	50	58
6	3	11	19	27	35	43	51	59
8	4	12	20	28	36	44	52	60
10	5	13	21	29	37	45	53	61
11	6	14	22	30	38	46	54	62
12	7	15	23	31	39	47	55	63

A Couple of Lessons Learned

- High wind flight is scary
- Waiting for wind can take a while, it was the right call to launch despite gusty conditions
- The cost of a glide landing is real (time & $$). It’s worth the effort to increase probability of success.

RPX-07 Test Cases



Simulation not representative

Sim glide slope too high

May be room for “wing save” improvements

Landing gear collapses

Sideslip too high

Descent rate too high

Obstacles

Kite is heavier

Damage > broken props & landing gear

CM creeping forward

Gear digs in soft dirt

tipover

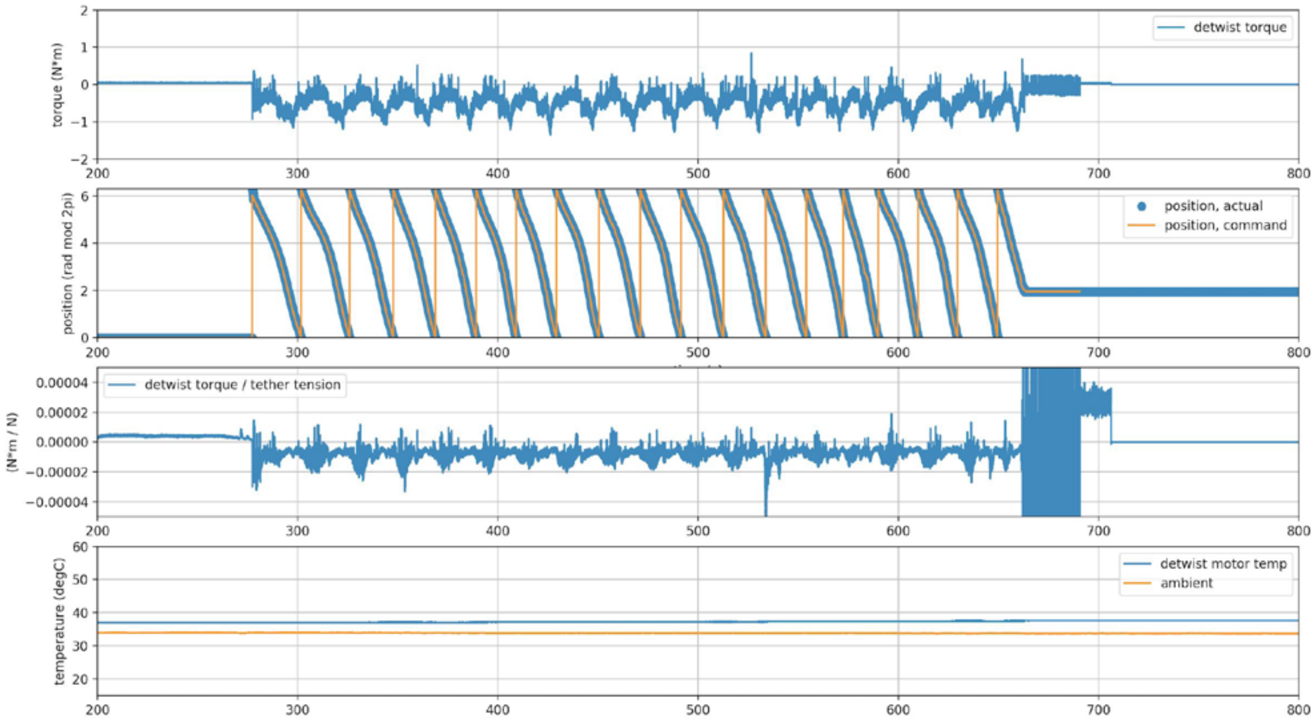
No LOS to kite

No wind direction information

No target alpha on touchdown

Pilot lacks information

Detwist Looks Good



Power Systems
RPX-07 Lessons Review

Flight: 2017-11-16

Executive summary

- Ground power failure:
    - Interaction between controls and generator and ground power
    - Solution is 70% in-hand
    - Path forward is clear
- Ozone controllers
    - Some small process / build issues
    - Overall, performance is GREAT
- LV bus loads in high winds
    - Average power demand is similar
    - Peaks are higher
    - Brownouts possible without 2nd battery

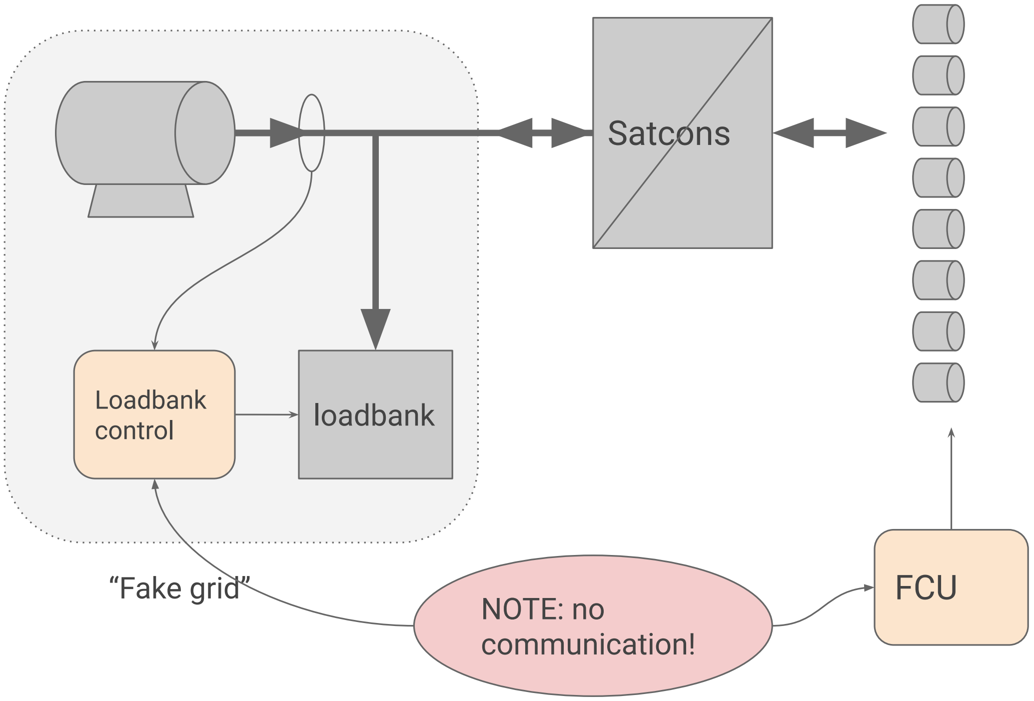
Contents

Ground Power
- What ended the flight?
- Possible solutions
- Progress report

Motor controllers
- Reliability
- Current control performance
- Stacking / control performance

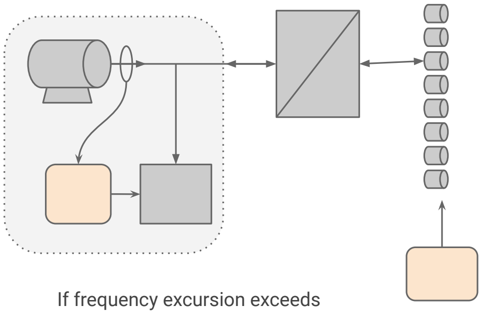
LV bus
- Total LV loads *vs.* RPX-06
- Possibility of brownouts
- Philosophy of redundancy

Ground Power Setup

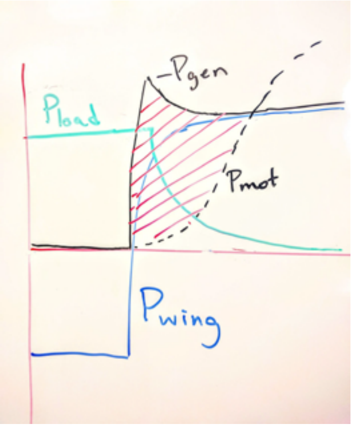


What Took Out the Ground Power?

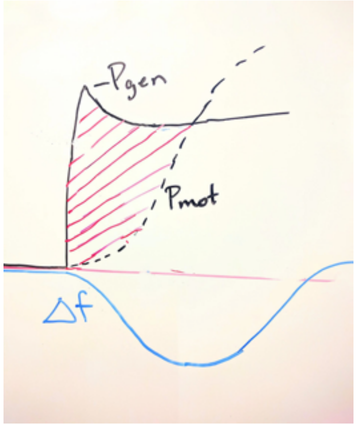
P_gen + P_lb + P_wing = 0
Tau_load ~ 1 sec
Tau_gen ~ 2 sec
J_gen ~ 100 kg*m^2 (guess)
Delta_E ~ 270 kJ
Time to tracking limit ~ 0.36 sec



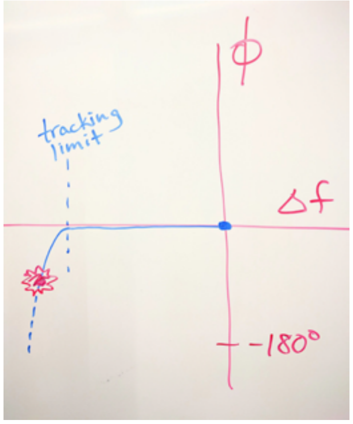
Fast control inputs and slow throttle response cause ENERGY DEFICIT



Energy deficit causes FREQUENCY EXCURSION



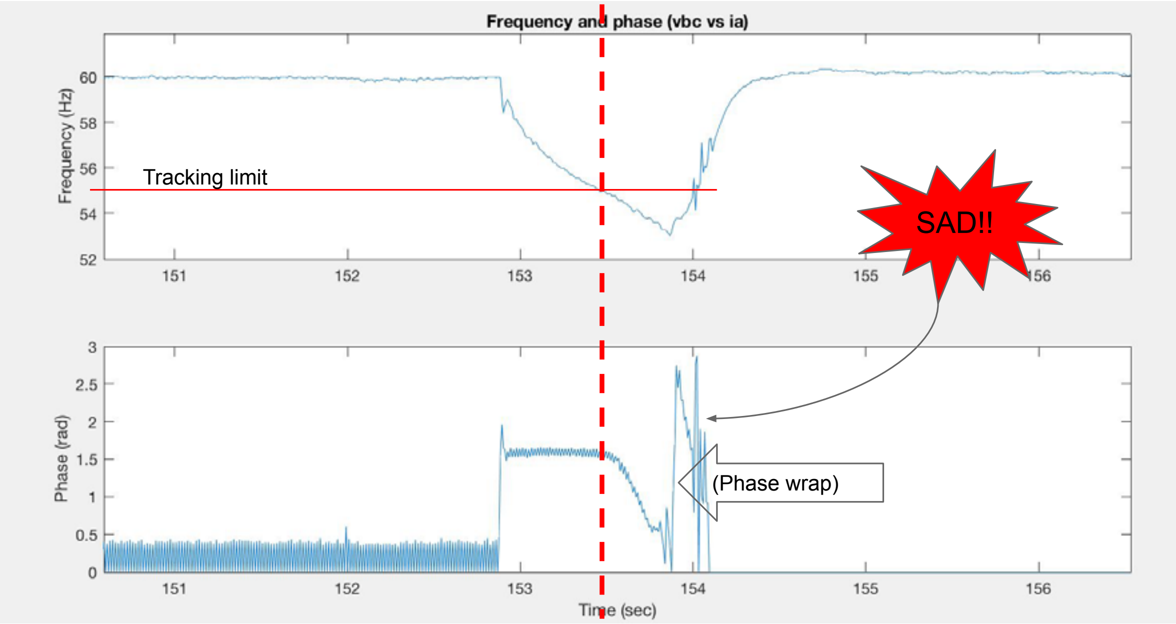
If frequency excursion exceeds tracking limit, PHASE DRIFT ensues



Phase excursion causes virtual short circuit, if severe enough

What Took Out the Ground Power?

Try to reproduce the problem at the E-lot:



Possible Mitigations

CONTROLS

- Motor solver improvements?
- Command slew rate limits?
- Smoother flight path control
    - Lower airspeed control gains?
    - Better airspeed feedforward?

POWER SYSTEMS

- Wider range of frequency tracking
- Pre-load generator for faster throttle response
    - Existing load bank → lower P_maxgen in FCU
    - OR: Install new load bank

ALSO

- Incorporate feedback from load bank into ground power telemetry data
- Incorporate generator load data into ground power telemetry data
- (Nice-to-haves)

Progress Report on Ground Power

FREQUENCY TRACKING

(Phase Locked Loop (PLL))

Done:

- Repeatable experiment that matches behavior in CL.

Still need:

- Validate ride-through with updated PLL code (wider tracking limits).
- Verify other related limits have margin throughout fault.
- Verify no CL systems are sensitive to frequency excursions (generator trip limits, UPS?)

Future:

- Verify GS02 systems can handle frequency and voltage excursions.

NEW LOAD BANK

Done:

- Spare cam-loks already in distro at CL
- Load bank cam-loks installed and operational

Still need:

- Current transformers on order
- Install new breaker at CL
- Local test at E-lot

Ozone Motor Controller Reliability / Build Quality

One main board required replacement
- Measurement noise linked to one of the two ADCs on the TMS570
- Have not looked into the root cause

One LV→ 12V blown fuse
- LV-12V DC-DC converter failure (b/69930384)

Broken POF transceivers
- Known problem, but we messed up

Loose phase connections
- Working in a hurry

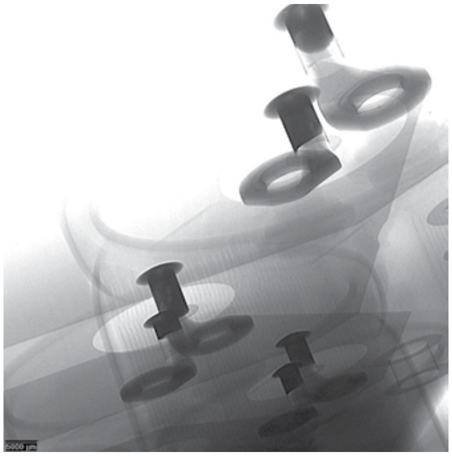
LV-12V:
- motor controller will monitor both 12V buses
- land if error occurs
- (status report?)

Serviceability on-kite:
- 10 out of the 11 sub-component failures listed above were fixed without breaking the cooling loop
- Progress!!

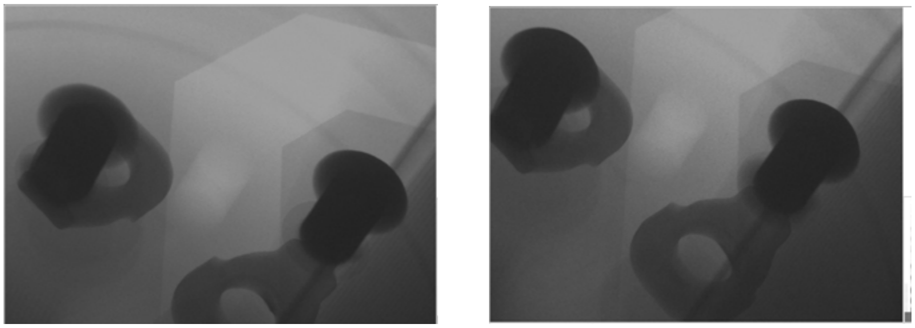
Ozone Capacitor Boxes

- Solder fill problems
    - Thick board
    - Poorly specified QC
    - Poor design entraps air under capacitors
- Reworked design
    - Air vents
    - Better QC reporting
- Success!!

BEFORE



AFTER



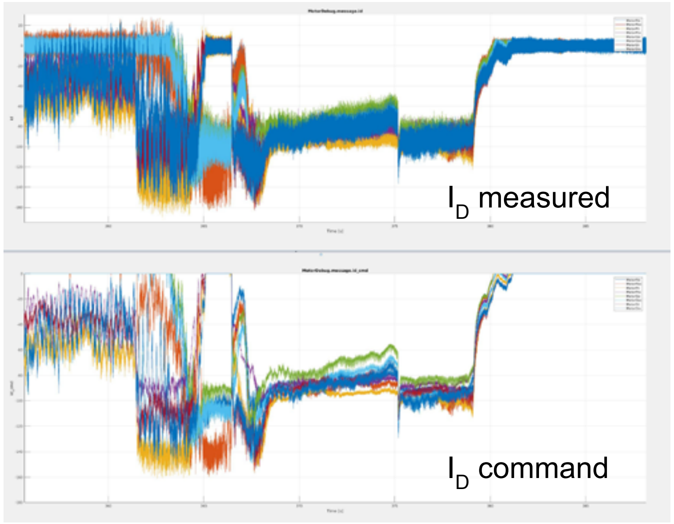
Ozone Motor Controller Performance (current control)

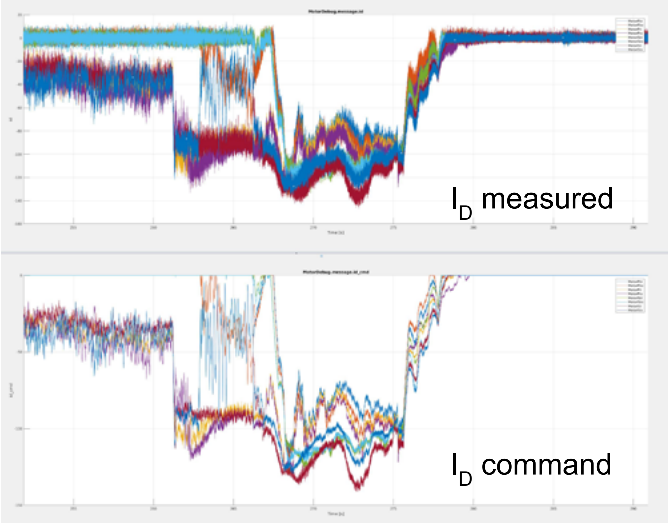
RPX06 Trans-in I_D

- 5x mechanical noise due to angle sensor error.

RPX07 Trans-in I_D

- Better current regulation despite running at half the switching frequency of Gins.
- Angle sensor error compensation code is working as expected.

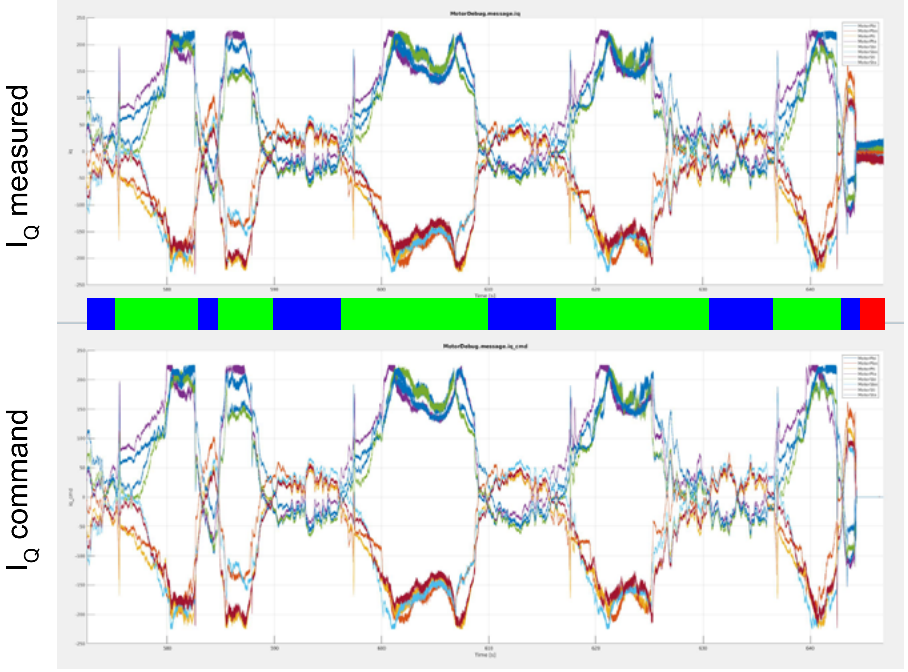




Ozone Motor Controller Performance (Current Control)

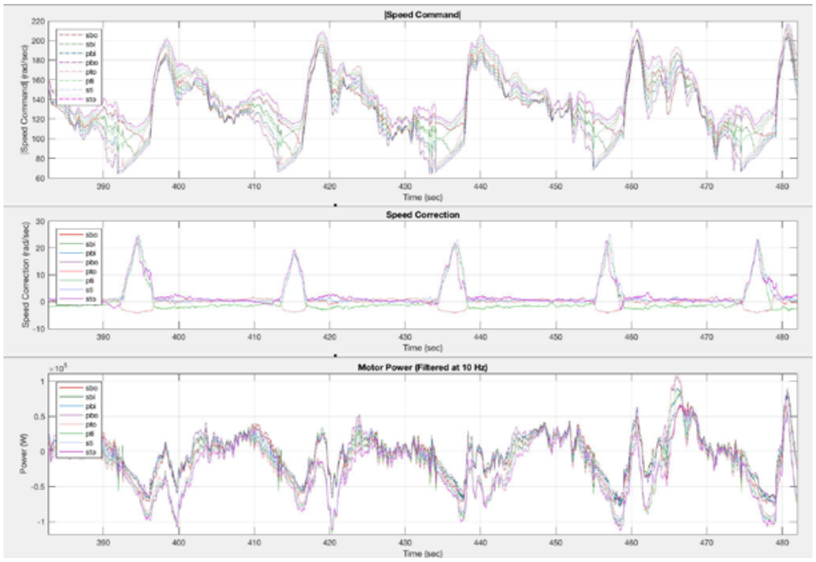
- Ozones had no trouble keeping up with rapid changes in I_Q command.
- Plot shows last four loops of RPX07.
- Sharp spikes associated with speed command discontinuities.

Green = generation
Blue = motoring
Red = MV lost



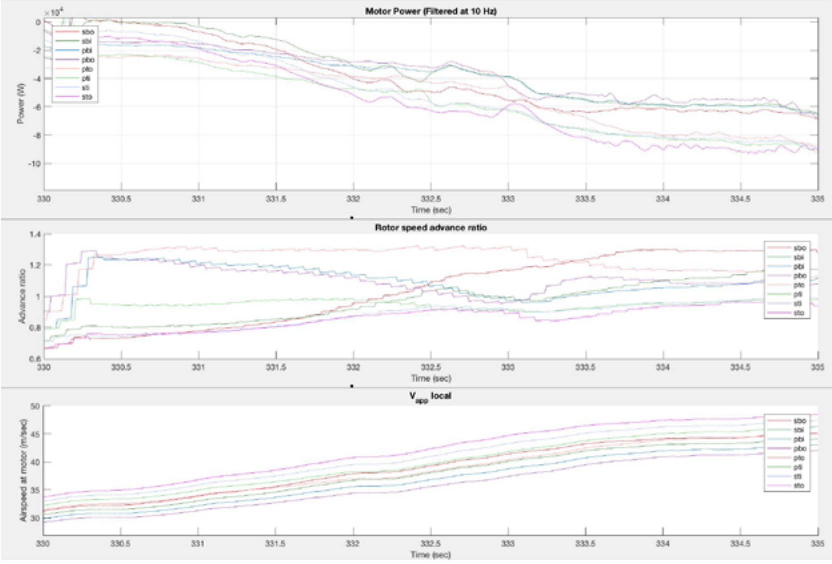
Stacking Control Performance

- Stacking controller is significantly backing off ¾ of motor pairs during period of generation.
- Backing off occurs during power extracting phase of the loop.
- Up against advance ratio limit
- Always SBO-PTO pair with PTO against the advance ratio limit
- PBI and PBO both hit the advance ratio limit first with no consequence.

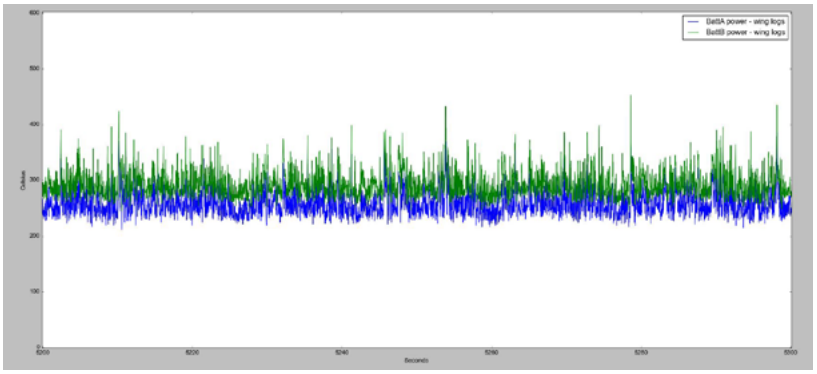


Stacking Control Performance (Power and Advance Ratio)

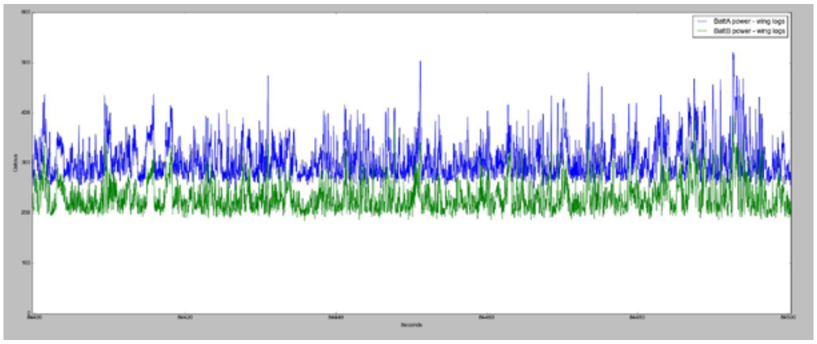
- At 333.5, despite having higher advance ratio and higher calculated apparent wind we see SBO flatten out its generation performance relative to PTO.
- Meanwhile, PTO improves its generation performance as the advance ratio increases (thought v apparent is also increasing).
- During period when they had similar v_app, PTO generated 25% more power with advance ratio < 1.2 compared to 1.3 for SBO.
- Based on prop models 1.3 is near peak power. Here it looks like we're slightly stalled.



LV Bus Loads vs. RPX-06



← RPX06



← RPX07

Plots show 100 representative seconds during xwind.

Similar power usage from last rpx, but somewhat higher spikes (probably servos in higher wind).

Note with MVLV and batt box, if we lose batt box, LV bus will brown out for any power spikes in excess of the MVLV's continuous power capability.

For RPX-08

- New ozones
- New capacitor boxen
- MVLV installed
- Controls improved w.r.t. drastic step loads
- Improved ground power step load handling

Avionics
RPX-07 Lessons Review

Flight: 2017-11-16

Executive Summary

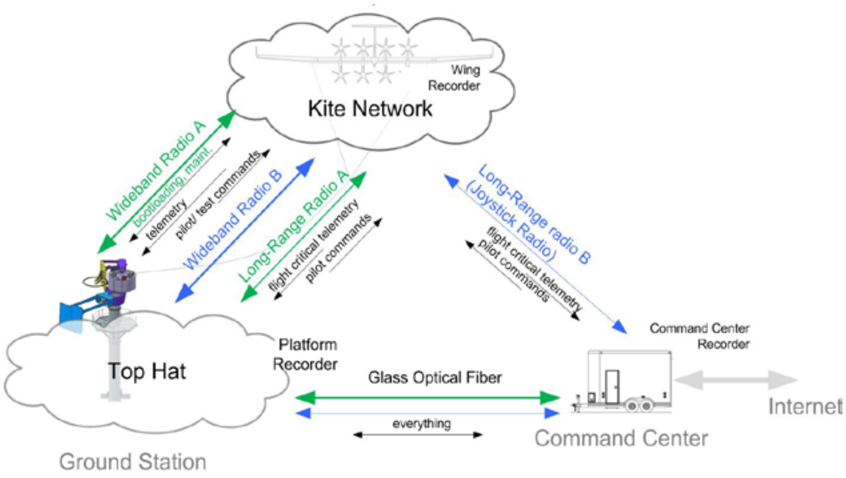
- Radio links (Wideband A, Long-Range A, Joystick B) performed worse for RPX-07 than for previous flights.
  - ⇒ Field day planned to inspect/maintain RF hardware at CL during YM600-03 integration.
- Redundancy allowed kite/ground communication until antennas cables severed on landing.
- Wideband Radio B (Silvus) *always* performs better than Wideband Radio A (Proxim).
  - ⇒ Propose to switch both wideband radios to Silvus for YM600-04.
- Both new Flight Control Units (FCU_A 01414, FCU_B 01418) that were used to bring up YM600-03 manifested problems (bug 67850932, bug 68319985) during RPX-07 dry runs.
  - ⇒ Need more rigorous burn-in / final system tests for new hardware

Overview

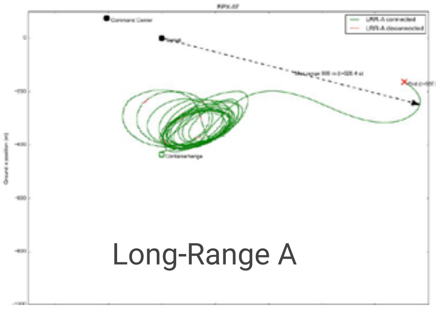
- Kite/Ground link performance for RPX-07
- RPX-02 to RPX-07 link connectivity comparison
- Status of bug 69789643 Starboard A Load Cell 5 V reference warnings on RPX-07

Radio links - how much have we relied on redundancy?

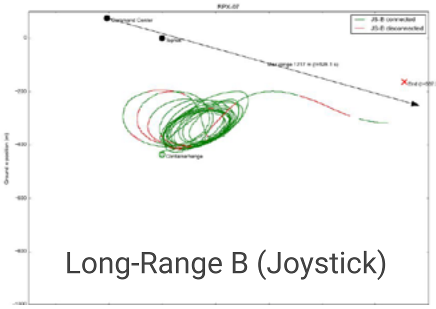
- Concept of Operations:
    - We have two independent networks (A, B) on the kite and on the ground.
    - Each network is bridged by a wideband (~6 Mbps) and a long-range (A:~60 kbps/B: 1Mbps) link.
    - Long-range radios carry flight-critical telemetry and pilot commands for off-tether operation.
    - Wideband radios carry telemetry + all the long-range radio traffic.



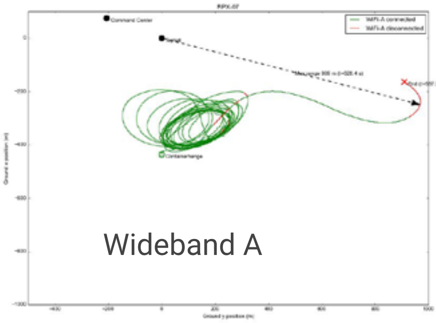
RPX-07 Kite/Ground Radio Link Performance



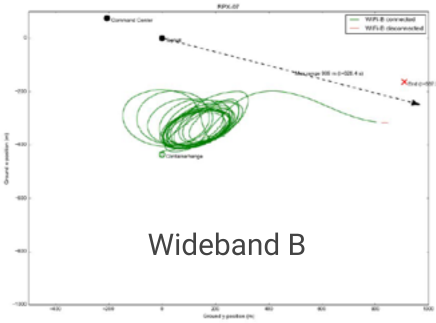
Long-Range A



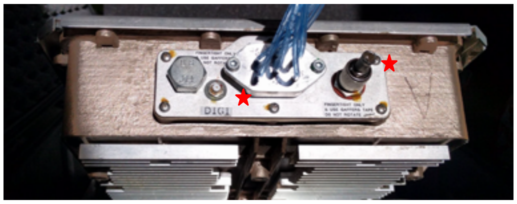
Long-Range B (Joystick)



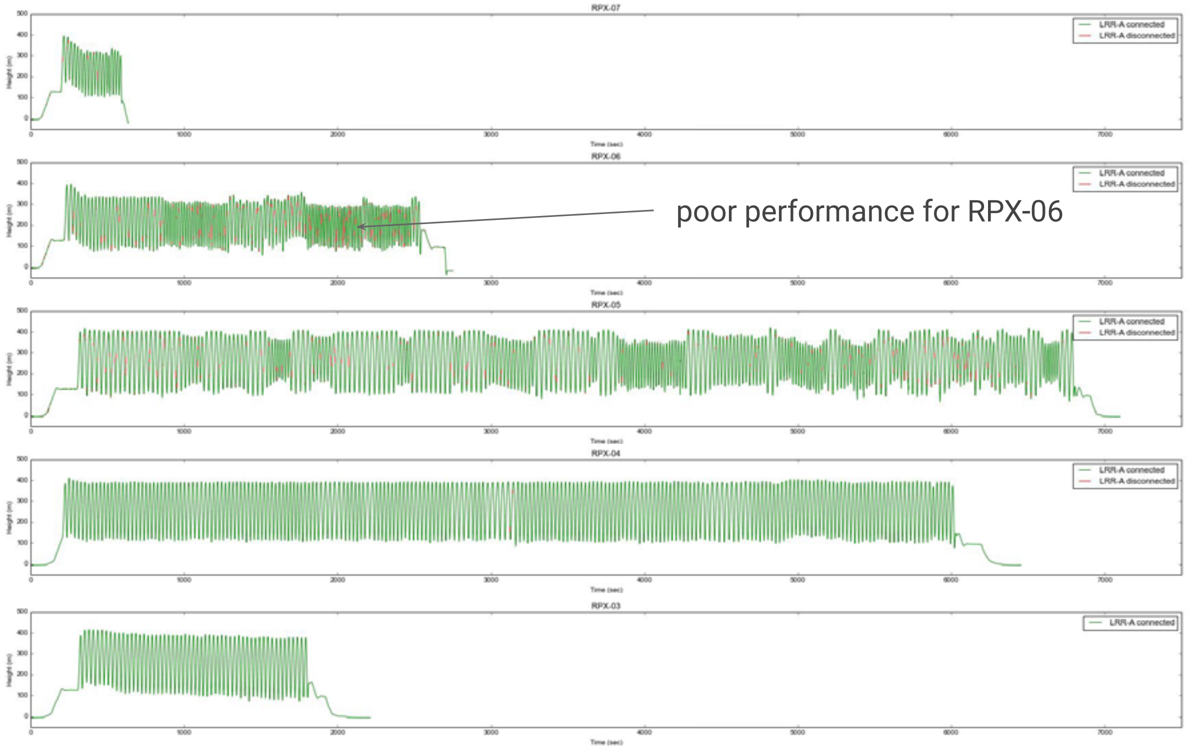
Wideband A



Wideband B

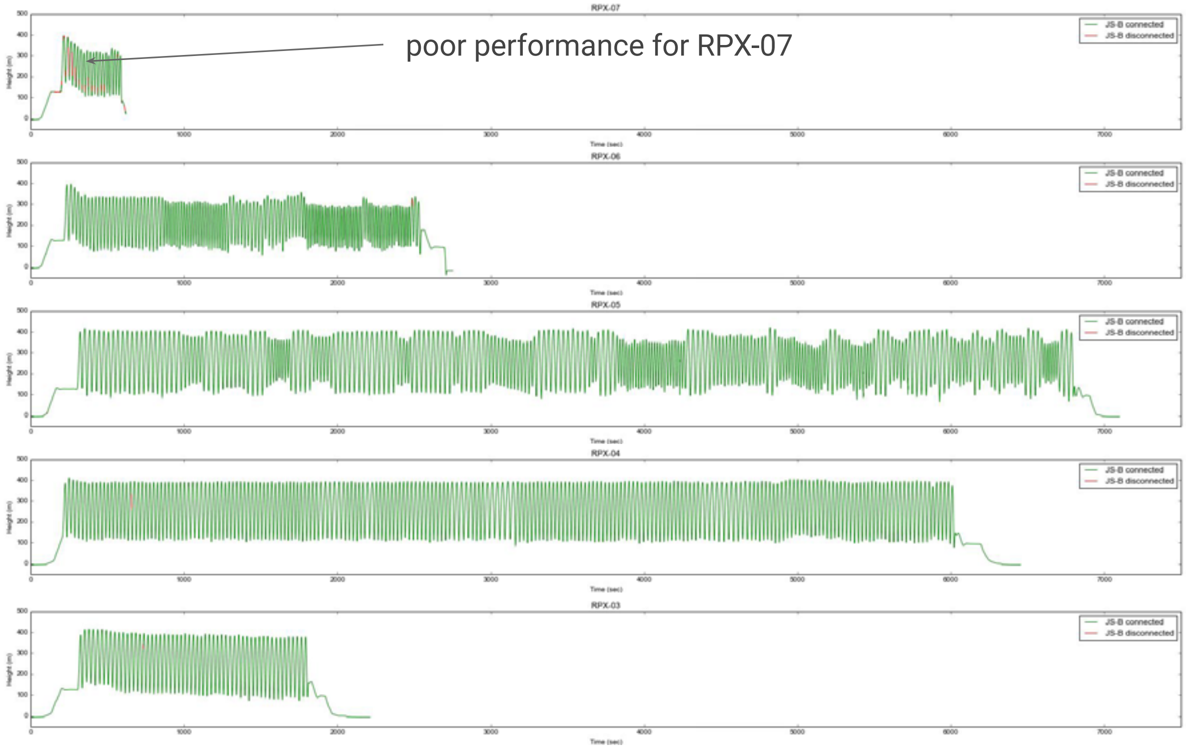


- LRRA allowed us to land
- Wideband B allowed us to collect continuous command center telemetry for the on-tether operation.
- Long Range Radio and GSP antenna cables severed during landing.



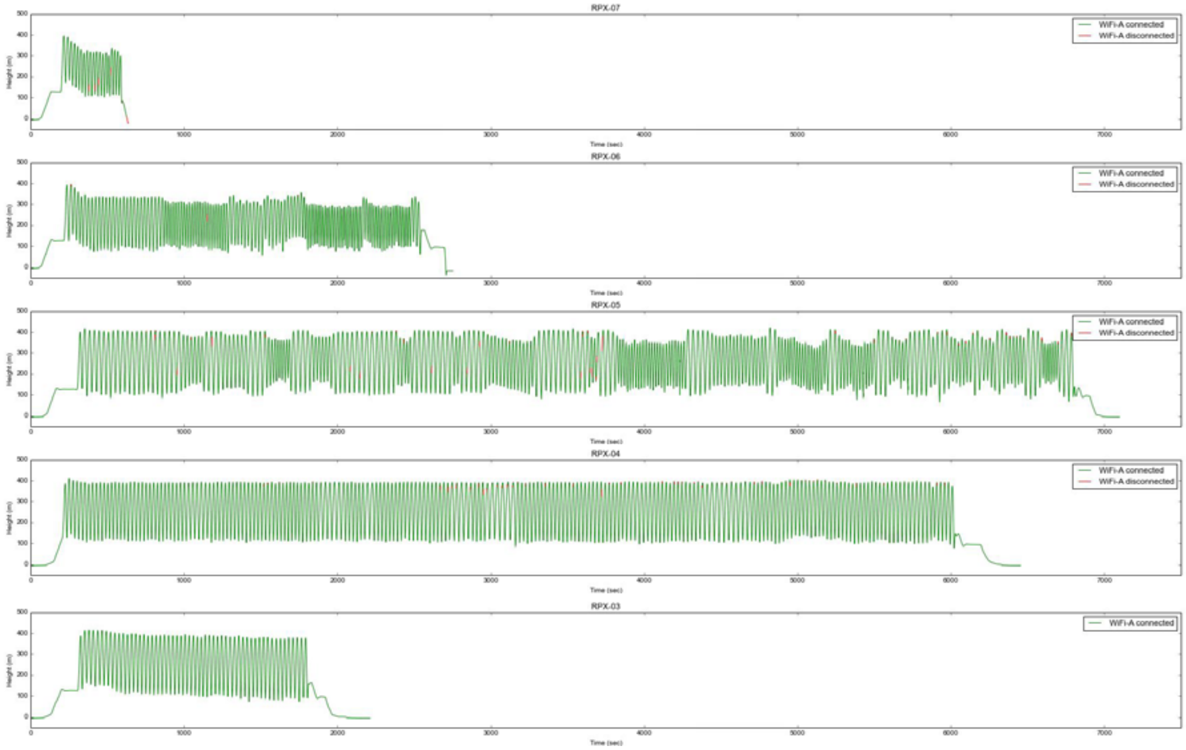
poor performance for RPX-06

Long-Range Radio A Link Performance

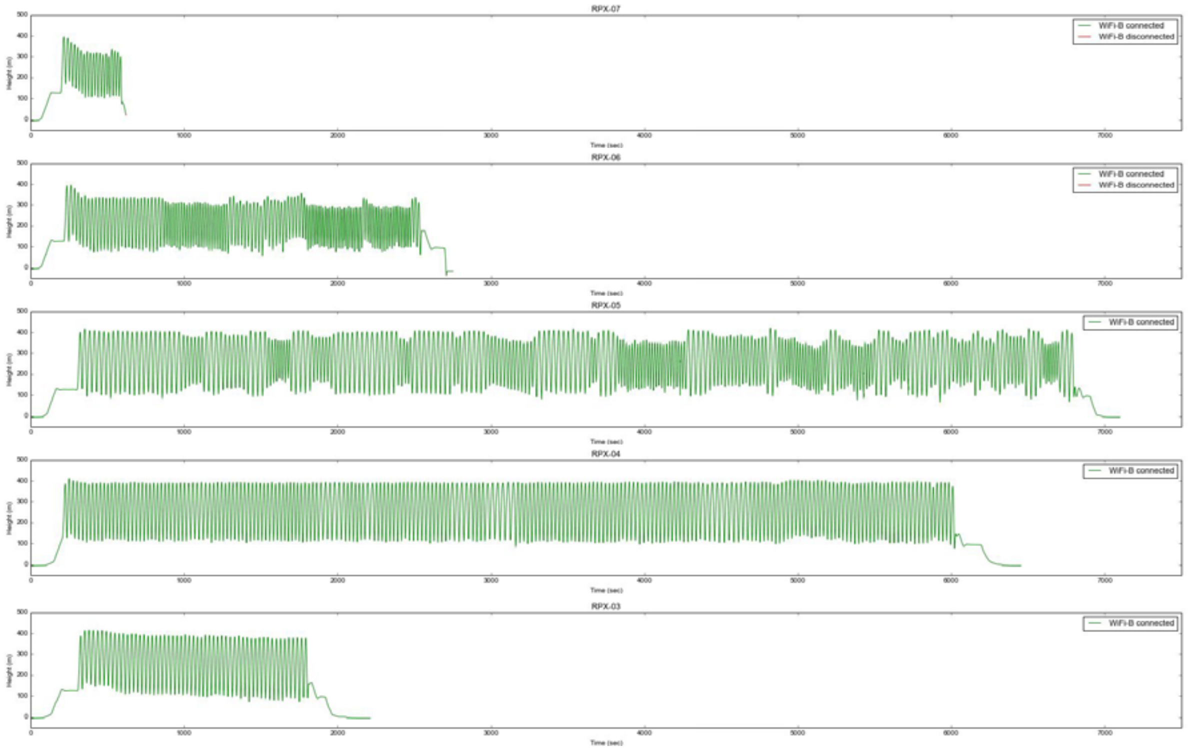


poor performance for RPX-07

Long-Range Radio B (Joystick) Link Performance

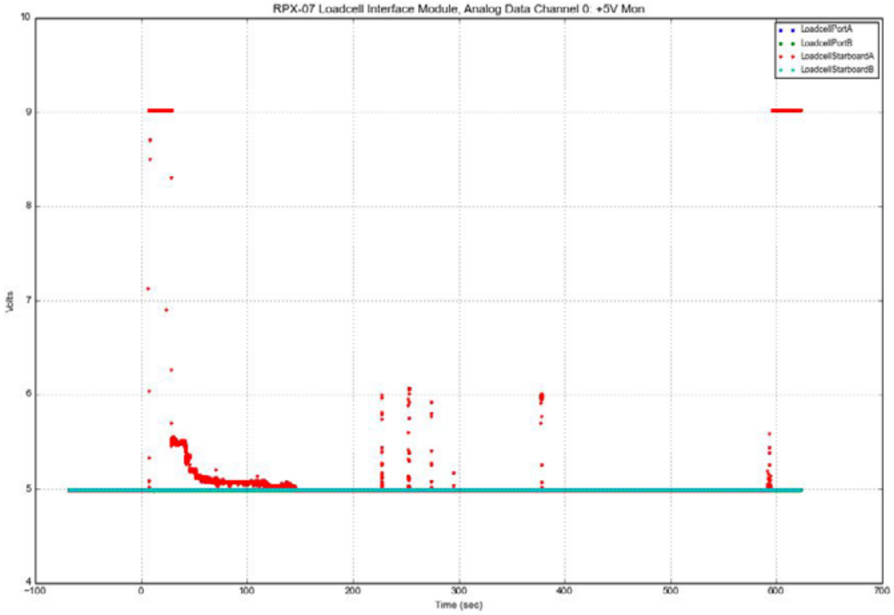


Wideband Radio A Link Performance



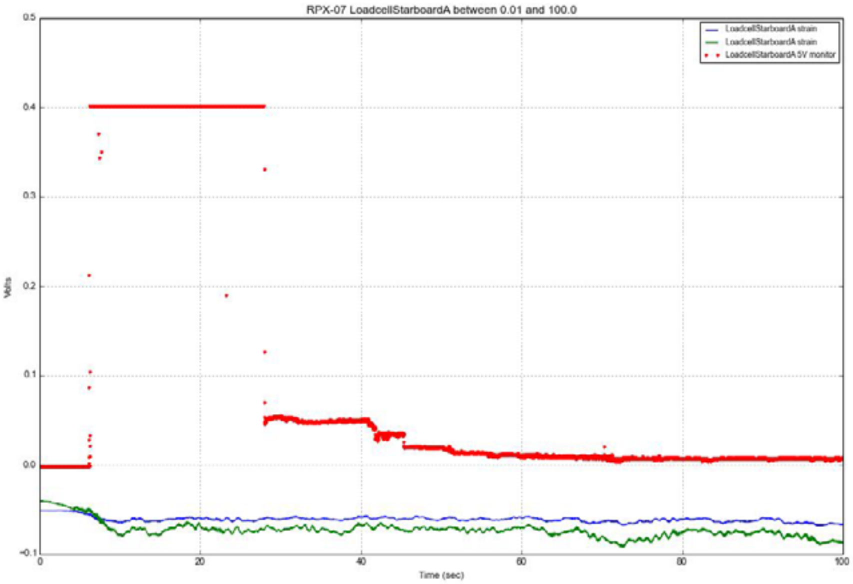
Wideband Radio B Link Performance

Starboard A Load Cell Interface Error: +5V Monitor



- Bug 69789643
  Starboard A Load Cell 5 V reference warnings on RPX-07
- Hardware fault, to be investigated (hardware to arrive today).

Starboard A Loadcell Interface Error: Strain Measurements



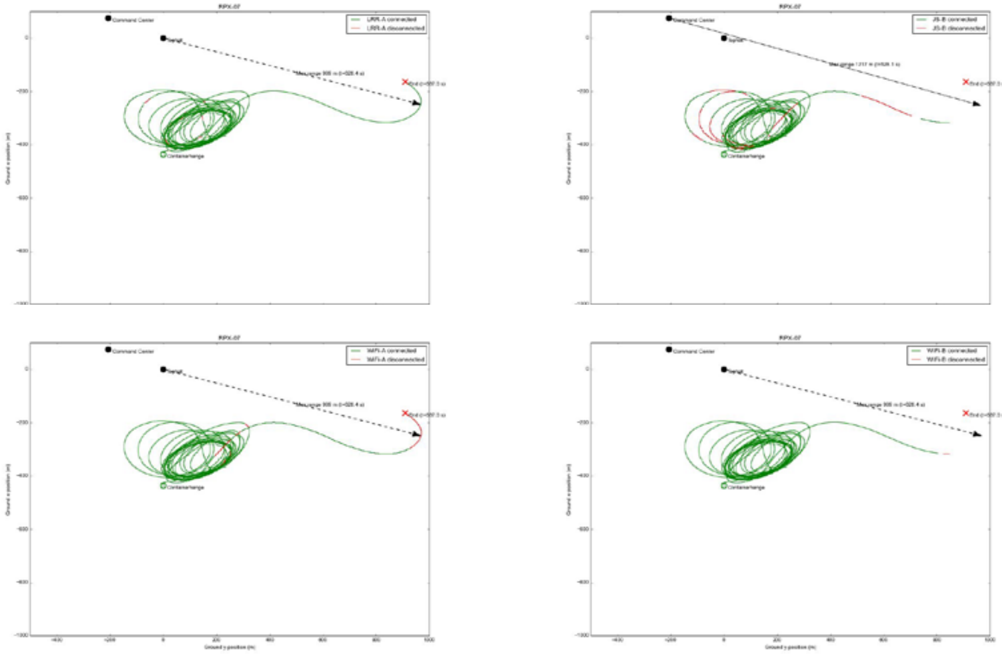
The 5V Reference is used by the A/D converter for the load cell strain measurement.

The measurement appears unaffected.

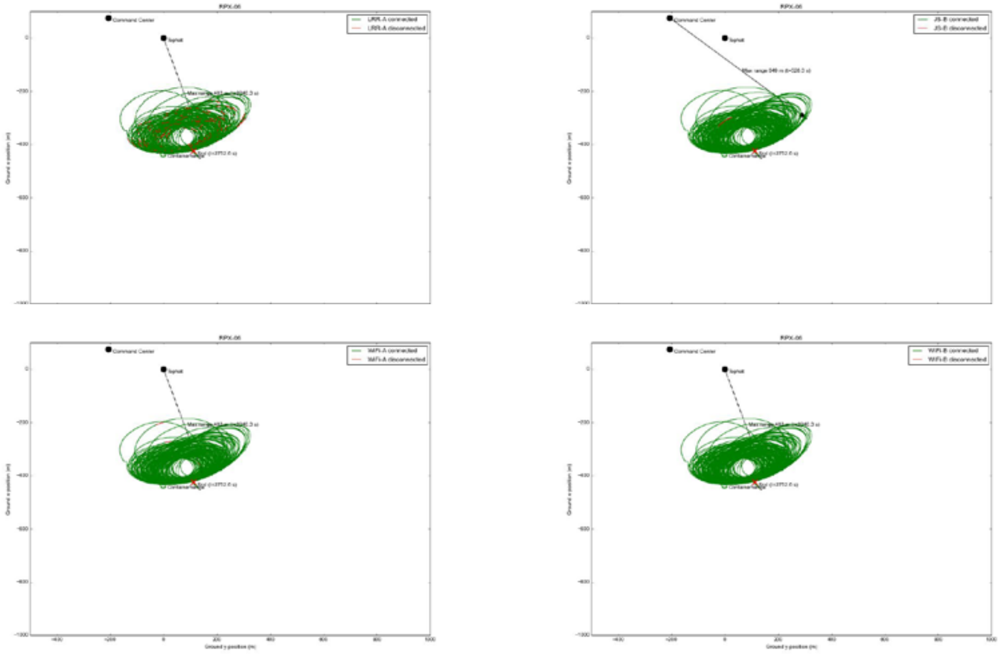
Ongoing Investigations

- Bug 69789643 Starboard A Load Cell 5V reference warnings on RPX-07
- Bug 68319985
  - FcA (in FCU_A 01414) stopped communicating randomly
  - TMS570 Recorder board FCU_B 01418 did not boot up.
- Bug 67850932 IMU on Flight Computer C on YM600-03 on dry run on 10/11 not communicating
- Bug 32032107 Bad RX traffic on the STO port of CSB. (FCU_B 00002)

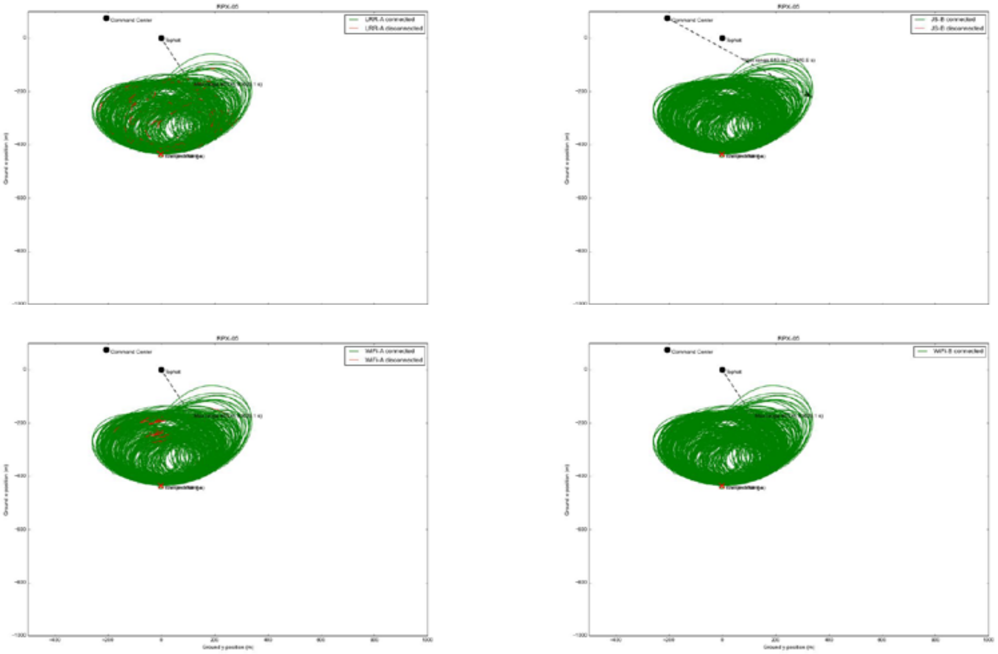
RPX-07 Kite/Ground Radio Link Performance



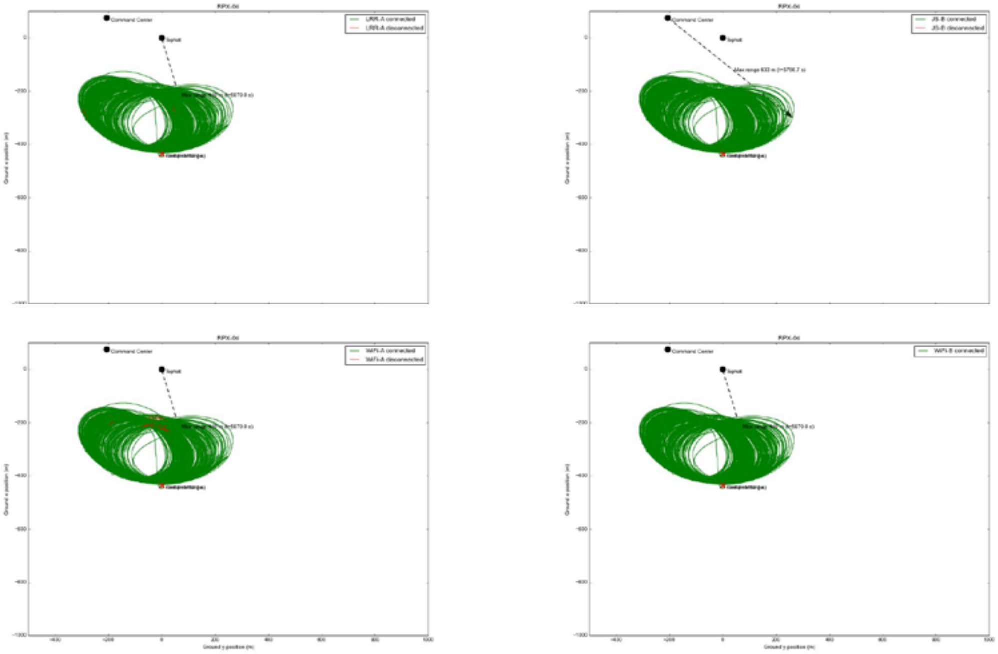
RPX-06 Kite/Ground Radio Link Performance



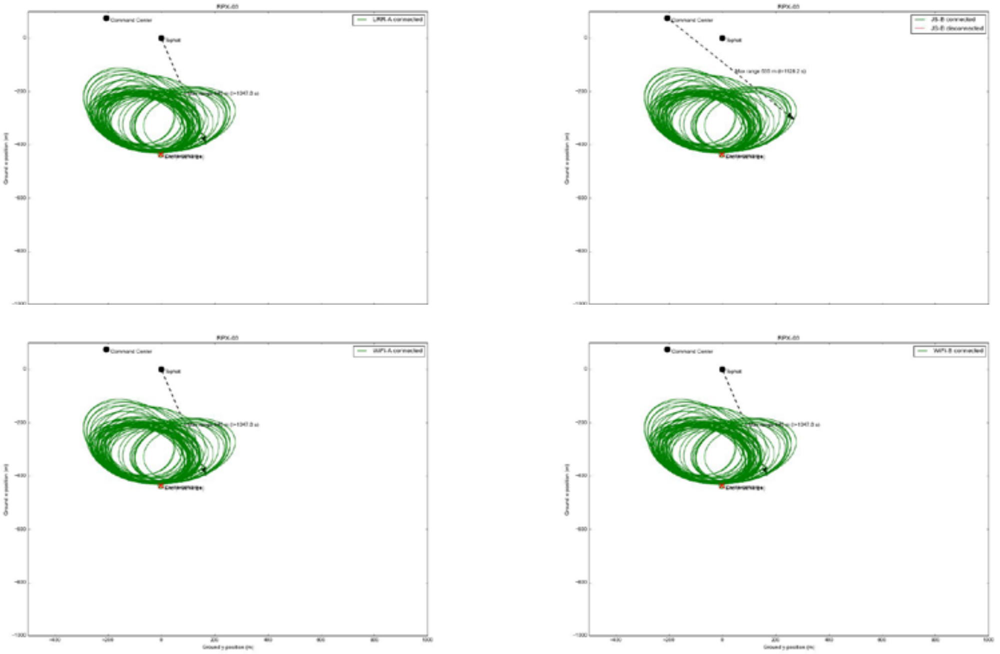
RPX-05 Kite/Ground Radio Link Performance



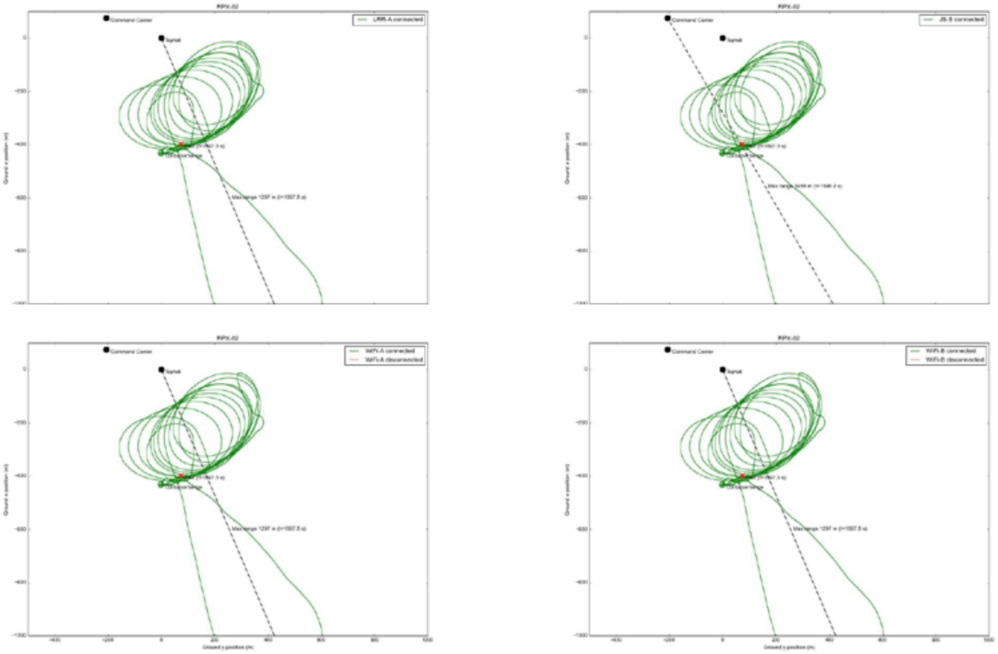
RPX-04 Kite/Ground Radio Link Performance



RPX-03 Kite/Ground Radio Link Performance



RPX-02 Kite/Ground Radio Link Performance



RPX-07 Lessons
Aeromechanical

Flight: 2017-11-16
Presentation: 2017-11-30

RPX-07 Executive Summary of What Happened

AERO
- **Slats worked! no separation at a higher alphas**

THERMAL
- All temps cool, some low margin items if ambient was 40C

ROTORS
- They made mucho power.

LOADS
- Mostly benign loads; exception being the last loop

TETHER
- Bridle fairings appear to shake. Unknown if shake is due to the stalled stuck section or if the flutter heave mode is being excited; Tether fairings did not experience the same result
- Tether fairing angle measurement questionable

RPX-07

AERO

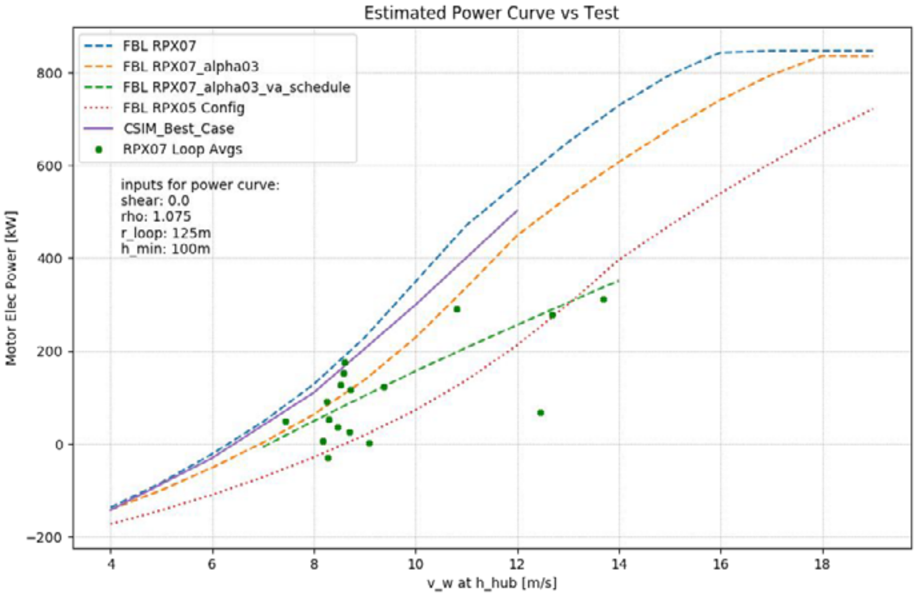
Aero Improvement Check

How did power curve estimates go?

- Single case over wide wind speed range hopefully provides good data…
- … but didn't fly for very long

Record high loop power largely due to higher winds

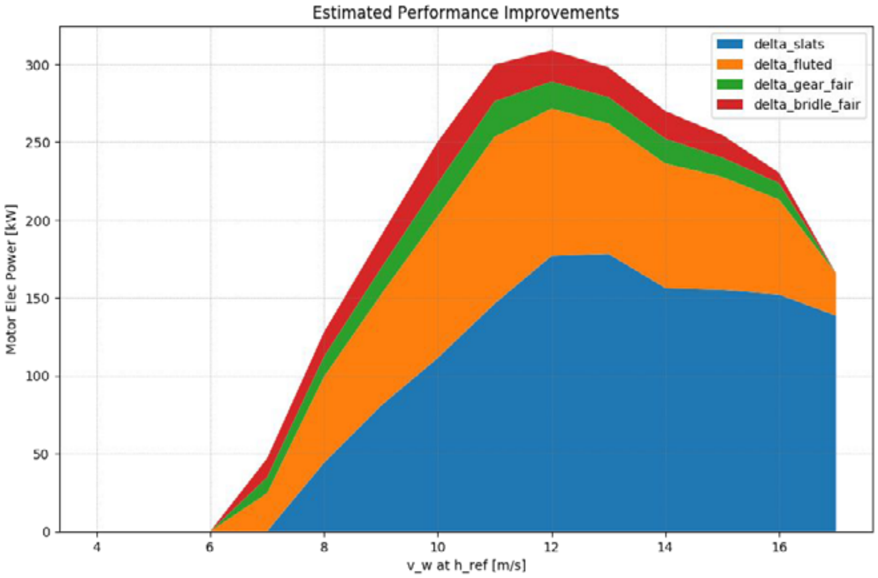
- Remember: ~4x the power available in the wind @ 13m/s vs 8 m/s
- Did not operate the kite ideally for those wind speeds
- Estimate for case flown is close to best power curve without aero improvements at higher wind speeds
  - Possible to hit that power without aero improvements



Not enough data to confirm power curve estimates - Fly More!

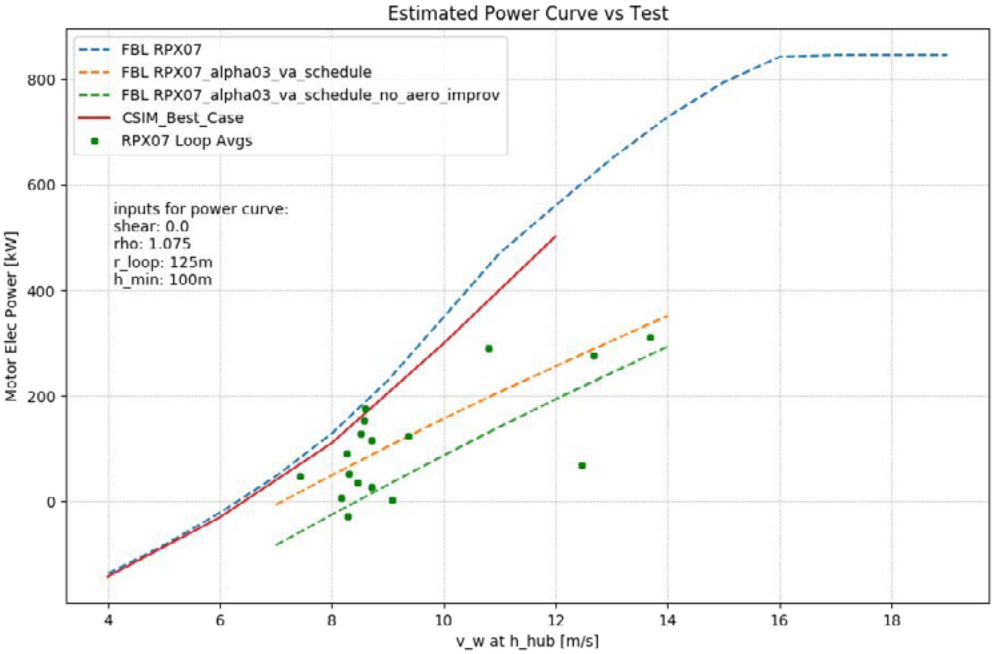
Aero Improvement Check

- How did our rough estimates of improvements
  compare to measured power increase?
  - [internal ref: aero improvements]
- Shown is best case improvements of aero changes
- Assumptions:
  - Kite flown as best as FBL model can
    - Airspeed schedule selected by optimizer
    - Tension and power limiting in place
  - Aggressive use of slats
    - Curves shown assuming mean operating C_L of 3.2 (alpha 9.5 deg)
  - Constant flight path
    - R_loop: 125m, h_min: 100m



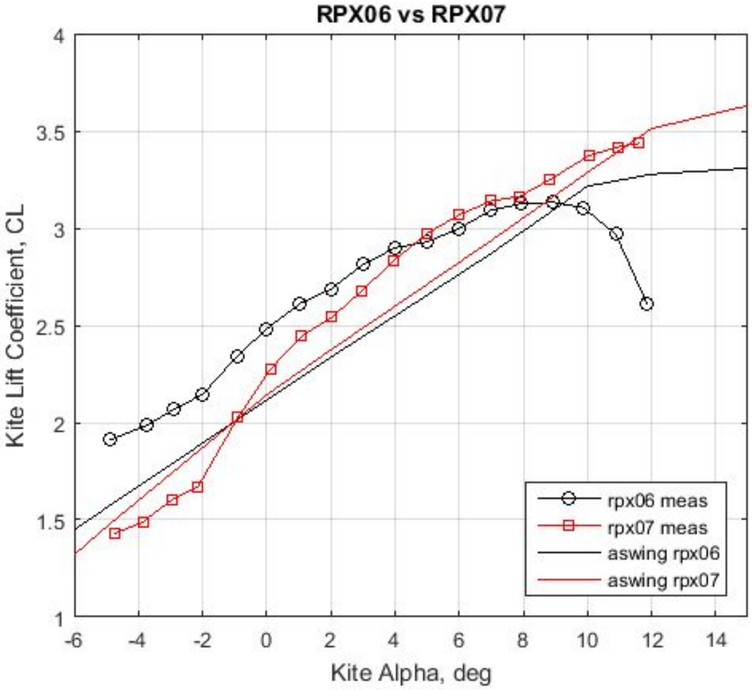
Aero Improvement Check

- What about improvements in the "as flown" condition?
  - Some indication that we actually saw these improvements at the lower wind speeds…
  - … but few data points, and unable to make a clear case



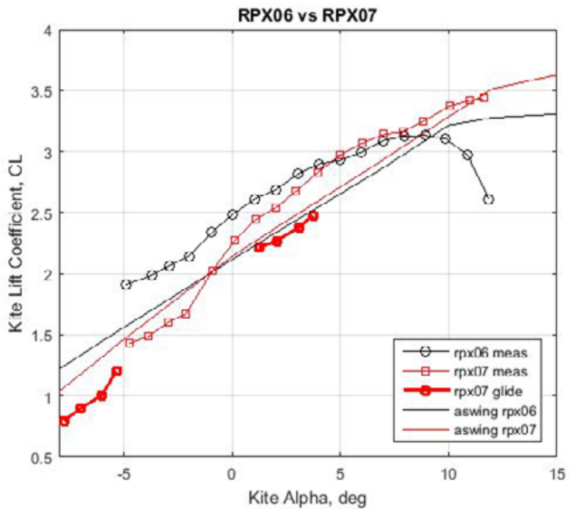
Lift - RPX-06 vs RPX07 (effect of slats)

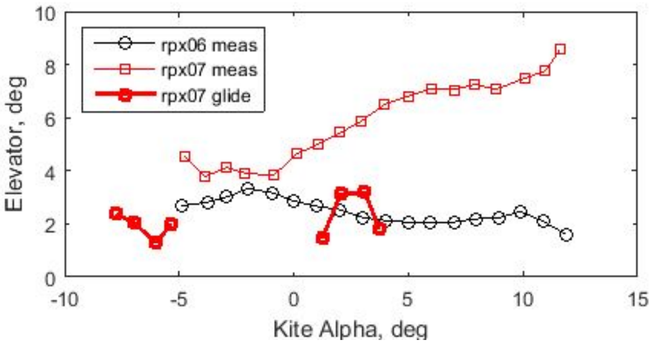
- Filtered data to points that are within +/- 2 deg of target beta (sideslip angle)
- Averaged data within 1 deg alpha bins
- Slats appear to have extended the lift curve slope, as intended
  - Tuft videos confirm no main wing separation even up to highest peak estimator alphas (~12 deg)
- Overall lift magnitudes still higher than expected
  - Need to apply new bridle load pin data
- Note: not with any corrections applied to pitot estimates

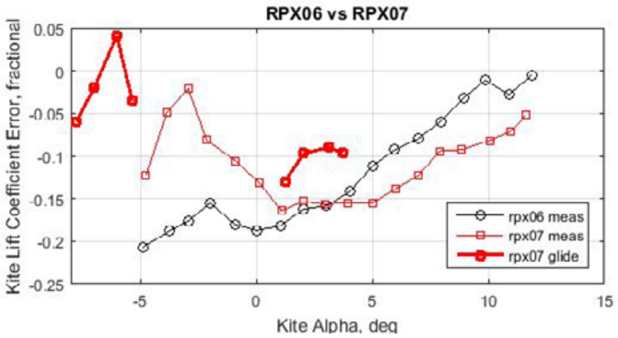


Lift - Glide

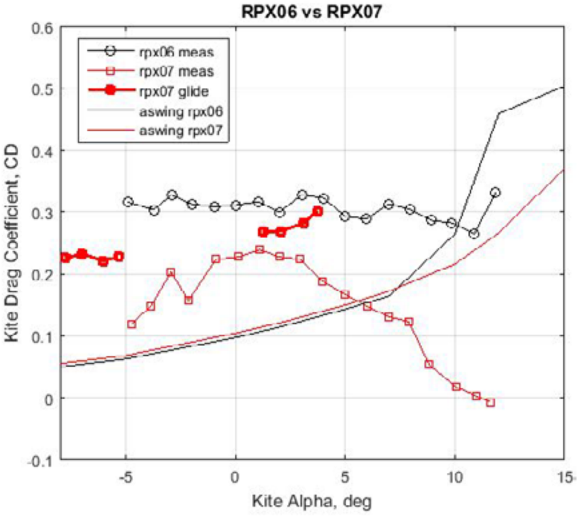
- Glide portion, filtered around beta = 0 +/- 2 deg
- Magnitude of lift decreases at 1-4 deg alpha in glide portion vs crosswind
  - From elevator trim pitch decrease?
- Error in glide portion slightly lower
  - (Error is not simply difference from aswing database line)
  - Removes tether load cell uncertainty

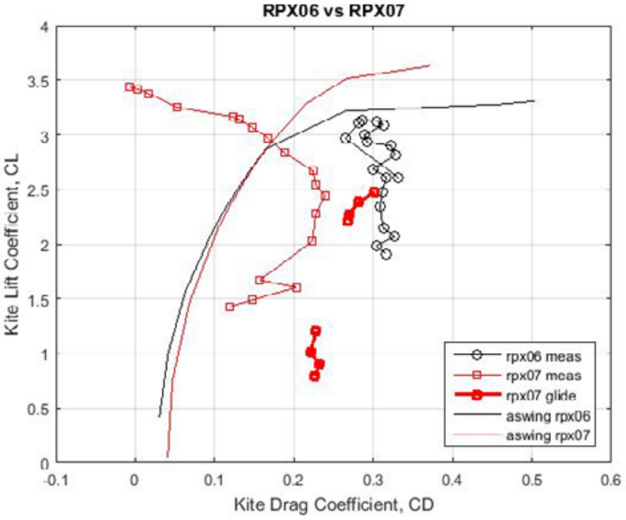


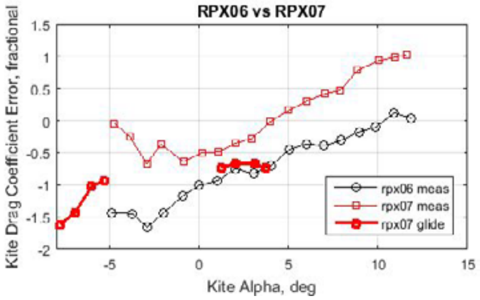




Drag

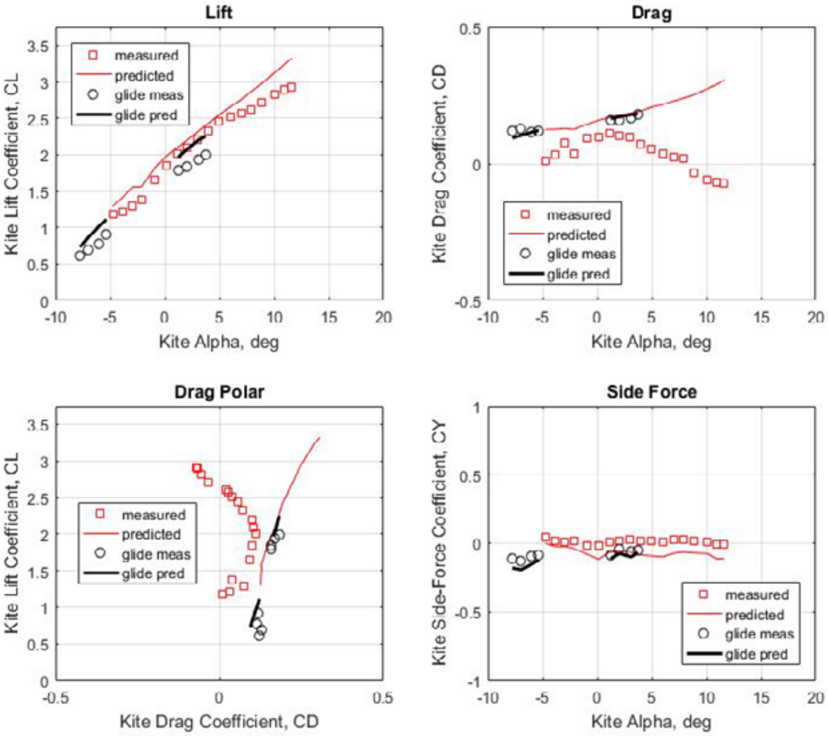






- Note: This drag estimate does not include tether
    - bridles seem to be double-counted in dynamics replay... need to compensate
    - “measured” in tether force, and also lumped into parasite drag model of kite
- Any error in rotor force modeling gets lumped into kite drag (unlike lift direction)
    - Glide showed rotors thrusting... need to investigate that further
- To-dos
    - Make sure this is consistent (no double-counting)
    - Compare with bottoms-up drag buildup from ntucker@
    - Chase down possible rotor force errors

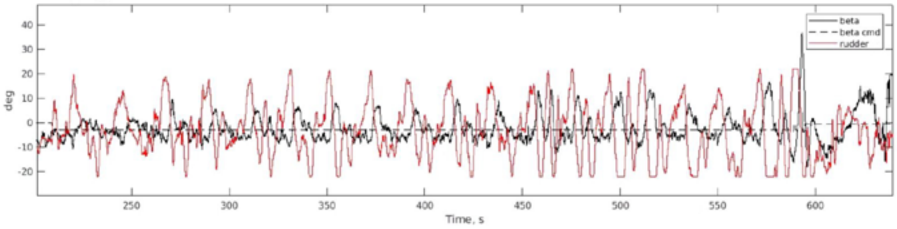
Update: Force Coefficients

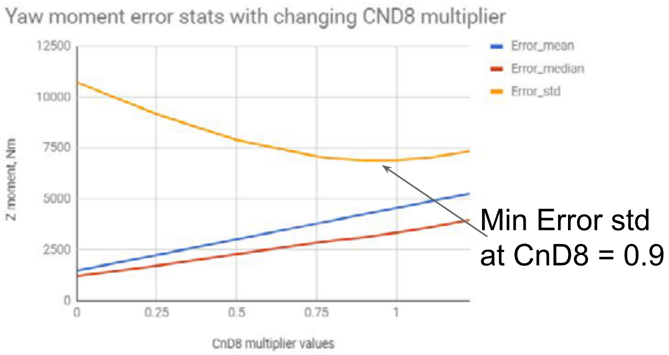


- Updated analysis from post-RPX07 sim updates:
    - Pitot correction [internal ref]
    - Parasite drag offset change [internal ref]
- Glide matches drag very well now. Clearly some error when the tether is attached.
- BHP load cell lift correlation is improved too.
- Lift in glide looks lower than tables expect, could be a Reynolds number difference that is not accounted for (tables are for a single high reynolds number).

Rudder

- Constantly hitting the limits (even with the rotors help)
- Using Dynamic Replay:
    - Min standard deviation is around 0.9 * CnD8
    - Might indicate the control derivatives are too high/not accurate in database





Min Error std at CnD8 = 0.9

Address the rudder database fidelity and sizing for RPX-08

RPX-07

THERMALS

- Ozone Modules estimated to have > 50°C thermal margin in crosswind at 40 C and current power levels
- The same position dependent heating happens on lower, inner pylons as was seen in RPX-05 and 6. This indicates air flow differences cause heating.
- Rudder Servo heating needs more investigation.
- FCU fans will be needed in hotter weather.
- Additional Plots and data [internal ref]

RPX-07 Thermal Summary   Ambient 21-22°C

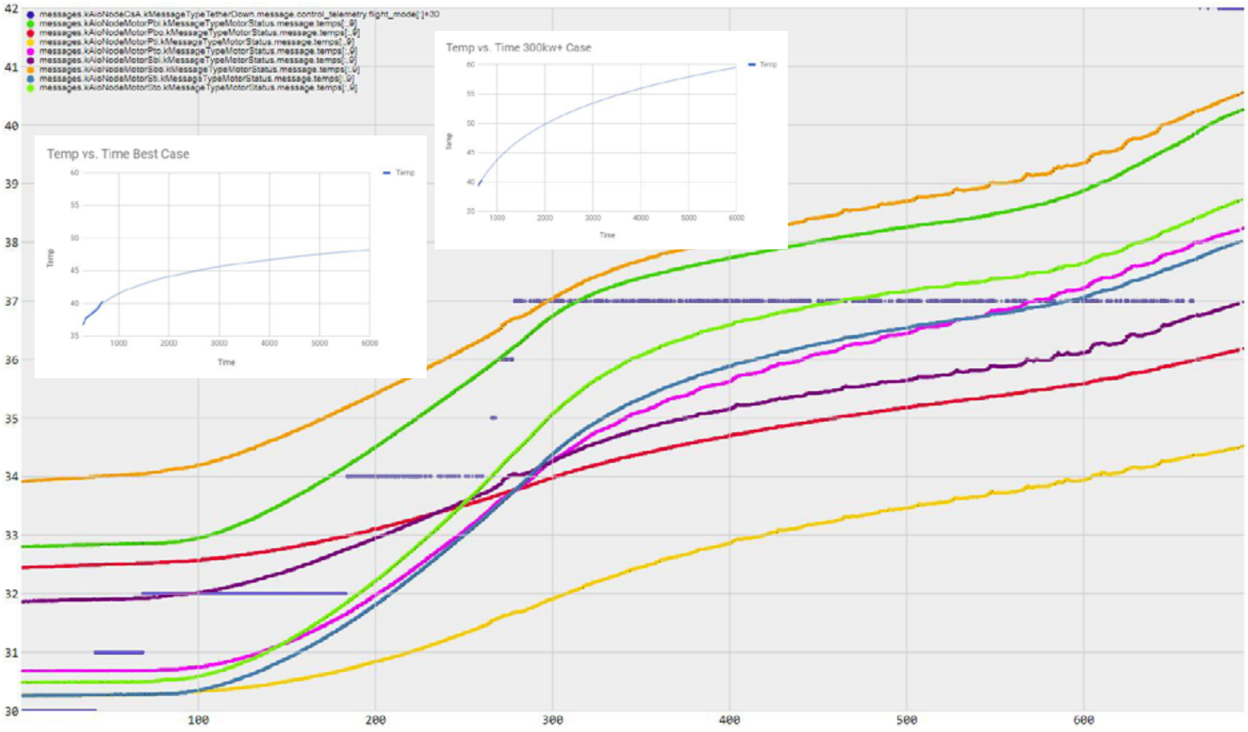
Component	Notes
Wing Tip Light Node	50-51°C 0-5C margin @40°C
FCUs	43°C on Perch, decreasing during flight Still need fans for 40C° ambient 1C margin on perch @40°C
Servos	Rudder Servo reported 50°C delta in short flight Further investigation needed into TC accuracy
Servo boards	Rudder servo AIO reach 62°C Rudder R22 Max 42°C 18°C margin @40°C
Motor controllers	Highest module temp in trans in 50°C 40°C margin @40C Highest capacitor temp 41C and climbing (est 45-60C steady state 300kw loops) 30C margin @ 40°C
Bridle boxes	Max Temp 33°C on perch ~20°C Margin in flight @40°C
DC-DC converters	MVLV not installed. Motor controller 80V-12V not instrumented.
Motors	39°C rotor max. 41°C margin @ 40°C
Battery boxes	Peak after x-in of 52°C.
Satcontainers	34°C Max in Container.
Groundvionics	No Reading
Tether	Tether fairing sensor destroyed. Top hat sensor tracks ambient. No Remarkable data
GS slip ring	No sensors installed

Ozone Film (internal) Capacitor Temps

400 s in X-wind

~⅓ of a Time Constant

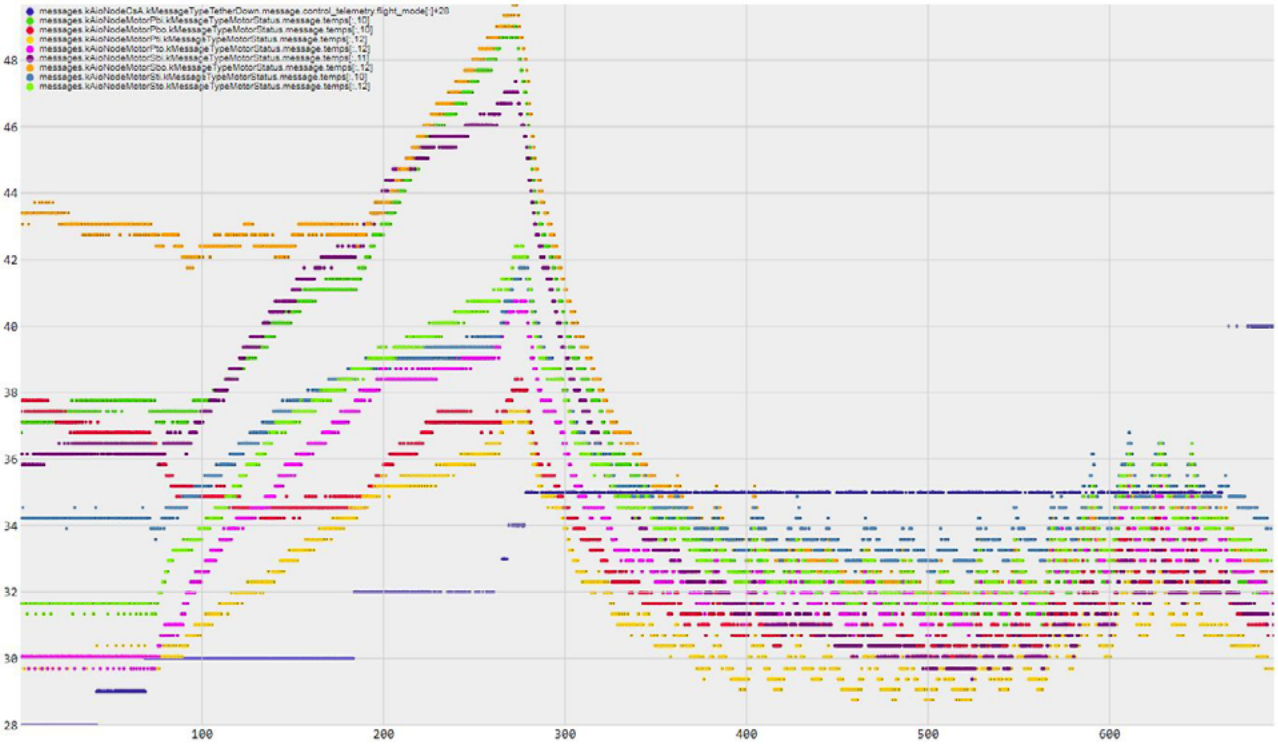
SBO Estimate 45-60°C at 5 time constants.



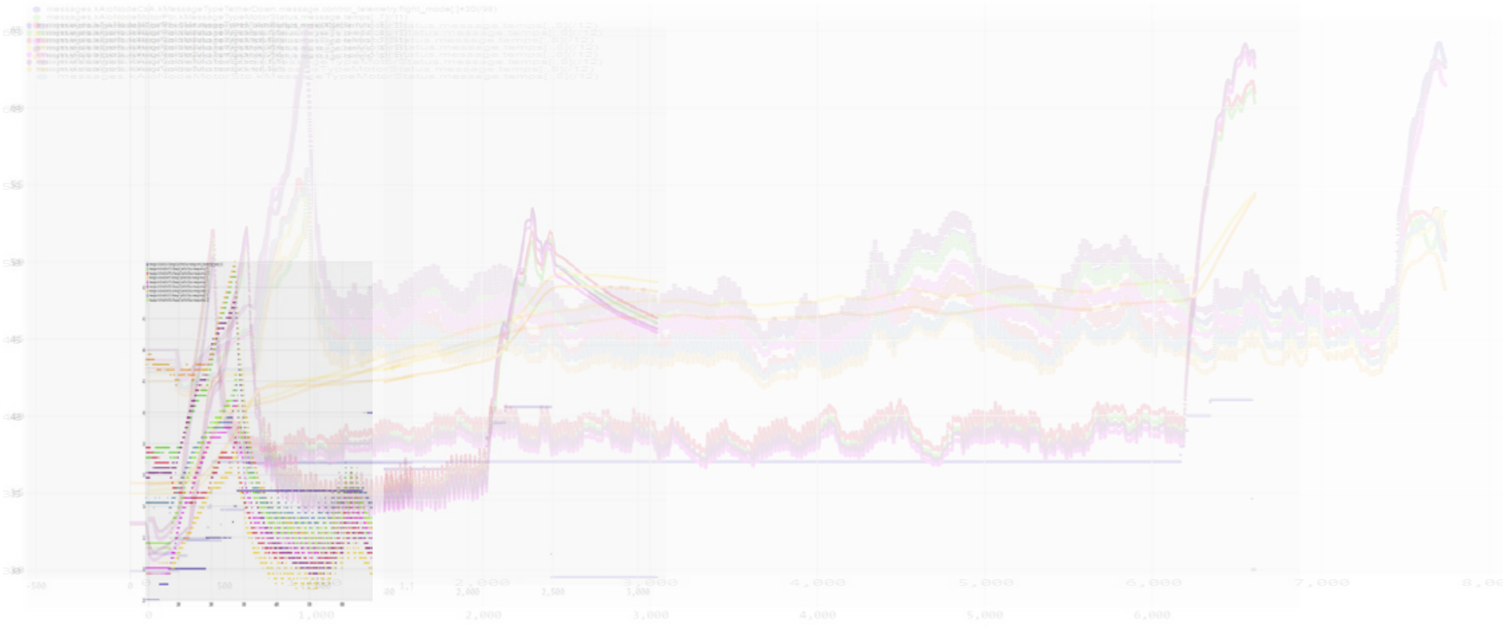
Ozone Module Temps (hottest believable module from each controller)

SBI Δ 11°C
PBO Δ <1°C

Mean Δ 8.3°C



Module/Cooling plate temperatures between RPX-03, 04, 05 and 07

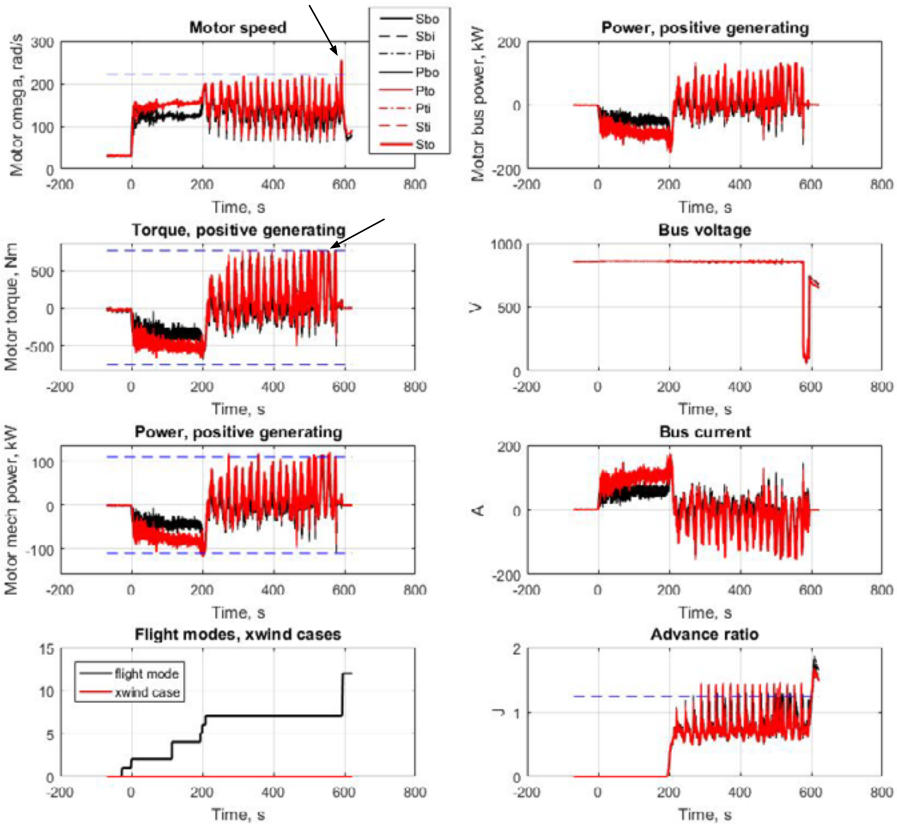


Gin Controllers increased module temps by 20°C in X-in
Ozone Controllers increased module temps by 8-10°C in X-in with 5-10% more mass

ROTORS

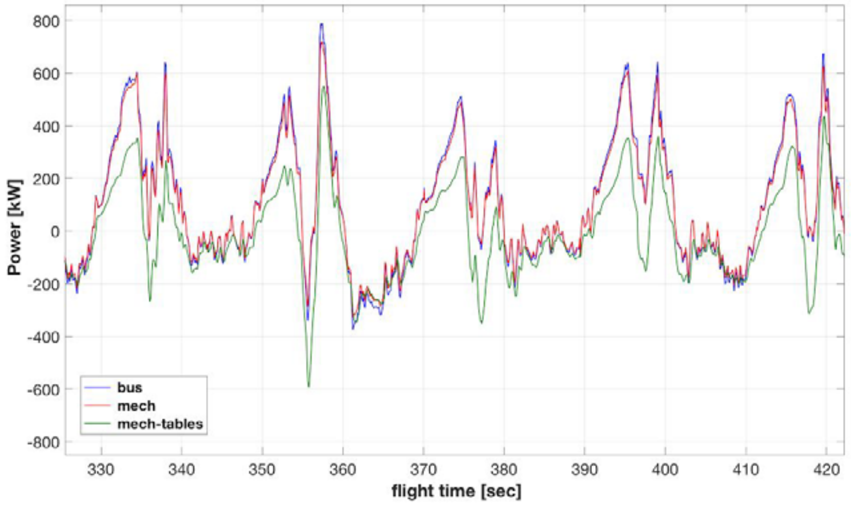
Rotors

- Motor torque limits
- Advance ratio limits
- Motor speeds never railed on the upstrokes
- Motor speed reached max ever during freewheeling portion after power loss



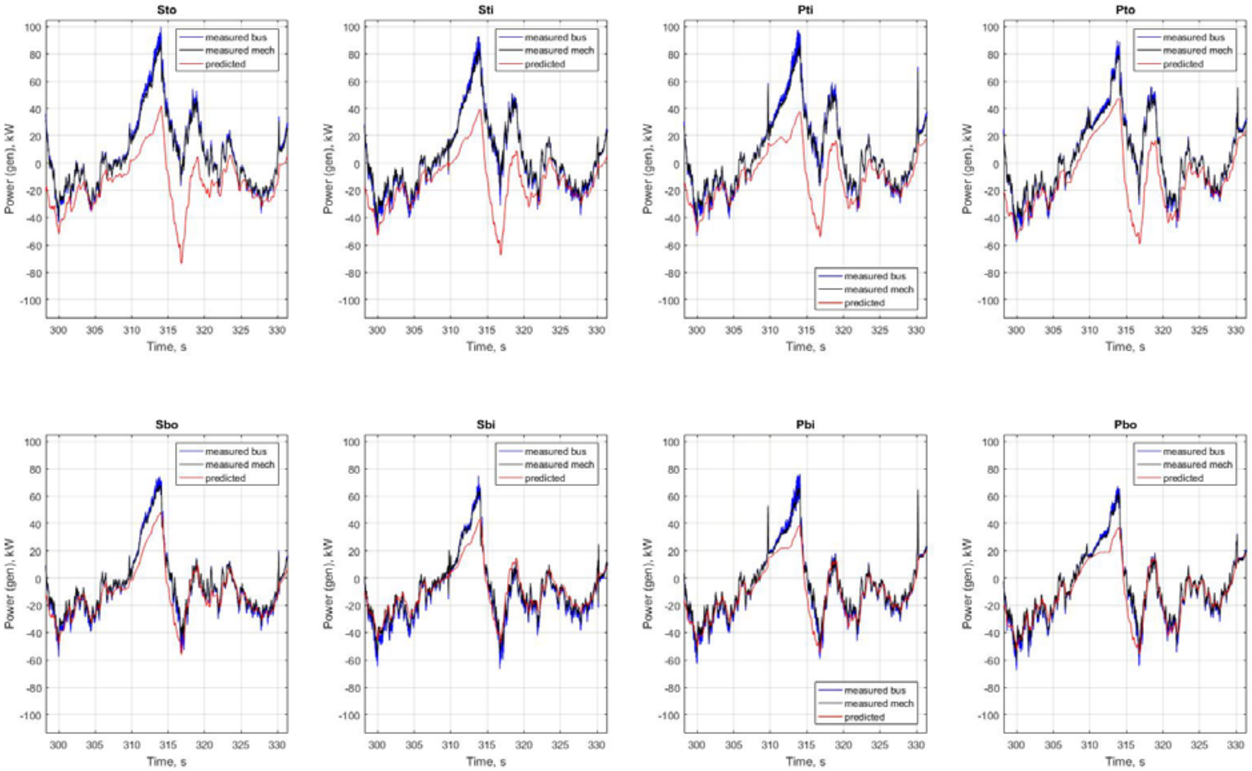
Rotors

- Large error between expected rotor aero model and measured power/torque
- Suspects:
  - Rotor table itself
  - Wing interference model



Rotors

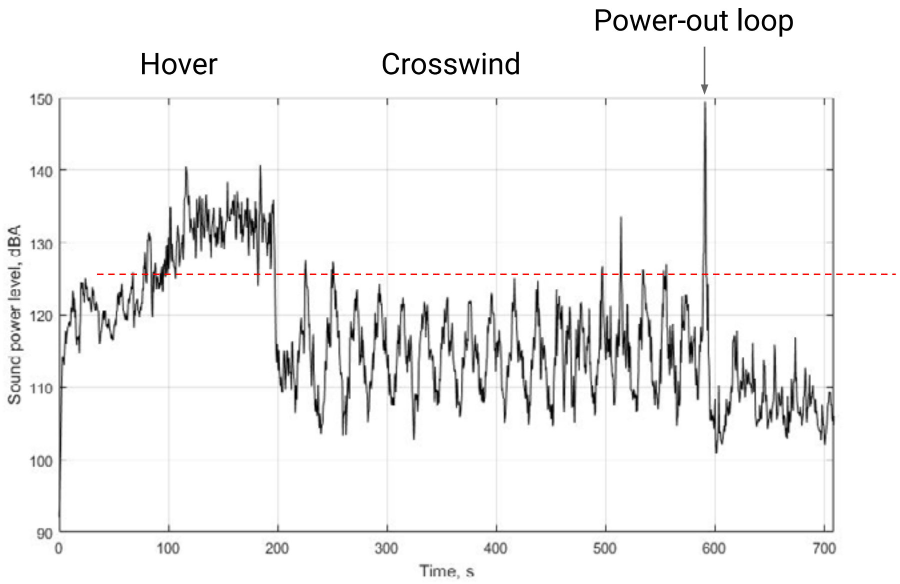
Per-motor basis



Sound Power

- Hover > crosswind
- Power-out crosswind is loudest
  - Highest ever rotor speed and kite speed
  - 250 rad/s and 65 m/s
- Crosswind generating loops are most quiet
  - Similar magnitudes as RPX-04

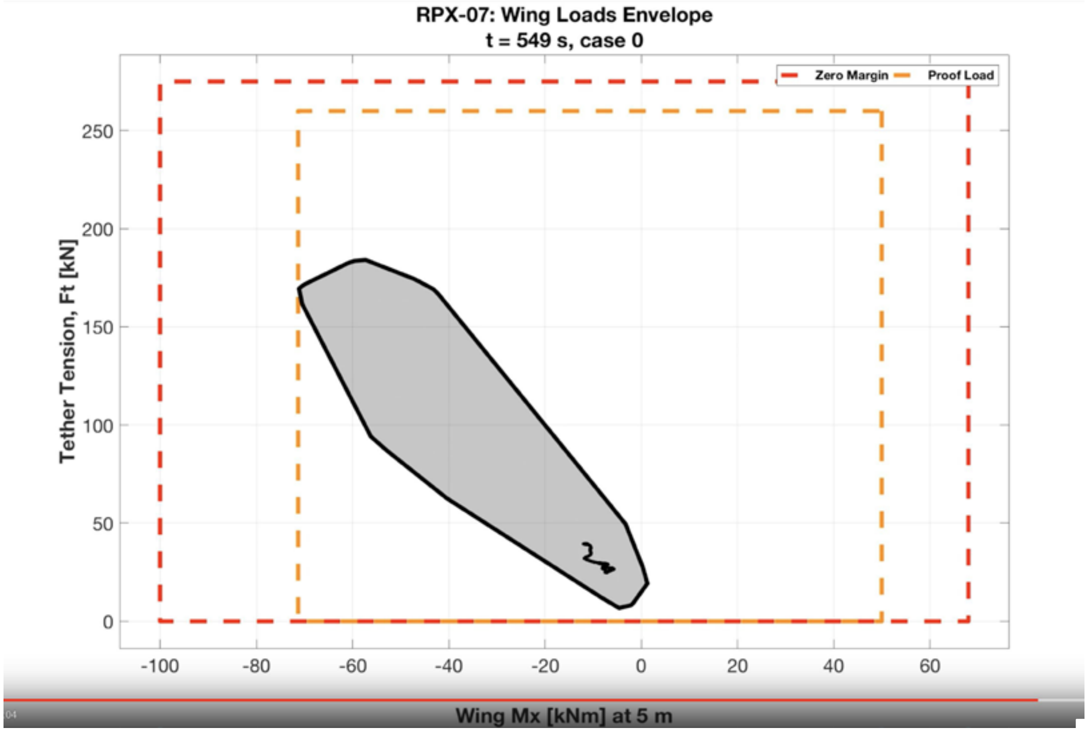
- To-do
  - model correlation
  - IEC average over crosswind portion



RPX-07

LOADS

Wing Loads

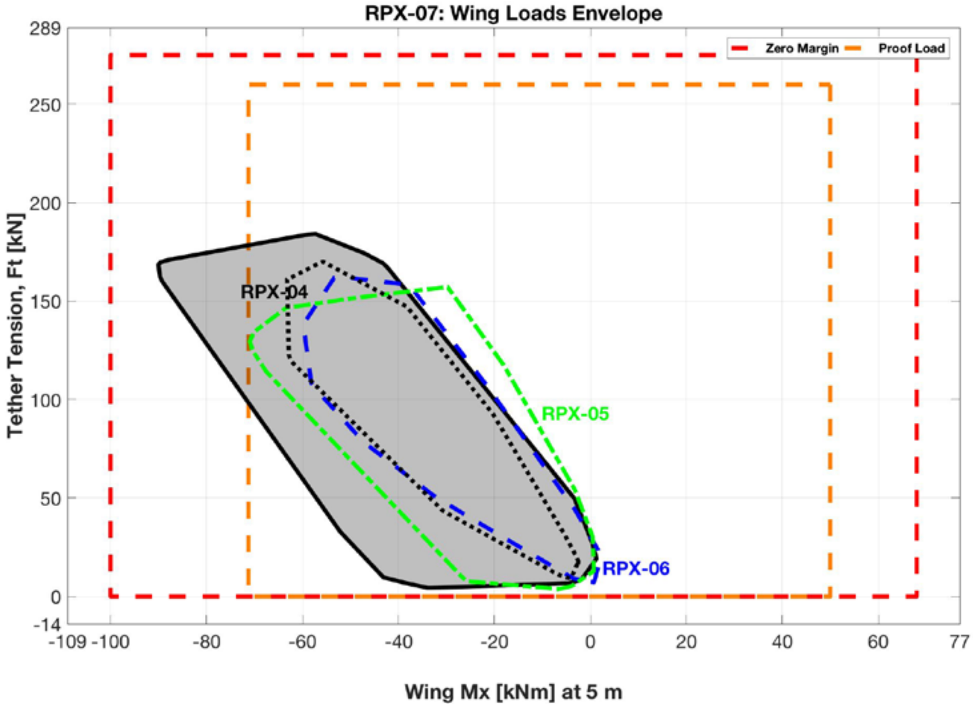


Loads Report
[internal ref]

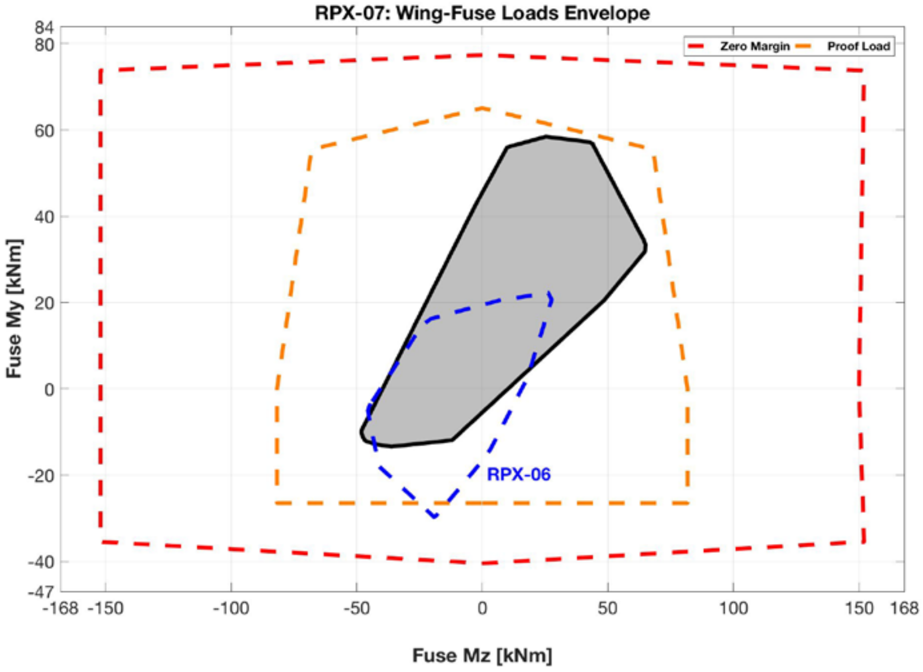
YouTube playlist
video "20171116
RPX-07 - Animation
- Exploring the
Wing Loads
Envelope"

Loads were fine up until the last loop

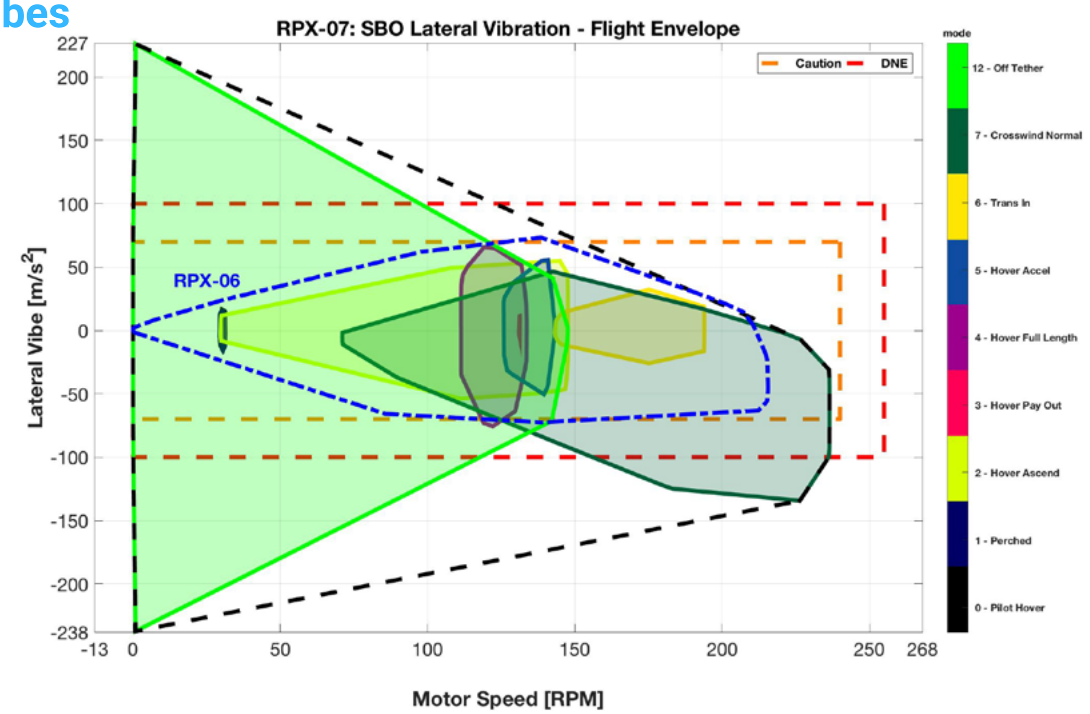
Wing Loads



Wing-Fuse Loads



Pylon Vibes



LL: Vibes okay until end of flight.

Telemetry wireless dropped out

- Was tested in multiple hovers and found working.
- Seems to be related to antenna orientation and reflections around the CH.
- Bug: 69379755

RPX-07

TETHER

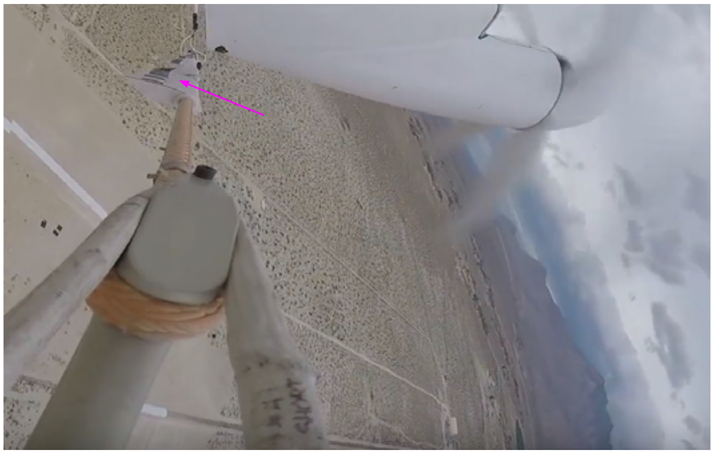
GSG jolt

- Bug 36788267
- Still shown here shows slight jolt. Still taken from YouTube playlist video “20171116 RPX-07 - View of Groundside Gimbal, Tether Attachment, and Detwist“
- no jumps in encoders
- Azi stiction during crosswind is better (smaller jumps)
- Plan to leave as-is

Tether dynamics

- ‘Bugs’ of tether dynamics that we may want to look into more :
    - Tether 'slapping' on downstrokes
    - Tether dynamics from sudden gust/lull when at low/moderate tensions
    - check how bridles are modeled in physics of cSim
    - Tether trans-out dynamics - drop and oscillations
- Interesting loop 12-13
- Tension generally 20-150 kN loops
    - max peak of 180 kN
    - min trough of 5.5 kN
    - Load ratio of .13 on average

Fairings



Summary - rotating sections

- Fairly successful—lots of video for observations but a few questions to address next flight
- Had some ‘bridle shake’ at airspeed over 40 m/s (YouTube playlist video “20171116 RPX-07 - Seventh Unconstrained Flight of Makani M600”)
- Underdamped heave vibration
- Lost middle fairing just before release
- Suspecting shedding from stalled fairing that was misaligned
- No instability observed on tether fairings
- Repeat test with a new design that has better bushings and exclude the section directly behind pylon 4, move GS slamstick to bridle to check frequency content of vibration.

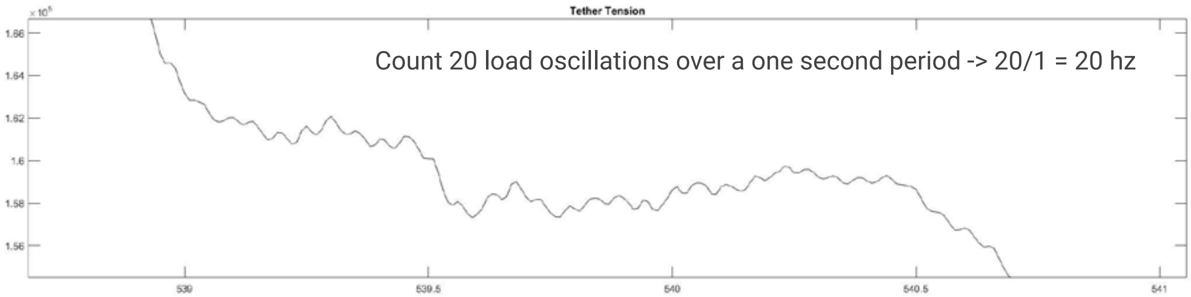
Fairings

Summary - rotating sections (cont.)

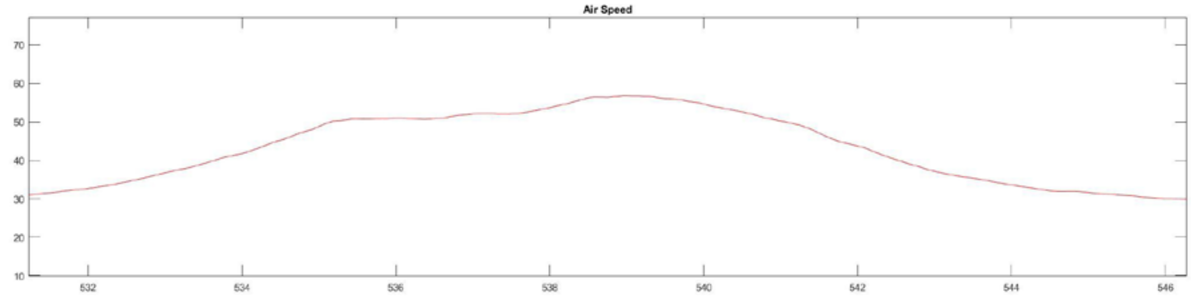
- Misaligned fairing on bridle (2nd from top) (YouTube playlist video “20171116 RPX-07 - Testing Faired Bridles on Makani M600 in Crosswind Flight”)
    - Rotating freely until ~3 min after launch, slight jump a few seconds into xwind
    - Suspect debris in bushing locking up the rotation

- Discrepancy between alpha of tether fairings (YouTube playlist video “20171116 RPX-07 - Testing a Faired Tether in Crosswind Flight of Makani M600 - Kite to Tether POV”)
    - Fairing with reference rod was nose in, *despite* higher margin; suspecting some interaction from the rod indicator
    - Next one down (YouTube playlist video “20171116 RPX-07 - Testing a Faired Tether in Crosswind Flight of Makani M600 - Tether to Kite POV“) aligned well with relative wind and was stable, *despite* negative margin
    - Repeat test with more sections, ditch the reference rod and just reference off centerline of fairing

Fairings



Count 20 load oscillations over a one second period -> 20/1 = 20 hz



Without IMU data we can check the frequency content of the load cells to check for load oscillations induced from the shaking bridles.

As the airspeed exceeds 50 m/s the frequency content in the tether tension is 17-20 hz consistently

---

Fairings

Now comparing frequency content in load cells to experimental data from U. Maryland Wind Tunnel for vortex shedding

Using a strouhal number of 0.18[1] and the projected area normal to the flow the shedding frequency should be close to 87 hz.

St = 0.18

Reference length = chord x sin(alpha) = .208 x sin(30)
= .104m

Air speed = 50 m/s

Freq. = St x air speed / reference length
= 0.18 x 50 / .104 = **86.5 hz**

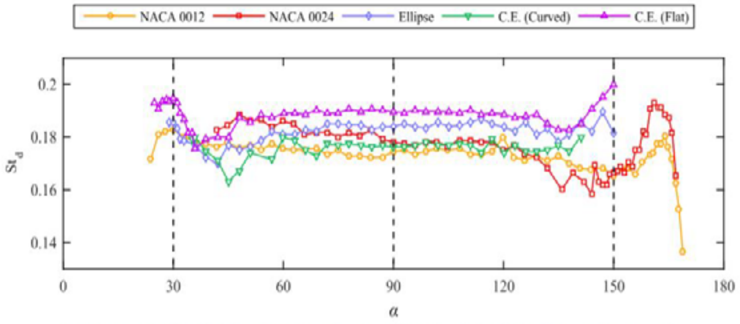


Fig. 15. Magnitude and frequency of unsteady airloads acting on four airfoils through 180° at $Re = 6.6 \times 10^5$.

Comparing 86 hz to the 17-20 hz content observed in the load cell data it seems unlikely that the stalled airfoil was causing the instability because this frequency is 4x of what was measured.

[1] Based on figure 15 of [internal ref] for an NACA 0024 at 30deg. Figure shown above.

Fairings

Then how does the the frequency in the load data compare to our own experimental ground testing data

String Frequencies, freq. = [sqrt (Tension / (mass/length)] / [2L]

Moffett Ground Test Bridle

Linear density: 0.7 kg/m (including fairing section)
Tension : 20-200 N
Length: 1m

Fundamental string Freq. **2.67-8.5 hz**
Fairing frequency*: **7-10 hz**

RPX Bridle

Linear density: 0.8 kg/m (including fairing sections)
Tension : 100-165 kN
Length: 7m

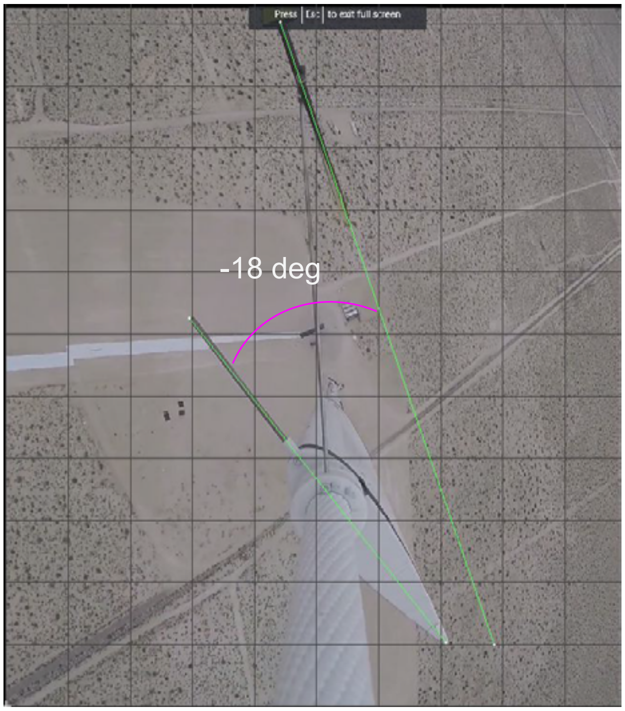
Fundamental string Freq. **25-30 hz**
Fairing frequency:** **17-20 hz**

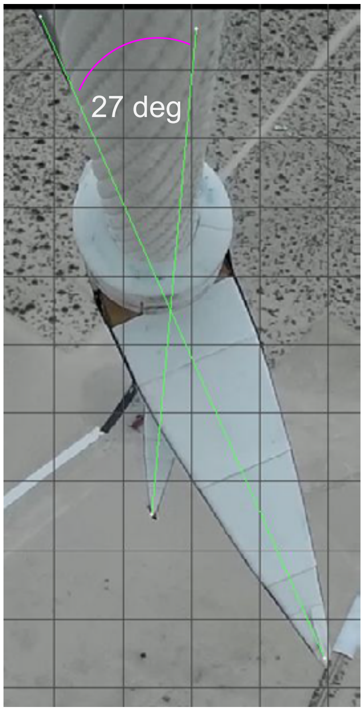
*based on stepping through Gopro footage
**based on small amplitude load oscillations consistent with airspeed the fairing oscillations were observed

---

Fairings

This is just a random comparison but.. -18 + 27 = 9 deg alpha on second fairing
Need loop radius and air speed with synced video to get an accurate measurement





Fairings

Summary - fixed section

- Initial misalignment, but this may have been enough to twist the tether
    - Although the camera itself probably played a role
- Slowly crept into alignment; also seemed stable

Tether Vibration

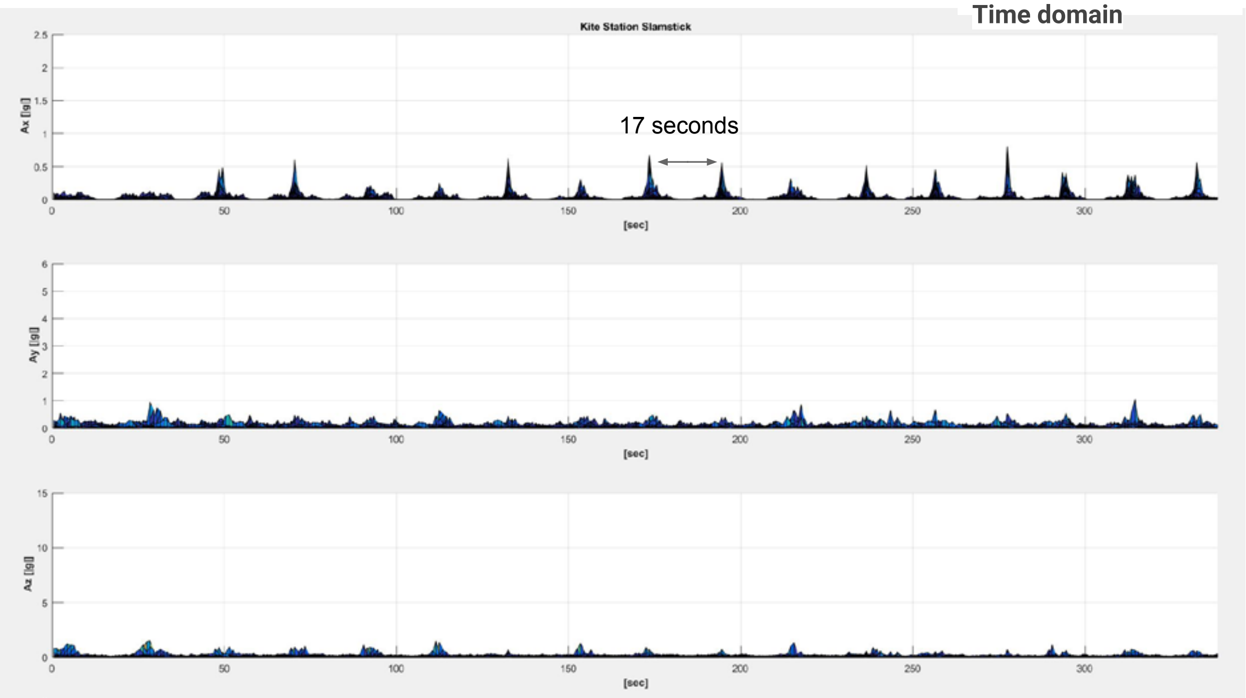
RPX-07 KS Slam Stick Frequency domain

New this flight (along tether axis)

Basically no vortex shedding with fluted tether

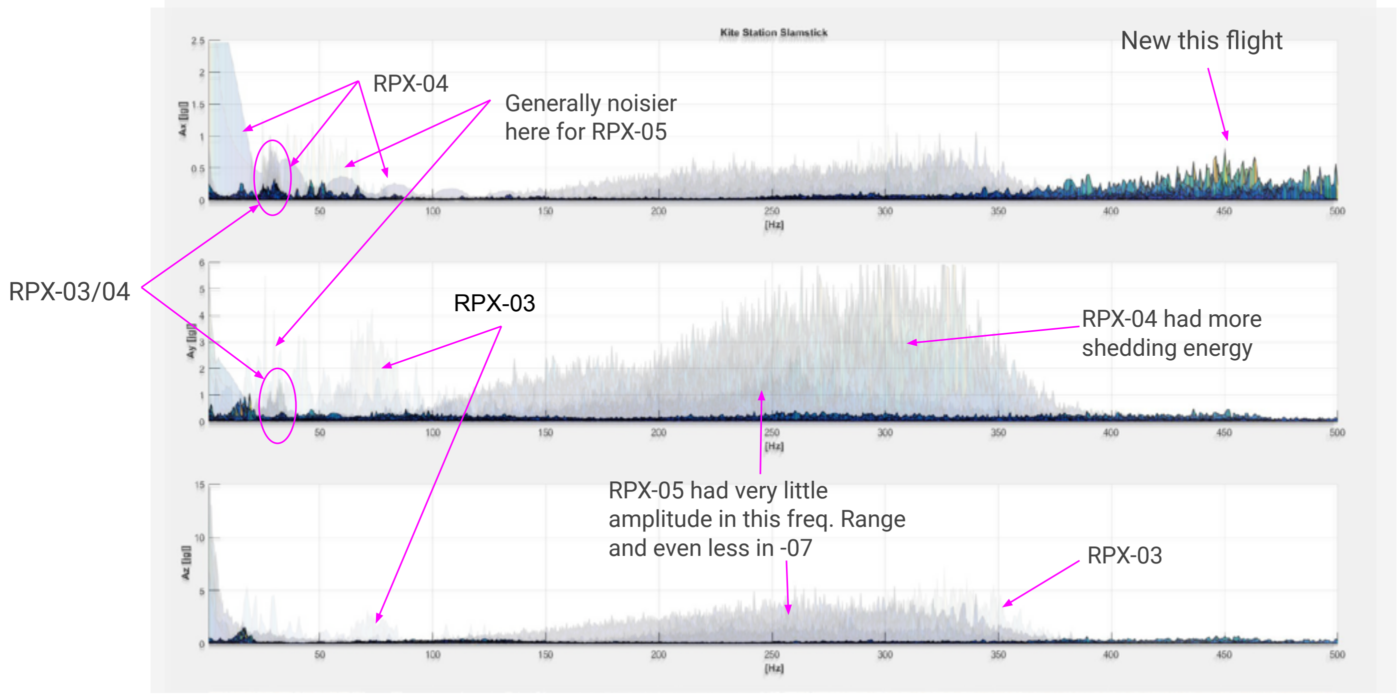
Tether Vibration

RPX-07 KS Slam Stick Time domain



RPX-07 Vibration Signature Differences

RPX- 03 thru 07



RPX-04

Generally noisier here for RPX-05

New this flight

RPX-03/04

RPX-03

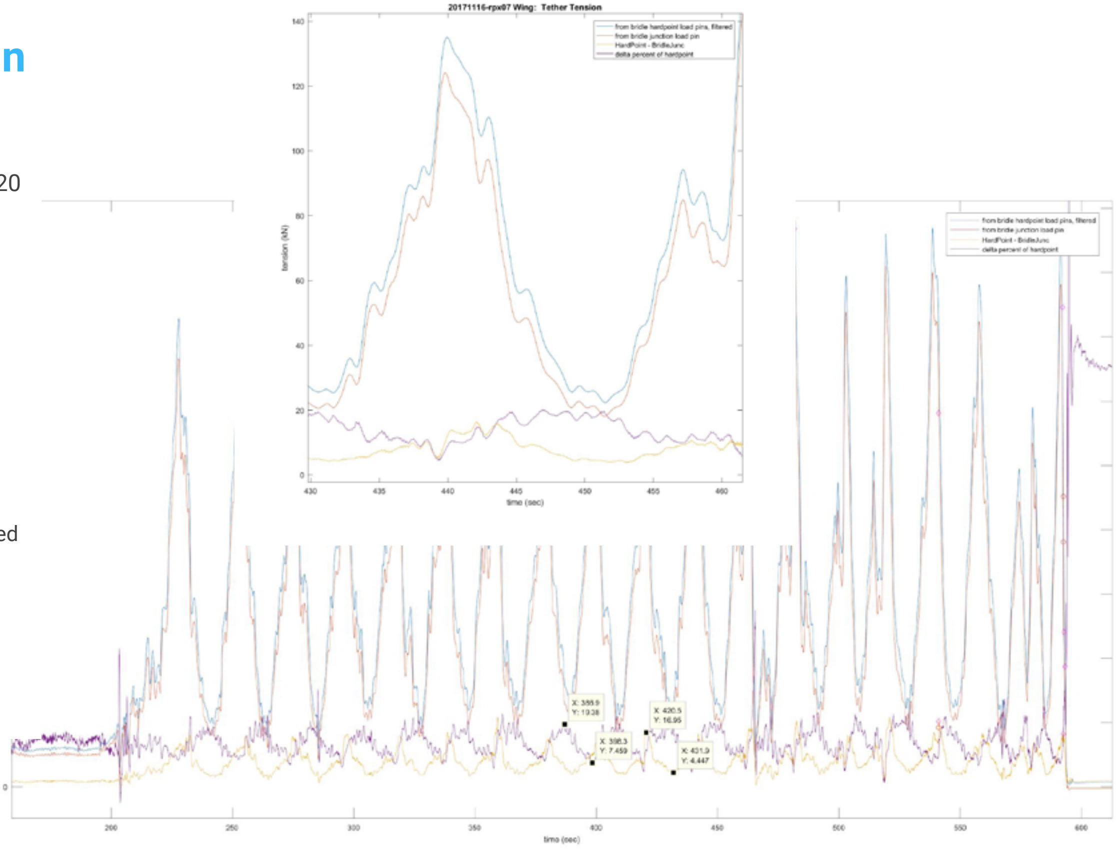
RPX-04 had more shedding energy

RPX-05 had very little amplitude in this freq. Range and even less in -07

RPX-03

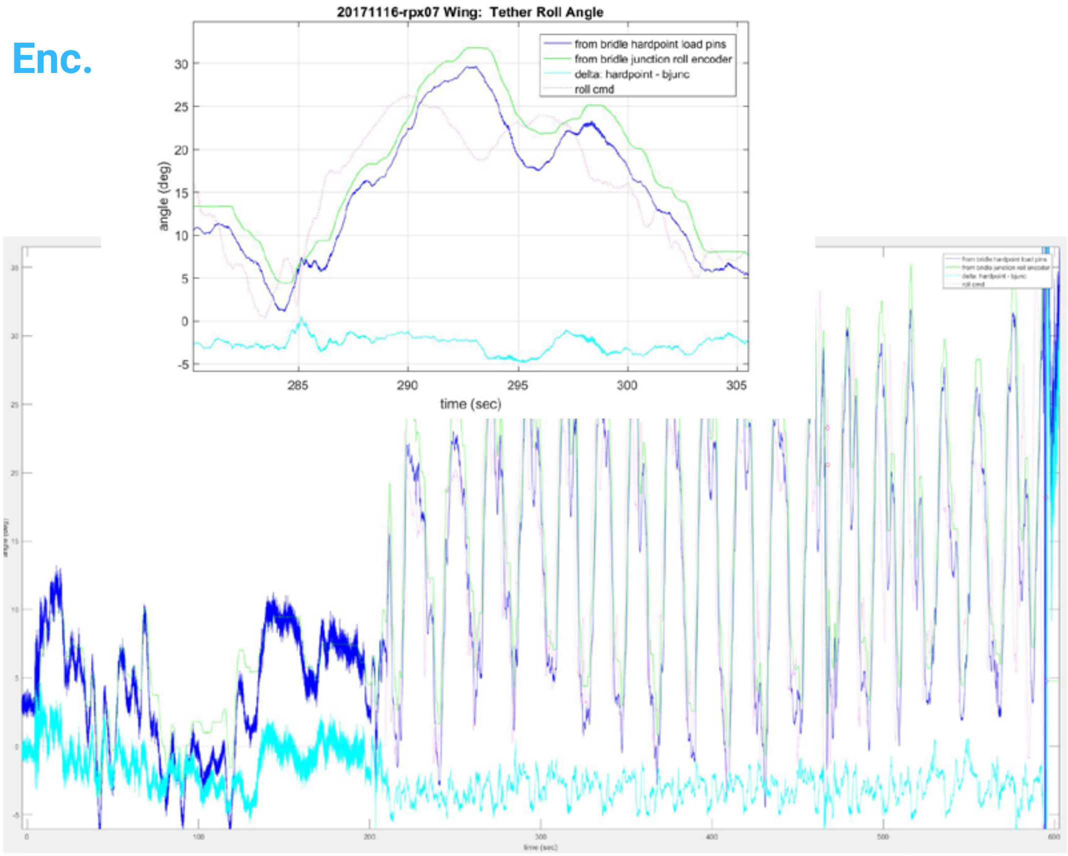
BridleJunc Load Pin

- BridleJunc reads lower than HardPoints
- 4-17 kN delta → ~10% (max 20 but only at low tension)
    - → about the same as our Cl deltas...
- Only updates @ 10Hz
- → should try to recalc aero coeffs w/ this load
- Bug 69812220
- We expected delta might be opposite
- Minor notes
    - BridleJunc slightly filtered (lags behind unfiltered tether tension)
    - Bridle junction load pin configuration



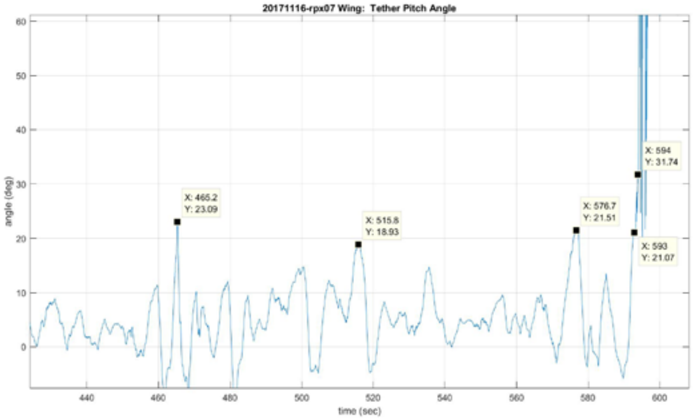
TetherRoll and BJunc Enc.

- Roll range of ~0-30 deg (limit 33.4)
- BridleJunc reads higher than HardPoints
    - Suggests we're rolled more with tether to port than we think
- Delta of ~3 degrees
- About 1-2 degrees of 'noise' from hardpoints
- Do we care about a constant offset or noise on roll measurement?



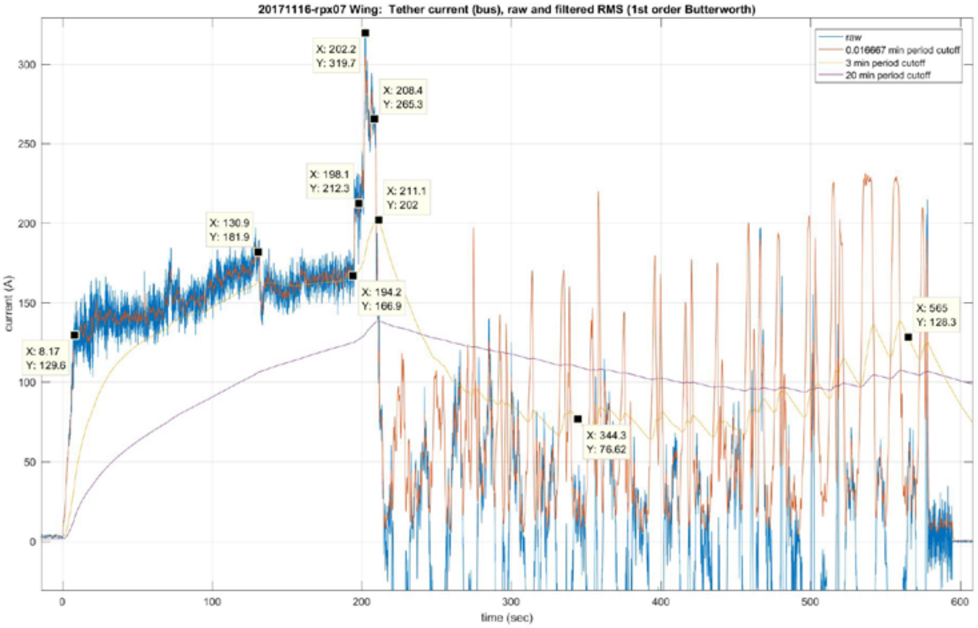
Tether Pitch

- Contact between bridle fairings and pylon **4 times**, Bug 69978773
    - Left marks/cracked nacelle, but seems no structural pylon damage
    - Contacted the 2nd fairing
    - Expected contact (w/o fairing) @ 17.7 deg
    - Achieved contact at just under ~19 deg as measured
    - Noticed extreme jump to ~90deg on final contact before release. Could this have future impact on controls? → file bug



Tether current

- Summary
    - Heavier → **higher** hover current
    - More generation → **lower** current until we cross-over to net generation, then **higher** current
- Details
    - 130-180A in hover
    - 215A in accel
    - 265-320A peak in trans-in
    - 75 A RMS during initial xwind
    - 130 A RMS at max gen



Tether thermals

- Ground side thermocouple
    - No noticeable temp rise - likely too short a flight
- Internal Fairing thermocouple
    - Sacrificed to the moon dust

Tether release

- Worked! Including signal sever
- We released at <1 kN of tension and high roll (tether weight on stbd bridle), so the MV connectors didn't pull out for ~1s

(screenshot from "20171116 RPX-07 - Seventh Unconstrained Flight of Makani M600 - Glide Landing [Full Flight]" on Makani technical videos YouTube playlist)

RPX-08 What Do We Want to Learn/Do?

- **PERFORMANCE IMPROVEMENTS**
    - Add more fairing to the tether (10 m?)
    - Increase rudder effectiveness (trailing edge extension?)
    - New bridle releases (higher margin, no wing damage risk)

- **INSTRUMENTATION**
    - Bridle Knot Load Cell pin - continue to utilize (pitch encoder?)

Selected Decks From All-Modes Lessons Learned Reviews

Contents

MAKANI

Controls
CW-01/02 Learnings Review
PART 1

December, 2018

Contents

Previous Controls Reports (Lots of good source material)
HH01 [internal ref]
HH02 [internal ref]
CW01 [internal ref]
CW02 [internal ref]

Executive Summary

Executive Summary - Statistics

- **Total Flight Duration**
  CW01: 1 hr 1 min
  CW02: 1 hr 43 min
- **Number of Loops**
  CW01: 81 (23.0 sec/loop)
  CW02: 222 (22.4 sec/loop)
- **Best Power Loop**
  CW01: -56.4 kW
  CW02: 78.3 kW
- **Wind Aloft Speeds**
  CW01: 9-10 m/s ish
  CW02: 8-11.5 m/s ish
- **Launch to Crosswind Duration**
  CW01: 8.6 min
  CW02: 8.9 min
- **Crosswind Duration**
  CW01: 31.1 min
  CW02: 82.8 min
- **HoverTransOut to Perch Duration**
  CW01: 21.6 min
  CW02: 10.8 min
- **Turnkey?**
  CW01: Pilot Hover Used
  CW02: Winch Speed Slowed

Executive Summary - High Level Observations

Things that Went Well

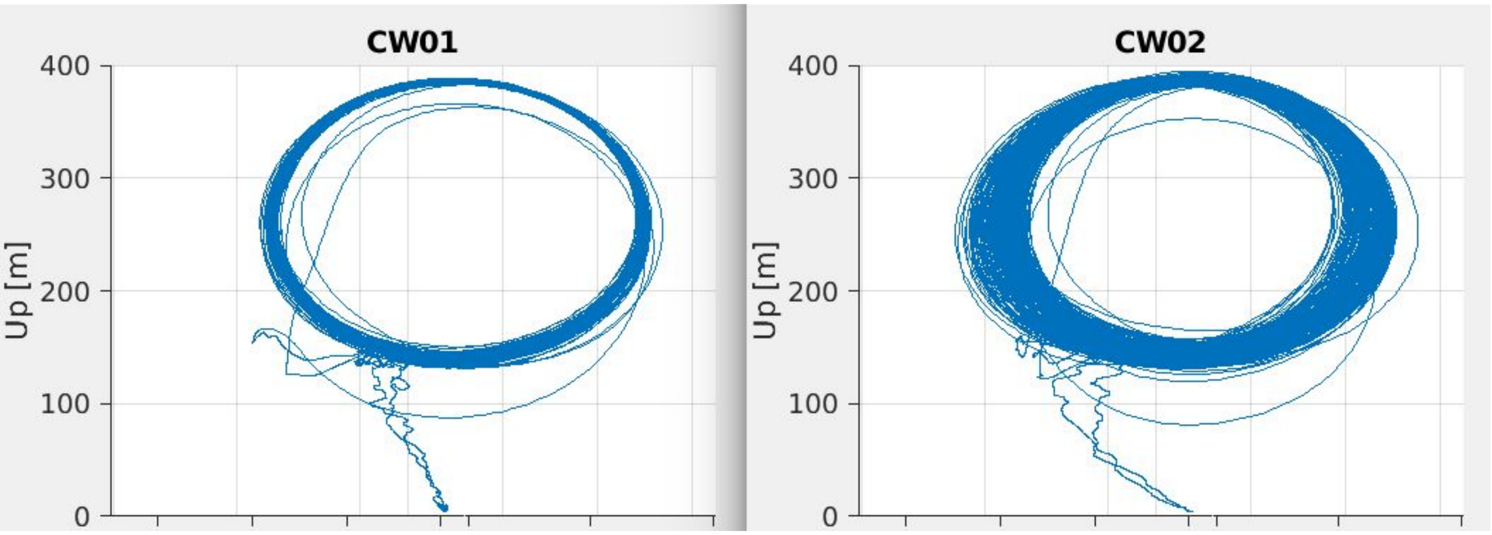
- Launch
- Transform Up
- Accel/TransIn
- Crosswind
  - Airspeed Control
  - Sideslip Control
  - Rudder Deflection Margins
  - Path Tracking
- TransOut
  - CW-02 looked great!
- Transform Down
- Land

Things that Need Improvement

- Payout
  - Tether Elevation Control
    - Better in CW02
- Crosswind
  - Aileron Deflection Margins
  - Angle of Attack Control
  - Power Production
- TransOut
  - CW-01 lost some altitude
- Reel-In
  - Tether Elevation Control
    - Better in CW02
  - Altitude Estimation (GPS Stuff)

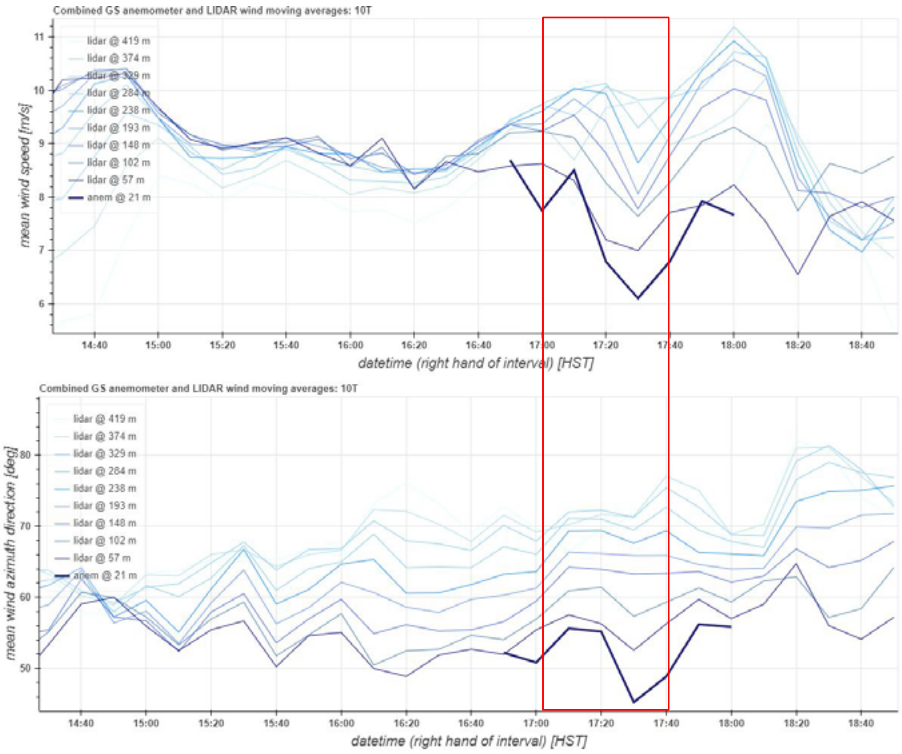
Flight Trajectories Viewed from Near Upwind

These are to scale and viewed from the same azimuth. Kite flies clockwise from this view.



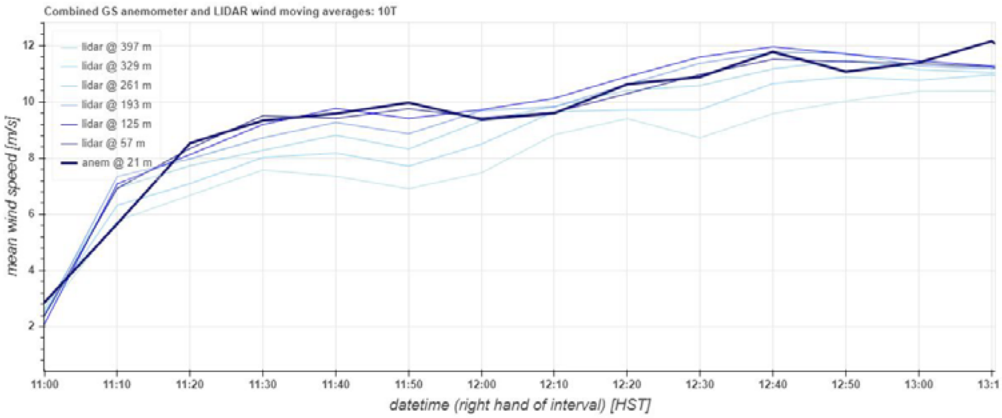
CW01 Wind

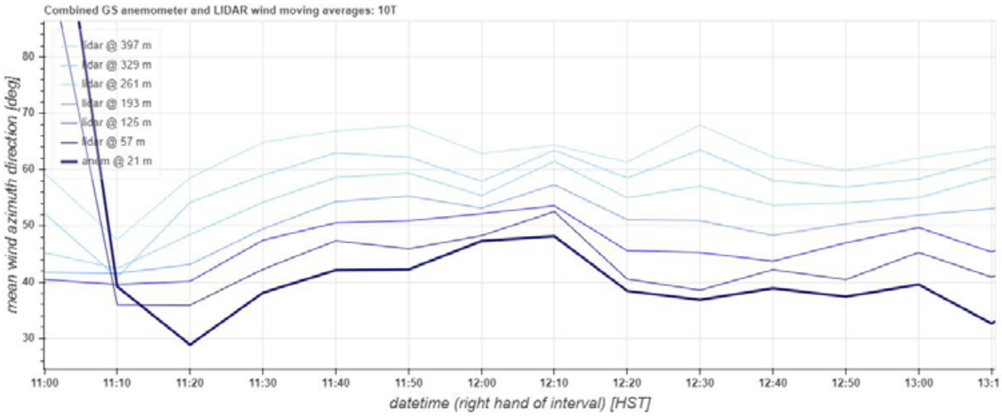
- Veer of about 15-25 degrees between 57 and 329 m
- 10-15 deg for 57 to 238 m
    - Forecast on day-of was predicting about 5 degrees between 60 and 240
- Before the flight
    - Note the peak wind speed at 150 m and usual reverse shear above that.
- During the flight
    - Altitude of peak wind speed was much higher, ~300 m



CW02 Wind

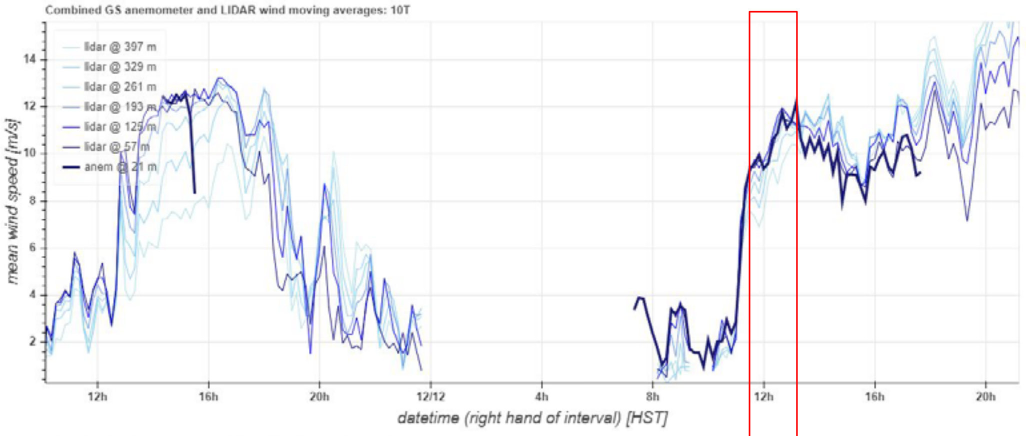
- Veer
    - 20 degrees between 57 and 397 m
- Shear
    - Modest during flight
- Very fast wind speed increase right before launch
- Significant wind direction shift as wind speed increased

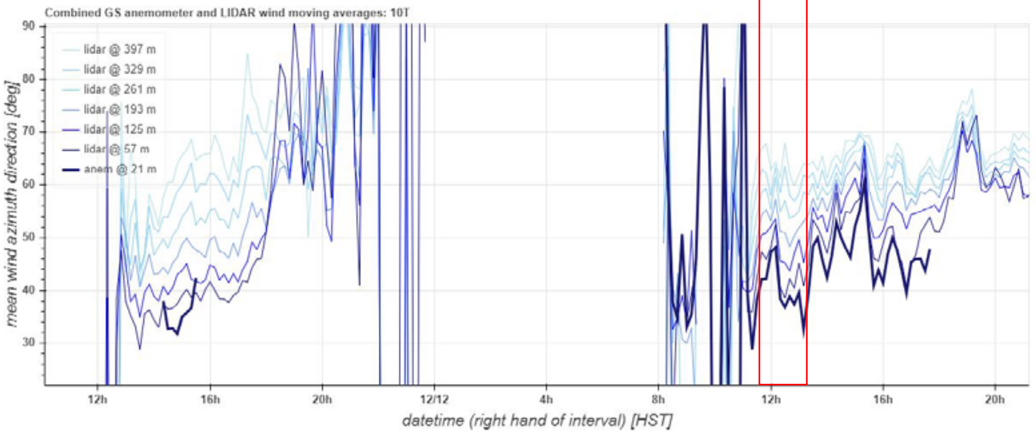




CW02 Wind

- Note: high shear and veer the day before

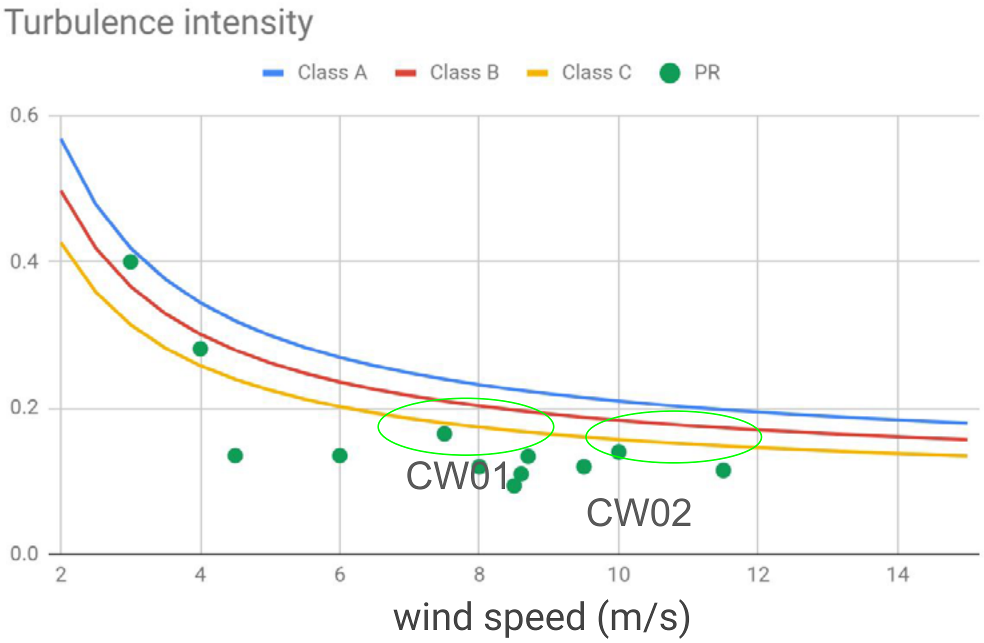




Wind — Turbulence Intensity

- CW01: 12-16%
- CW02: 10-14%

→ Class C [internal ref]?



Topics of Interest

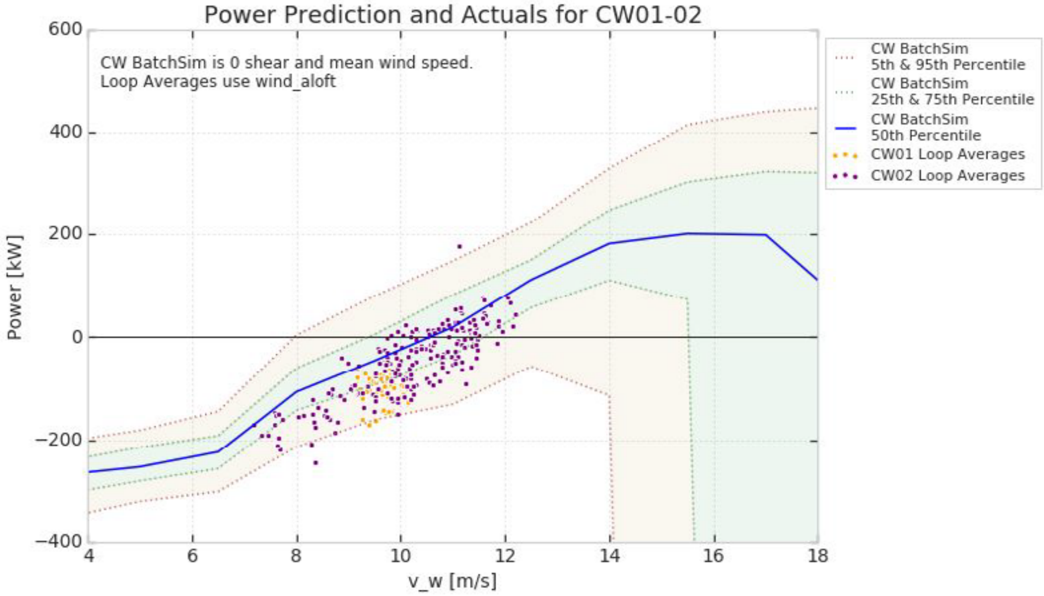
Power Production As Compared to C-Sim

Not quite an apples to apples comparison

- Mean wind from batch vs avg wind_aloft from flight

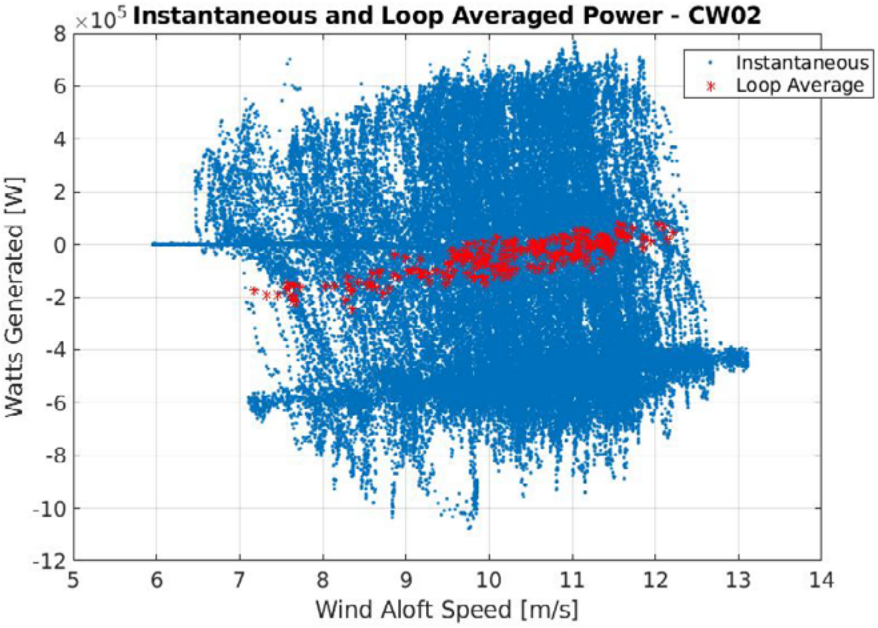
Should revive/revise power curve tool

- Incorporate into batch sim results



Large Power Production Amplitude

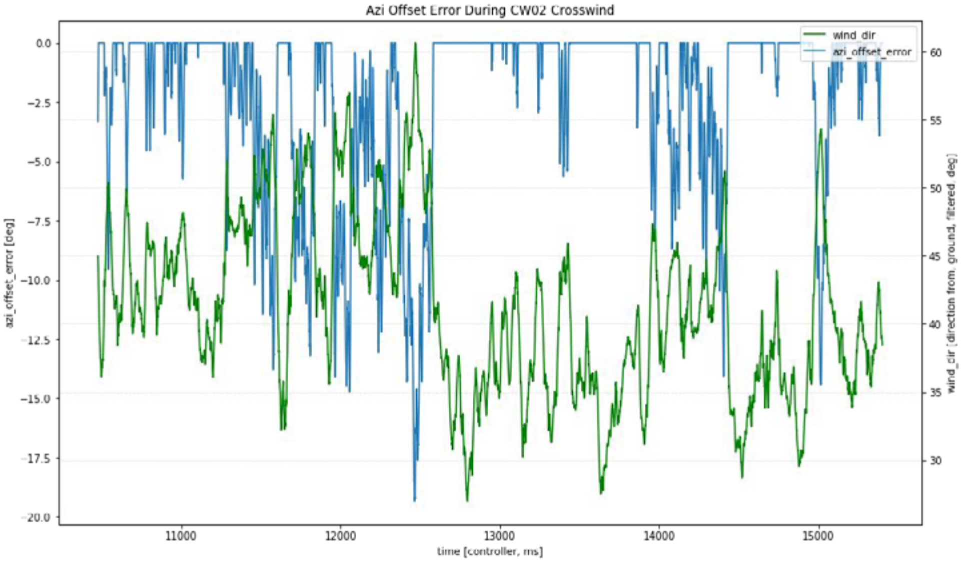
- Playbook is not focused on making power right now
  - Instead, focus is more on flight quality
- Large loops are easy to fly
- Large change in gravitational potential
  - Big amplitude in the power profile
- We pulled more than 1 MW instantaneously on the upstroke



Playbook Azimuth Saturation

Azi Offset Error = azi_target (cmd) - azi_raw_playbook

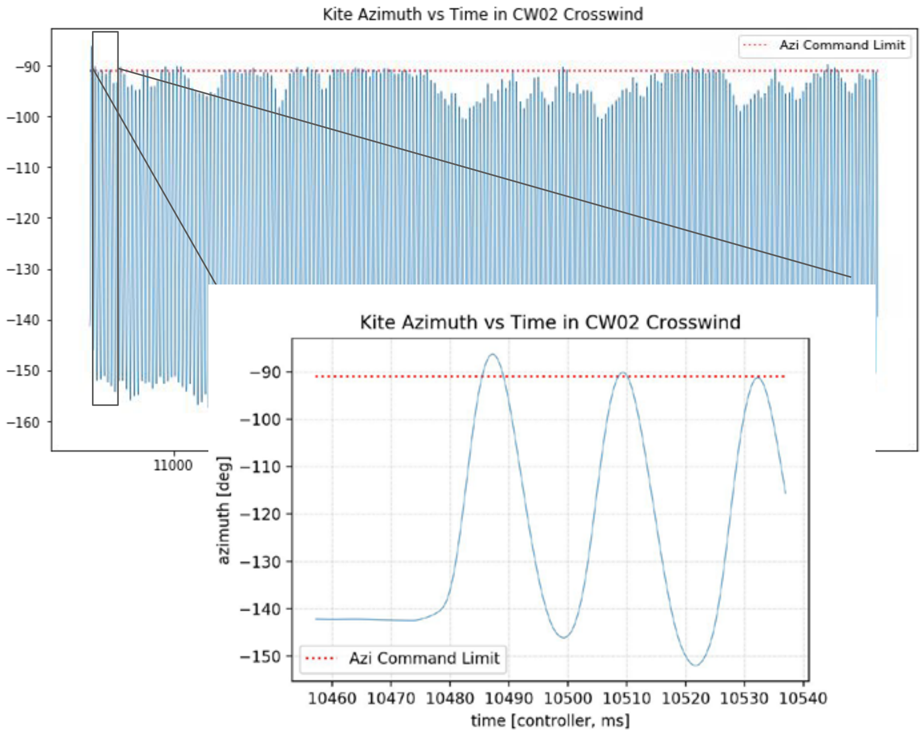
- ~43% of time playbook was saturated against azimuth limits
- Wind direction limit is 65 deg
    - Limit was set based on slow degradation of flight quality scores with increasing azimuth saturation



Playbook Azimuth Saturation

1st loop exceeds command limit due to:

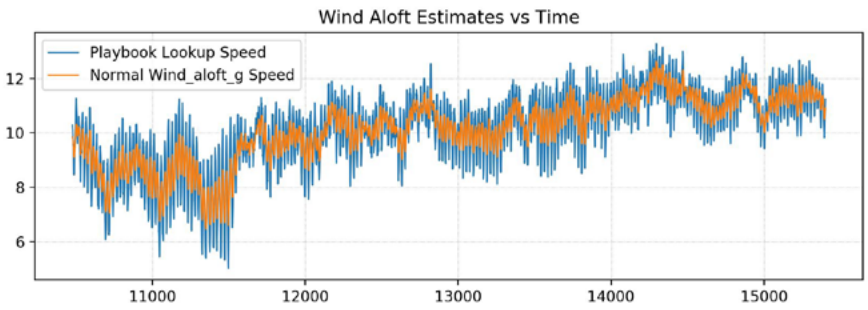
- Tiny amount from:
    - Drift downwind during trans-in
    - Change in wind speed estimate from g to aloft
- Almost all from:
    - Error in trans-in azi offset
        - Path center calc accounts for elevation effects, need to do the same for trans-in start

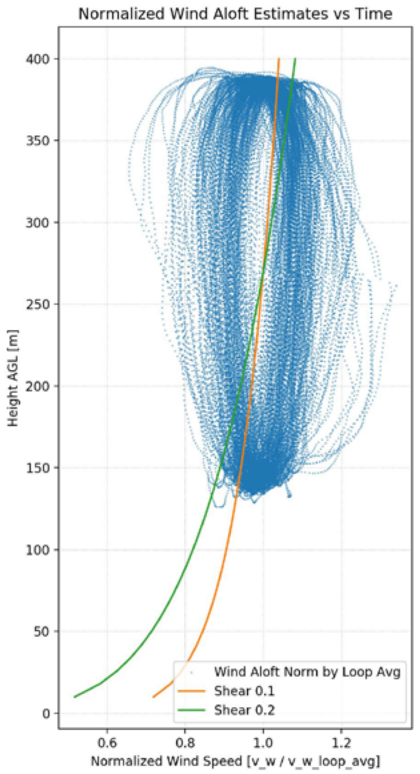


Playbook Lookup Wind Speed

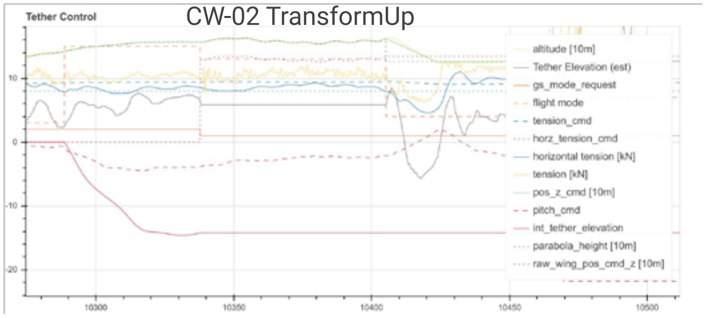
Varies too much from top to bottom of loop

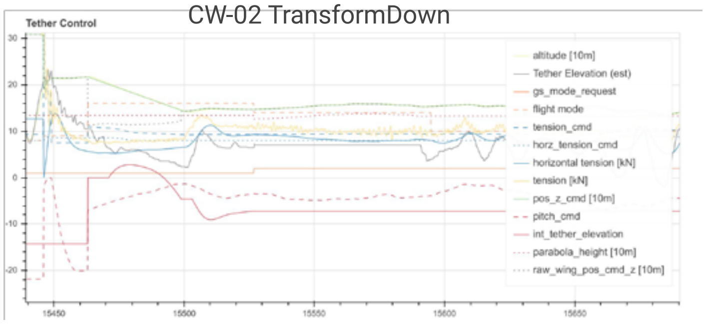
- Bigger cutoff freq than wind_aloft_g.speed_f
    - 0.03 Hz vs 0.01 Hz
- Why? Some early playbook tuning showed this performing better
    - Actual wind has more variety with altitude than simple shear models
    - Will experiment with more filtering





Tether Elevation Control in Transform (ECR 338)


CW-02 TransformUp


CW-02 TransformDown

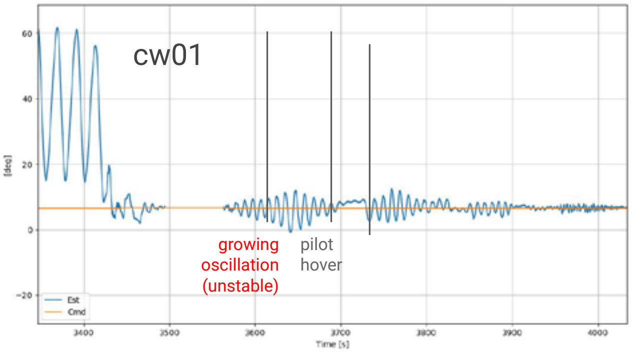
- **Elevation Angle Tracking**
    - Estimates not available during transform.
    - Observe from the start/end position, and flight video ("20181212 CW-02 - Second All Modes Flight" on YouTube shows TransformDown around 1:30:00) on YouTube playlist.
    - Target is 6.7 deg, got 6.61 deg on average (across 4 transforms in CW01/02), and 0.4 deg as std. dev.
- **Altitude vs Higher Tension**
    - Holding tension works well
        - With std. dev. ranging from 197 - 471 N.
    - Integrator usage is < 15 m.
    - Parabola-based offset did compensate for slight drop in tension.

Tether Elevation Control Oscillation

- **Change between CW01 and CW02:**
    - Reduced gain by 6 dB (2X)
    - Reduced roll-off filter by 2X
    - This was expected to reduce the gain at the oscillation frequency by 12 dB while maintaining phase margin.
    - Appears to have been successful.

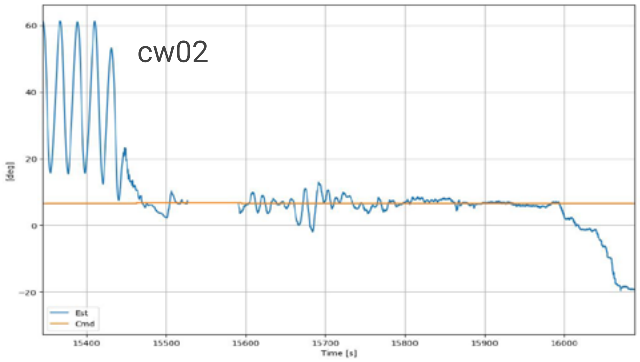
- In CW02, the tether mode was excited through unintentional feedback in the **feedforward** command. This needs to be addressed.

- ECR 376 [internal ref] (Changes between CW01 and CW02)
- ECR 375 [internal ref] (Active notch)

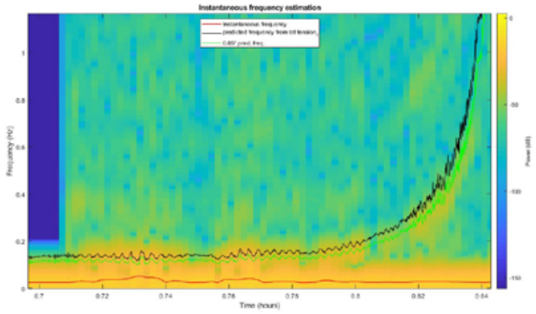

cw01

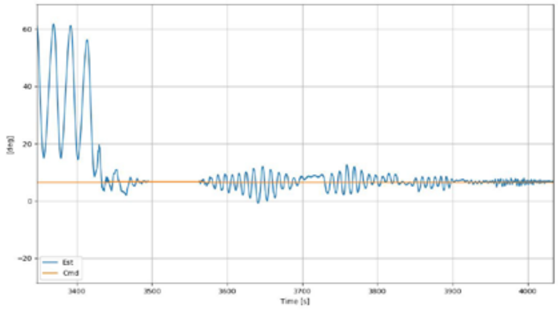
growing oscillation (unstable)

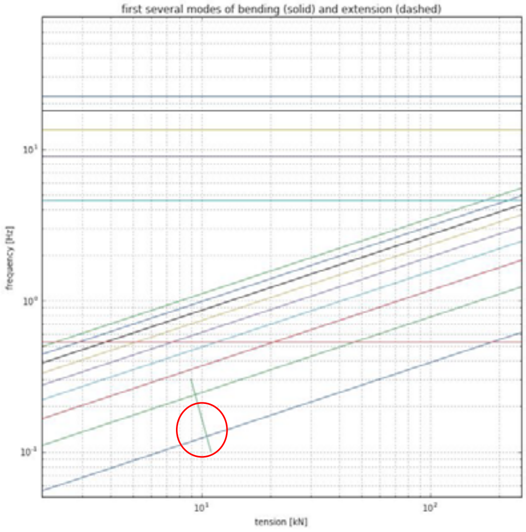
pilot hover


cw02

Tether Oscillations

- Observe oscillations ~0.1Hz
- Near the predicted first bending mode
- But also near the **predicted first extension mode** of a spring/mass system w/ catenary stiffness corresponding to:
    - 300 m payout
    - 5 kN horizontal tension
    - 7 deg elevation angle at ground
    - 99% taut
- 



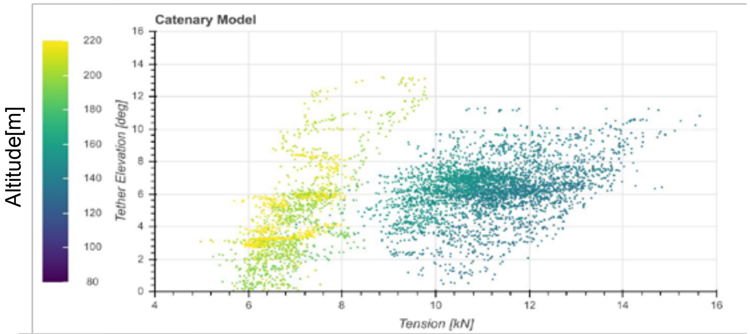


Our Prediction of Catenary Shape

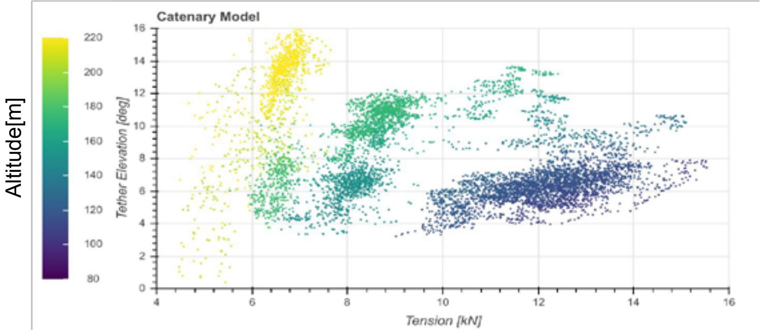
Sim

- Under-estimates the altitude needed by 20-30 m
- Is especially bad when tension is low
- Real flights show that the same tension/elevation target combination can yield different altitude (see 7 kN tension, at 6 deg elevation), is it due to tether dynamics (oscillation?)

Real Flights
HH-01
HH-02
CW-01
CW-02



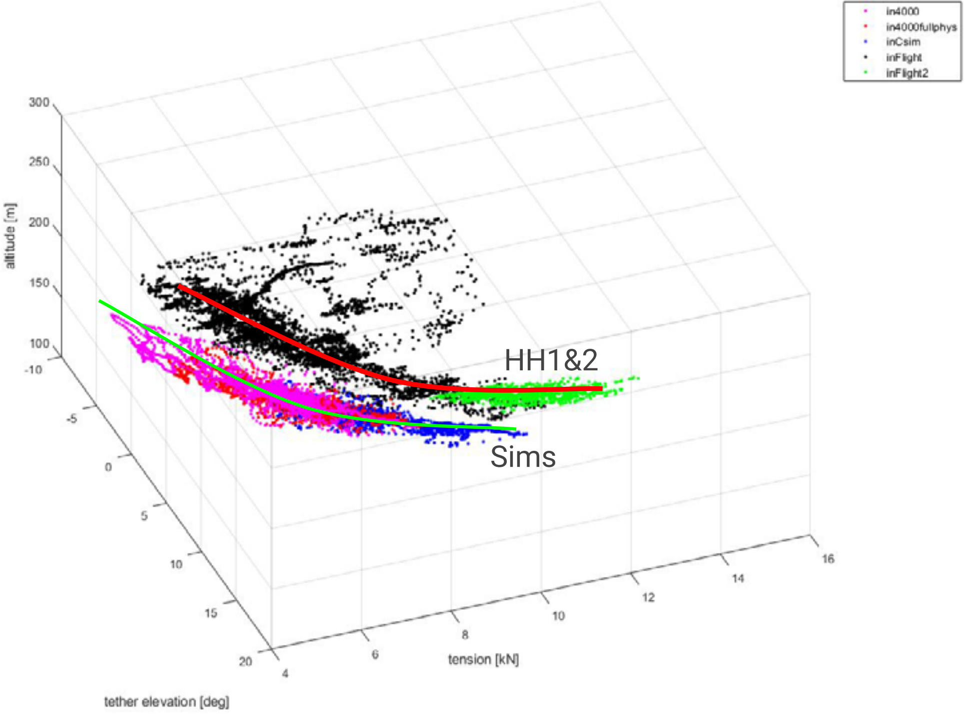
Sims



Our Prediction of Catenary Shape

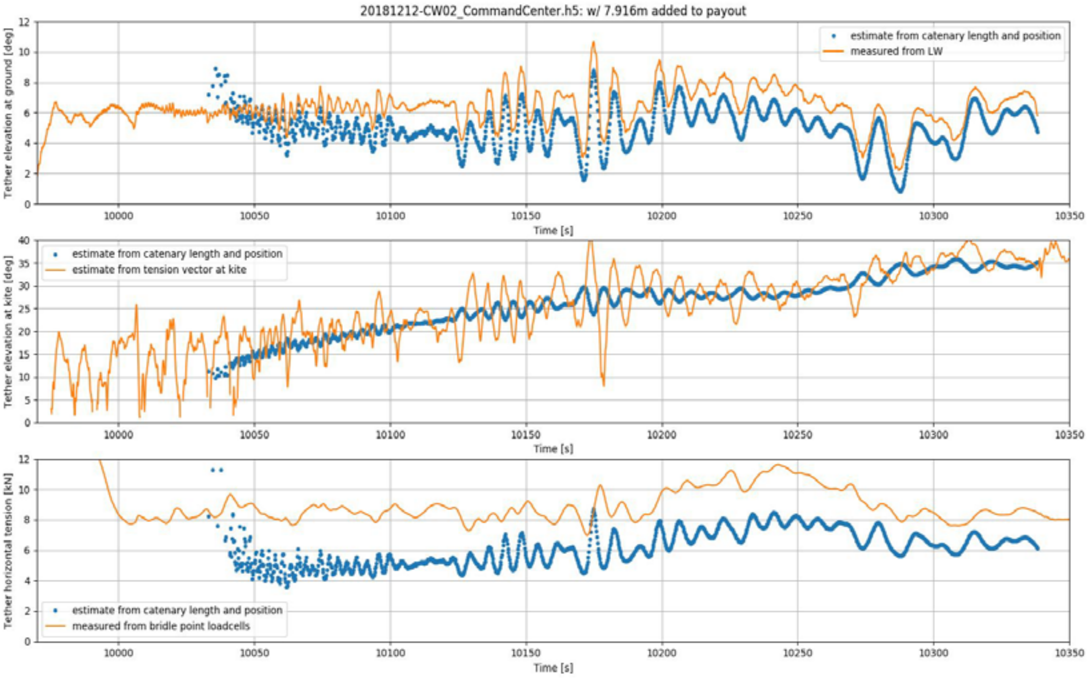
The relation between kite altitude, tether tension, and tether elevation, for a fully paid out tether, falls on different 'surfaces' between sim and flights.

- Tether drag?
- Differences in length?



Our Prediction of Catenary Shape: Based on Pay Out, End Positions

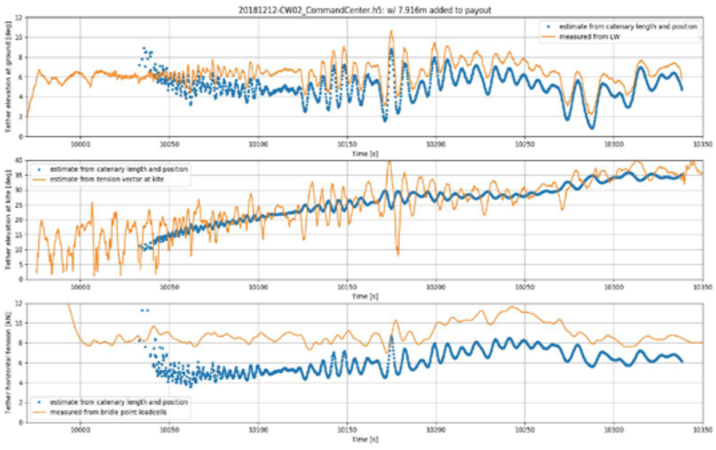
- Tether angle at GS matching decent
- Tether angle at kite matching very good
- Measured tether tension higher than expected



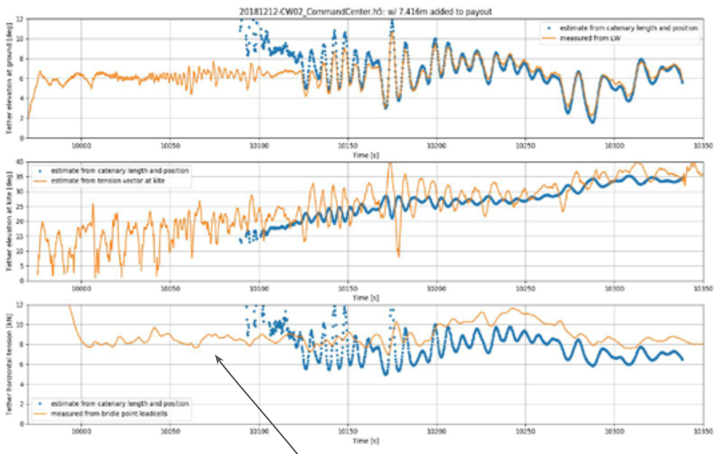
Bug 120242558

Our Prediction of Catenary Shape: Adjusting Payout Length

+7.9 m



+7.9-0.5 m



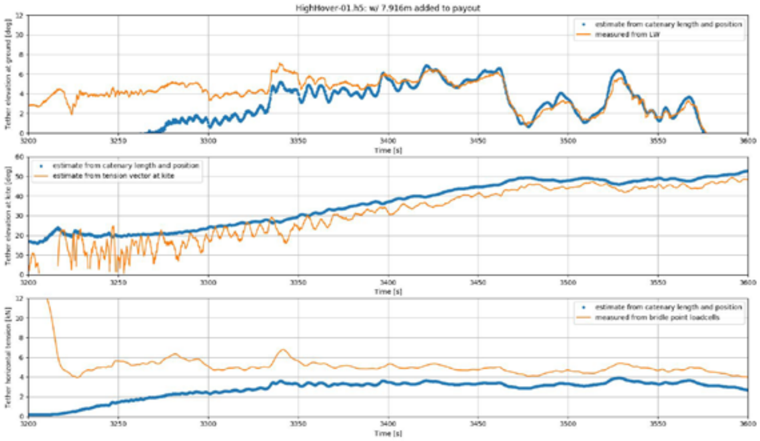
Need to account for bridle radius and tether not reeled onto drum

Can force a better match at longer payouts, but then physically impossible near perch

Our Prediction of Catenary Shape: Sim vs Reality

Sim

HH01

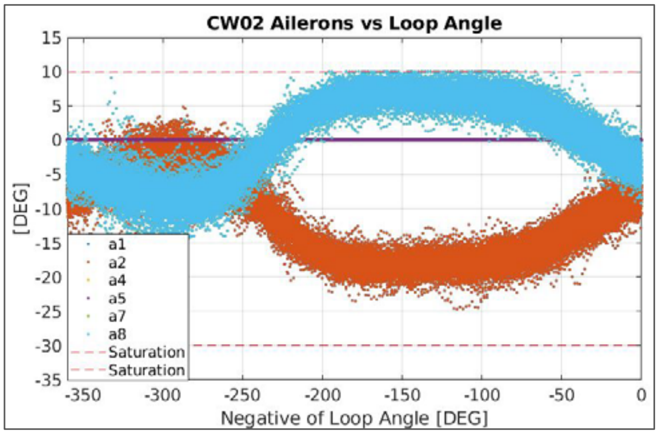


Tension in sim matches theory closer

Aileron Saturations

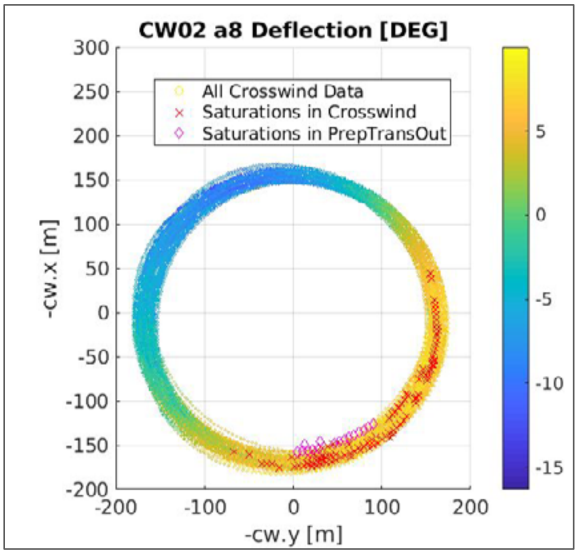
% Time Within 10% of Saturation **on Worst Loop**	a7	a8
CW01	6.57	6.55
CW02	13.85	12.98

- Only saturated A7 and A8 (starboard)
  - During downstroke
  - Between 3 o'clock and 6 o'clock
- CW02 worse than CW01
- Could decrease the "zero" aileron deflection to recover some throw on the + side
  - Would pay a lift penalty for this



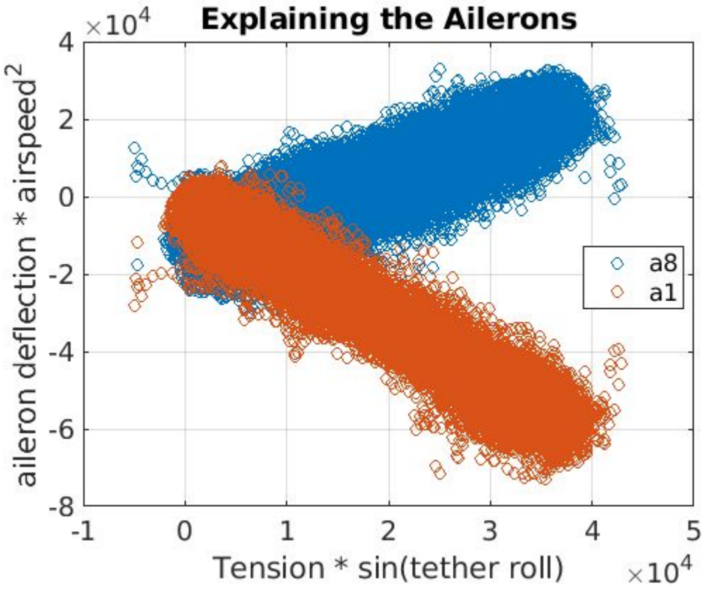
"Zero" aileron deflection

The midpoint of flap throw



Aileron Saturations

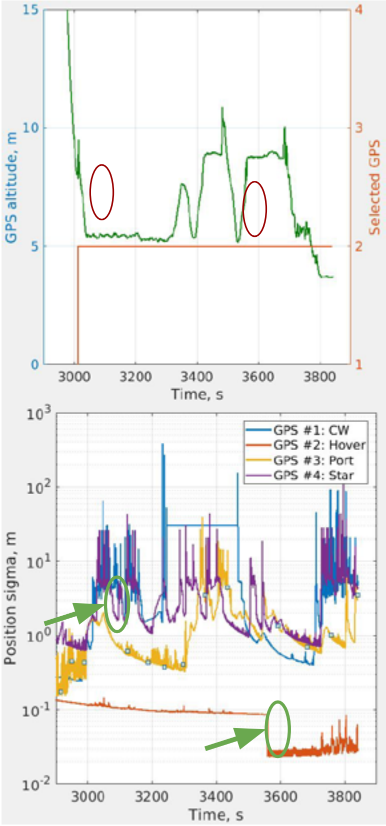
- **Bridle moment is completely dominant on the roll axis.**
    - Especially compared to the inertial roll moment of the kite itself!
    - Aileron responsibilities:
      Reject Bridle >>> Accelerate the Kite
- Can predict aileron motion by predicting bridle moment.
- To reduce aileron use, reduce the bridle moment. Bridle moment comes from:
    - Tension
        - Different airspeed or alpha
    - Tether roll angle
        - Different path
    - Bridle geometry (knot -> CG vector)



Altitude Estimate Issues During Reel-In (1/2)

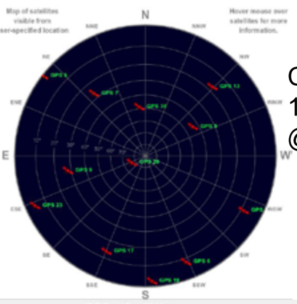
- During CW-01 we experienced discontinuities in the estimated altitude, driven by discontinuities in the GPS solution
    - CW-02 was smoother, without discontinuities
- These issues arose during Reel-In
- The first discontinuity happened when the selected receiver changed from the Crosswind to the Hover receiver.
    - The position error estimate of the CW receiver grew from ~1 m to ~5 m
    - The estimate jumped by ~1.5 m
    - The number of satellites in view by the CW receiver was 5 or less, whereas the Hover receiver was seeing 7-8
- The second discontinuity happened when the solution collapsed to a better one (carrier phase ambiguity?)
    - The jump in altitude was ~ 1 m

Bug 120552862

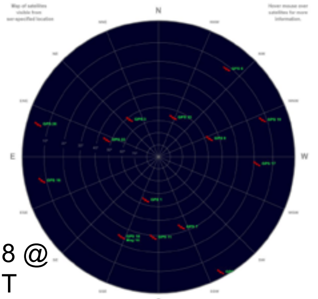


Altitude Estimate Issues During Reel-In (2/2)

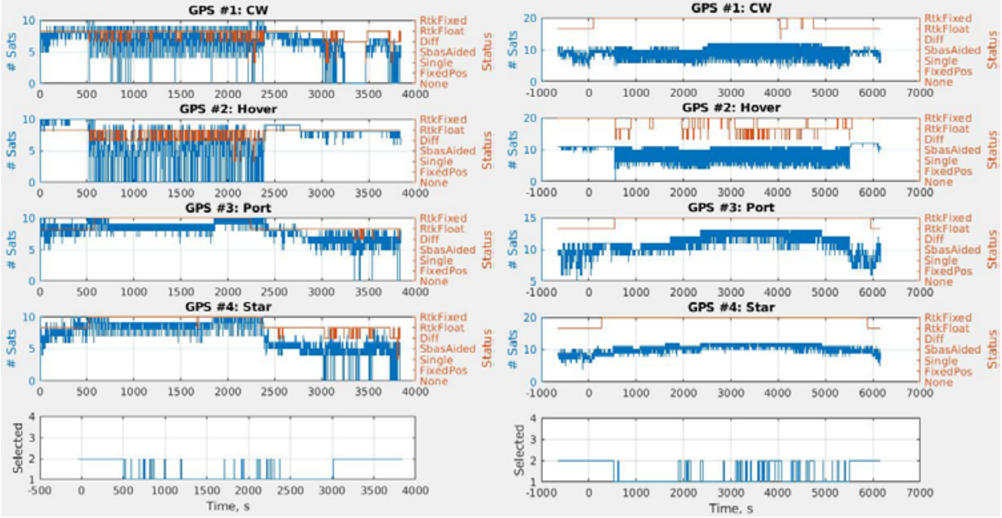
- Interestingly, CW-01 happened during a period of time with decreased GPS satellite availability
    - Only 3 satellites visible above 30 deg elevation
    - South-facing antennas would not see any above 20 deg elevation
- During CW-02 there were more satellites in view.
    - Never saw 0 satellites
- During CW-02 GPS receivers had solutions with RTK-Fixed accuracy, vs RTK-Float for CW-01



CW-01
12/06/2018
@ 5 pm HST

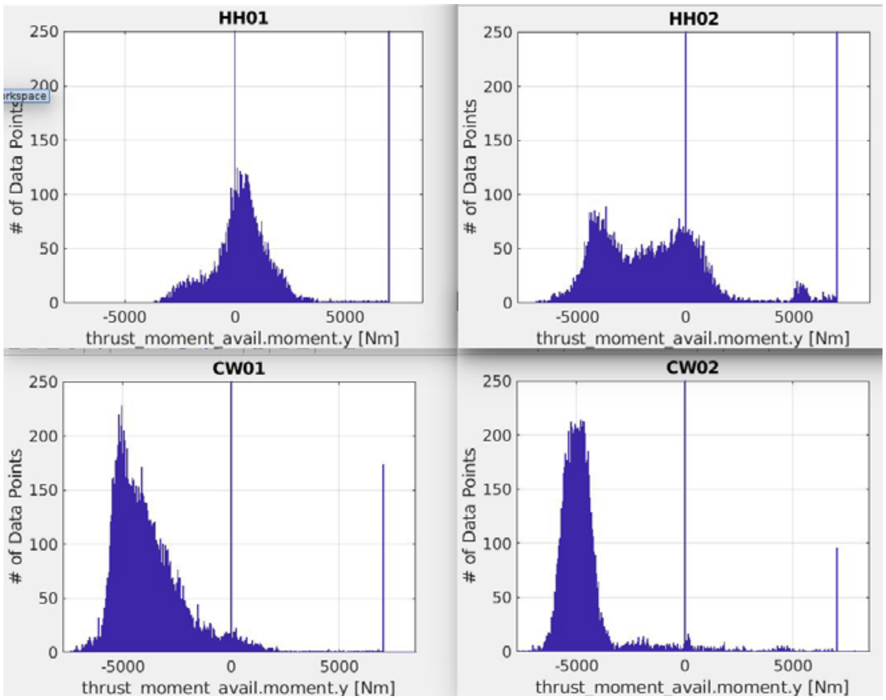


CW-02
12/12/2018 @
12 pm HST



Pitching Moment During Autonomous Hover Modes

- Pitching moment required for hover is large and negative for every flight EXCEPT HH01.
    - SN1 for HH01/02
    - SN4 for CW01/02
- HH01 experienced big negative tether pitch angles at the kite
    - Reduced our roll stiffening from the bridle. It was scary.
- This ***could be*** evidence that the “phantom pitching moment” is not aerodynamics but is instead due to the tether tension and bridle.



Executive Question

- Regarding CW-02: "According to our official go/no-go wind envelope, we were right at the edge, or perhaps a little across the line, on acceptable wind speeds. Yet, the kite flew beautifully! Was our criteria too conservative? Is our assessment methodology too conservative? Is there a way to use the successful actual experience to open the envelope a bit moving forward? In sum: according to our criteria that should have been a scary right at the edge flight, but in fact it was a yawner. Why? And what can we learn from that?"

Is Our Wind Window Too Conservative? Those Flights Looked Great!

First of all: Yes, it sure seems that way. We agree the flights looked very safe compared to RPX and (it seems) compared to C-sim (waiting on more formal and complete comparison here).

Other Things to Say

- Controls TL has a lot to say about this (our criteria in particular) but he is on vacation.
- Criteria based largely on (many) C-sim runs.
  - C-sim, for all its imperfections, remains our best tool for predicting flight quality.
- Right now, we are prepared to talk about differences between the predicted scores and the flight scores (next slide).
  - Rigorous C-sim comparison (Dynamics Replay, etc) hasn't happened yet.
- We can address THAT our C-sim predictions are conservative but not necessarily why.
- Speculations on Why
  - Physics mismatch between C-sim and flight
  - Wind mismatch between C-sim and flight (turbulence, shear, …)
  - Some shortcoming in our use of batch sims

Controls
CW-01/02 Learnings Review
PART 2

January, 2019

Agenda

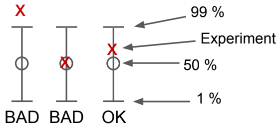
- Comparison: Monte Carlo analysis vs. flight test scores (20 min)

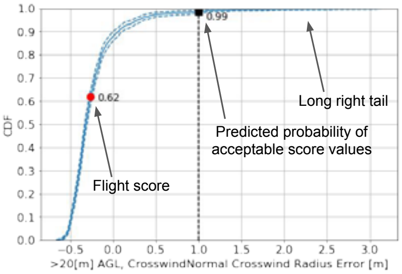
- Comparison: C-Sim vs. flight test (20 min)
    - Wind replay
    - Dynamic replay

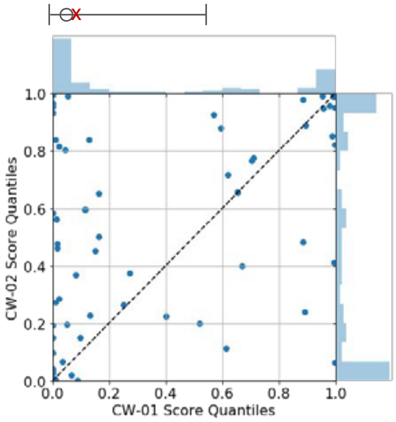
- Major Observations by Flight Mode (20 min)
    - New Flight Modes
    - Old Flight Modes

Comparison of Flight Test Scores with Monte Carlo Analysis (1/3)

- Monte Carlo is an uncertainty quantification technique. We project via sampling uncertainties in parameters to uncertainties in performance. After a flight, we look at where the scores fell within the predictions.
- After CW-01/02, we obtained 1000 samples using flight-day wind speed and shear exponent.
- Results:
  - Most of the available flight scores for both CW-01 and CW-02 fell in very high or very low percentiles.
  - Scores do not seem to fall in the same range between flights; errors are not consistent biases.
- Sources of errors:
  - Uncertainties (inputs) are mismodeled (or unmodeled)
  - Models are inaccurate
  - Scores are not well defined
    - Scores are synthetic algorithms that attempt to summarize a full trajectory
  - Flight test measurements are inaccurate
- Caveat: not all scores are available using flight data (only ~70% have non-NaN values).

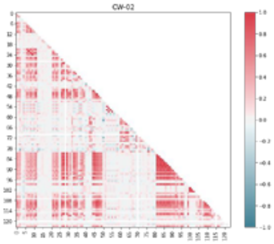






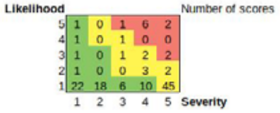
Comparison of Flight Test Scores with Monte Carlo Analysis (2/3)

- Score correlations
  - Some areas of overlap is expected: bad trajectories trigger more than one score.
  - Ideally scores are uncorrelated, meaning they explore different areas of the flight qualities/performance.
  - About ~10% of score pairs present abs(correlations) higher than 0.5, which means that score lumping at high/low values is not explained by score definition/design.
- Current most likely explanation for mismatch of prediction to flight experience is narrow predicted uncertainty bounds (underpredicting ~~uncertainty~~ variance).
- It is also interesting to look at score risks (even though scores are not risks):
  - Tables on the right show predicted risks we flew in.
  - CW-01 high risk scores are shown on the right (score and [quantile]).
  - High risk scores are clearly overpredicted.
  - High risk scores are somewhat correlated.
    - This is good: less failure modes
  - Similar results seen for CW-02.
    - 2 more high-risk scores.
    - Somewhat weaker correlations.



CW-01

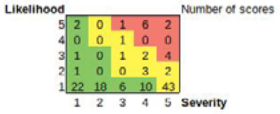
Table #0: Monte Carlo Wind Speed [m/s] @ 21 [m] AGL = 8 shear exponent = 0.1



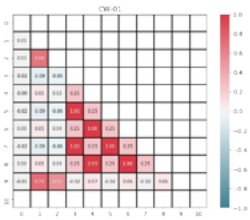
Likelihood						Number of scores
5	1	0	1	6	2	
4	1	0	1	0	0	
3	1	0	1	2	2	
2	1	0	0	3	2	
1	22	18	6	10	45	
	1	2	3	4	5	Severity

CW-02

Table #0: Monte Carlo Wind Speed [m/s] @ 21 [m] AGL = 10.5 shear exponent = 0



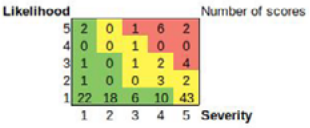
Likelihood						Number of scores
5	2	0	1	6	2	
4	0	0	1	0	0	
3	1	0	1	2	4	
2	1	0	0	3	2	
1	22	18	6	10	43	
	1	2	3	4	5	Severity



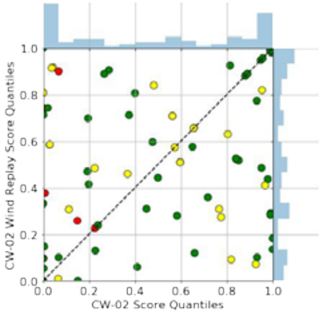
-Crash- Vortex Ring State - Number of Rotors [num_rotors]: 0.00 [0.00]
-Crash- >20[m] AGL, CrosswindNormal Rotor Stall Margin [-]: -0.85 [0.04]
-Crash- CrosswindPrepTransOut Rotor Stall Margin [-]: -0.91 [0.00]
Hover - Perch to CW Max thrust_moment[thrust] Saturation Duration [s]: 0.00 [0.00]
Hover - CW to Perch Max thrust_moment[thrust] Saturation Duration [s]: 13.40 [0.00]
Hover - Perch to CW Max thrust_moment[moment_y] Saturation Duration [s]: 0.00 [0.00]
Hover - CW to Perch Max thrust_moment[moment_y] Saturation Duration [s]: 13.40 [0.00]
Hover - Perch to CW Max thrust_moment[moment_z] Saturation Duration [s]: 0.00 [0.00]
Hover - CW to Perch Max thrust_moment[moment_z] Saturation Duration [s]: 13.40 [0.00]
>20[m] AGL, CrosswindNormal Angle-of-attack (w/o initial transients) [deg]: 0.58 [0.00]

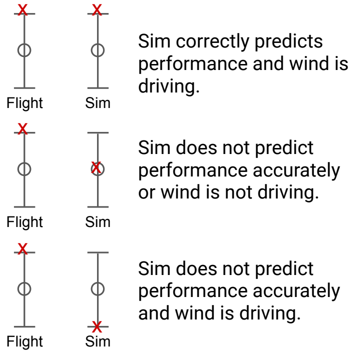
Comparison of Flight Test Scores with Monte Carlo Analysis (3/3)

- How well can we reproduce flight performance in the simulation if we match the wind?
    - We can map score quantiles from flight to simulated trajectory with flight-day winds.
    - Score colors match the score risks
        - High risk scores were overpredicted (flight scores fell in low percentiles)
    - Scores from wind-replayed trajectory are much more spread
    - Still trying to understand the implications, but some thoughts are in the cartoons below:



Likelihood	1	2	3	4	5
5	2	0	1	6	2
4	0	0	1	0	0
3	1	0	1	2	4
2	1	0	0	3	2
1	22	18	6	10	43



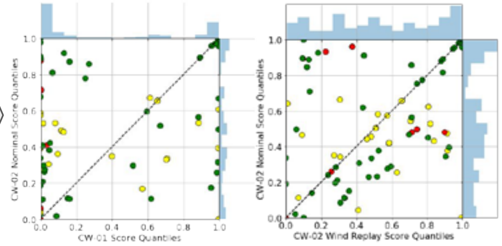


Sim correctly predicts performance and wind is driving.

Sim does not predict performance accurately or wind is not driving.

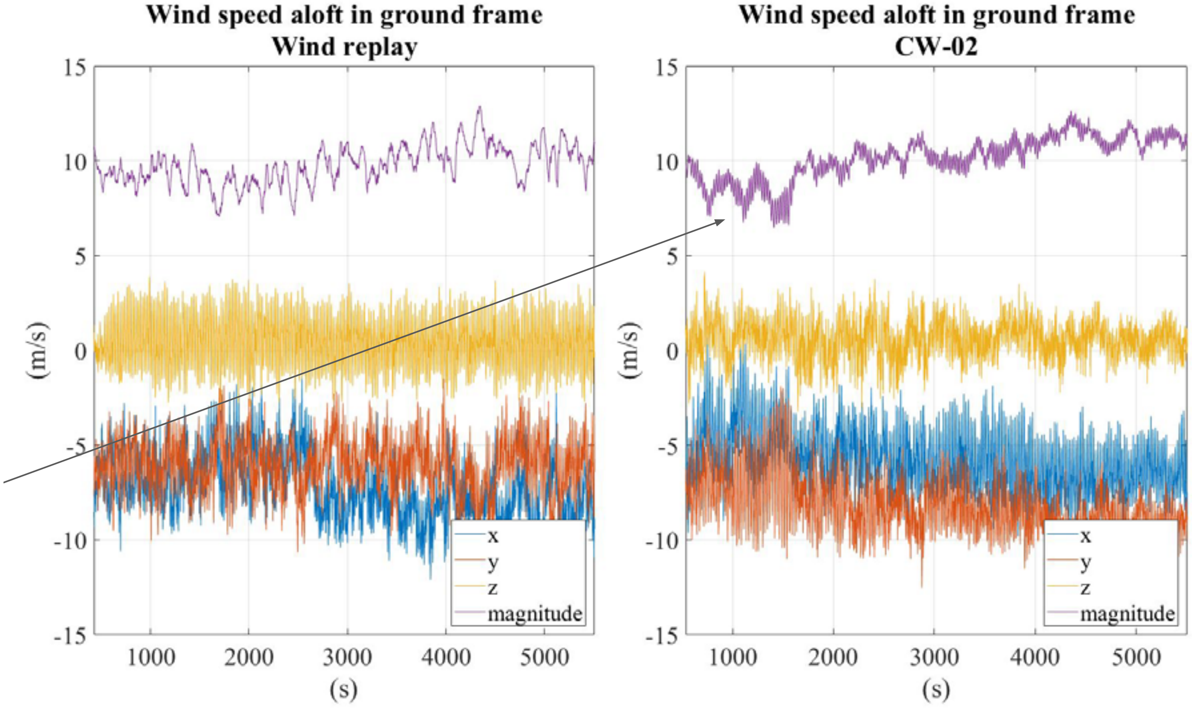
Sim does not predict performance accurately and wind is driving.

- Simulated nominal quantiles do not fall around the 50 %-ile.
- Scores present discontinuities or are bounded, which provide distributions harder to work with.
- May indicate other issues with the simulation.
- CW-01 flight vs. nominal are very different:
    - Indicating simulation mismatch with reality
- CW-02 wind replay vs. nominal (sim vs. sim) shows better agreement:
    - CW-02 presented larger changes in wind speed vs. CW-01.
    - Need to investigate if this is captured in the sim.
    - Currently wind speed and shear exponent are epistemic variables; may not be the case.

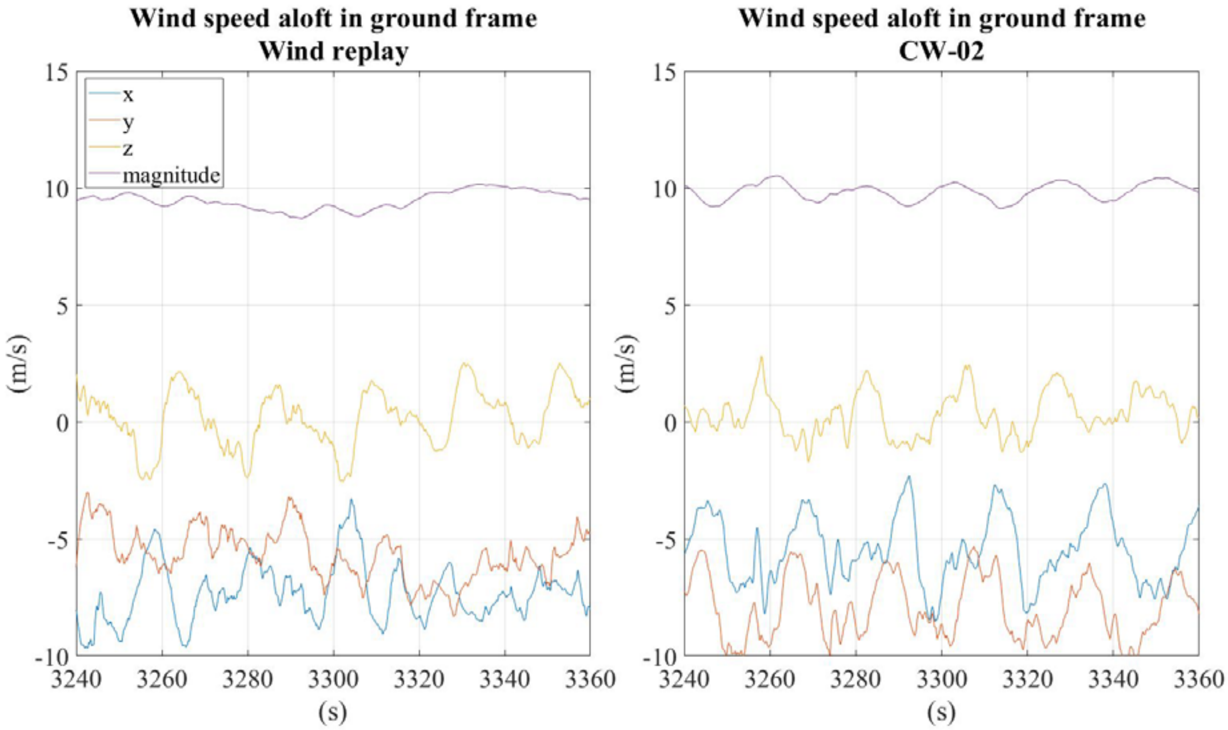


Wind Replay Analysis

- **Method**: run the C-Sim with the same controller and similar wind as CW-02. Compare.
- 25s period content missing in the replay because no shear is assumed.
- Focus on 120 s (6 loops)



Wind Replay - Wind Aloft



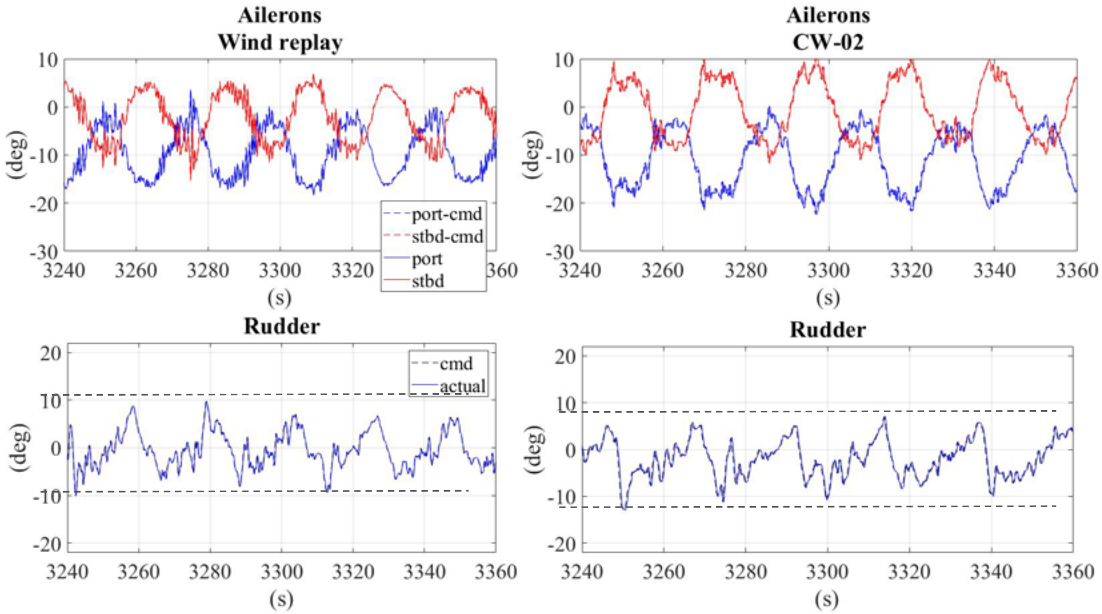
Wind Replay - Lateral Control

(Y-axis limits are allowable range of motion)

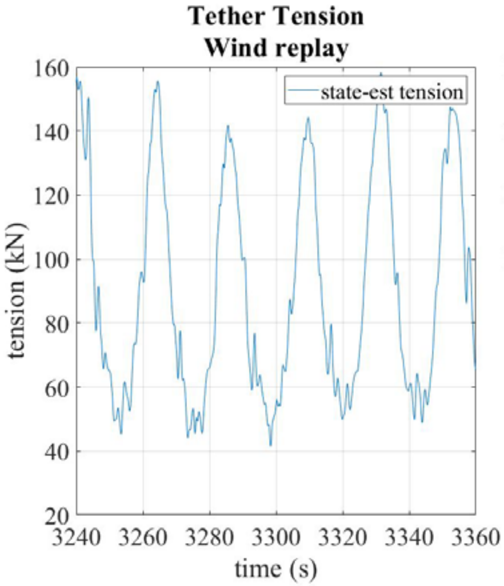
- Significantly more aileron deflection in flight test

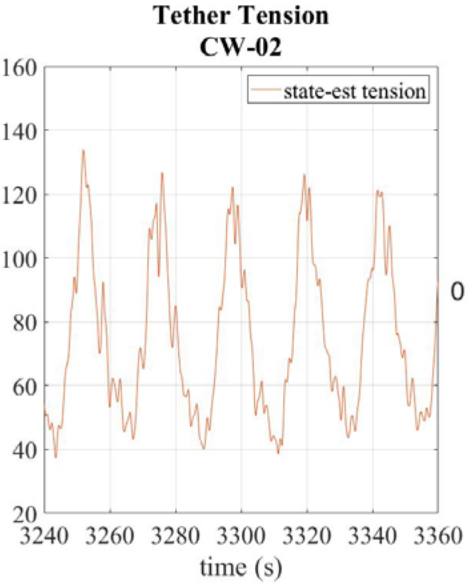
- Are real ailerons less effective than simulated?
- Is the magnitude of the tether disturbance greater in reality?
→ Compare tether roll angles, tension.

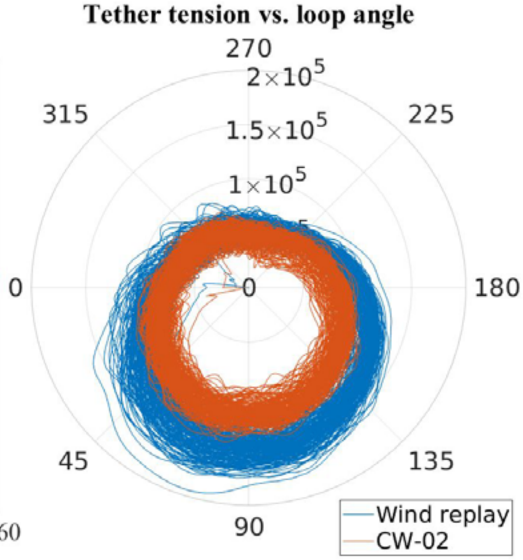
- Similar rudder min/max amplitude, but ~ 5 deg. trim offset.



Wind Replay - Tether Tension





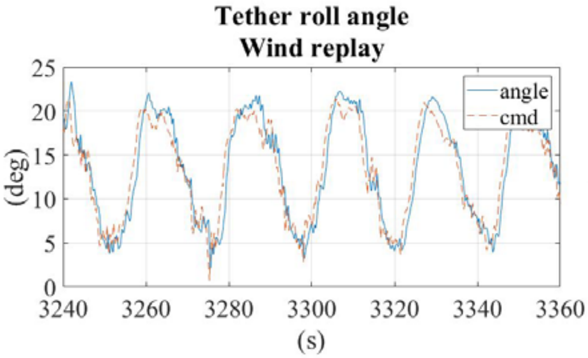


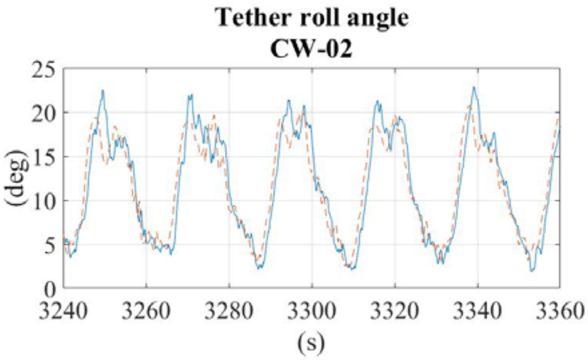
- The tether tension is significantly overestimated by the C-Sim.
- The dynamics replay analysis shows that is due to over-estimated lift force.

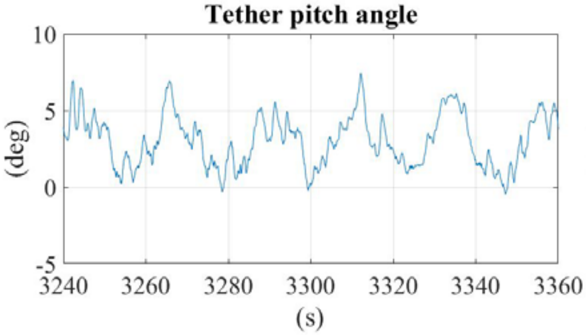
Wind Replay - Tether Pitch & Roll Angles

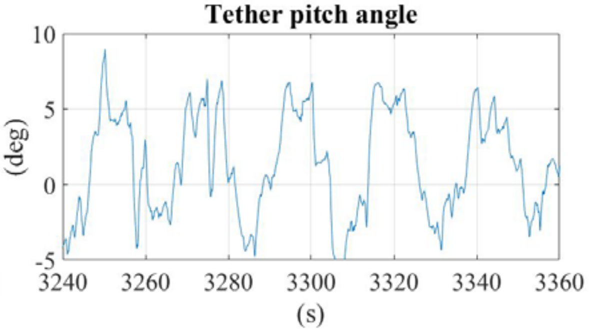
- Tether roll angle is well predicted by the sim.
- The min/max amplitude of tether pitch however was much greater in flight test than in the sim.
- **Why?**

Bug 125325478





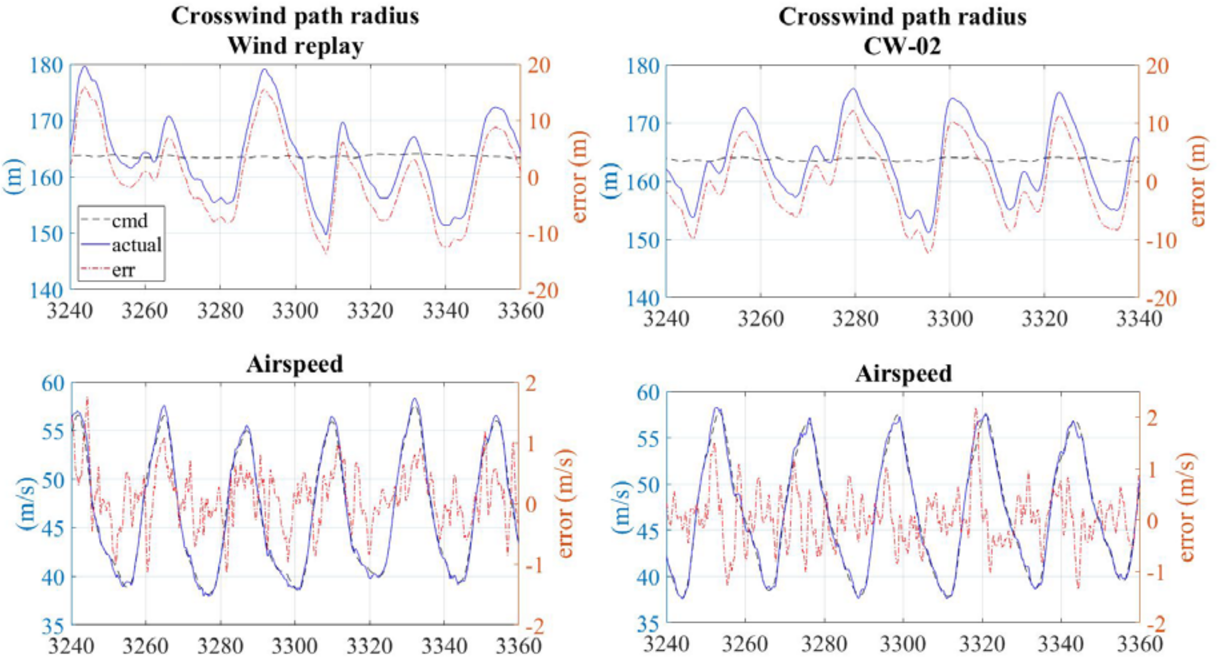




Wind Replay - Crosstrack & Airspeed Control

Very Good correlation:

- Airspeed error < 2 m/s in both flight test and C-Sim.
- Loops are slightly bigger (+ 5 m) in C-Sim.
- Crosstrack error is similar.

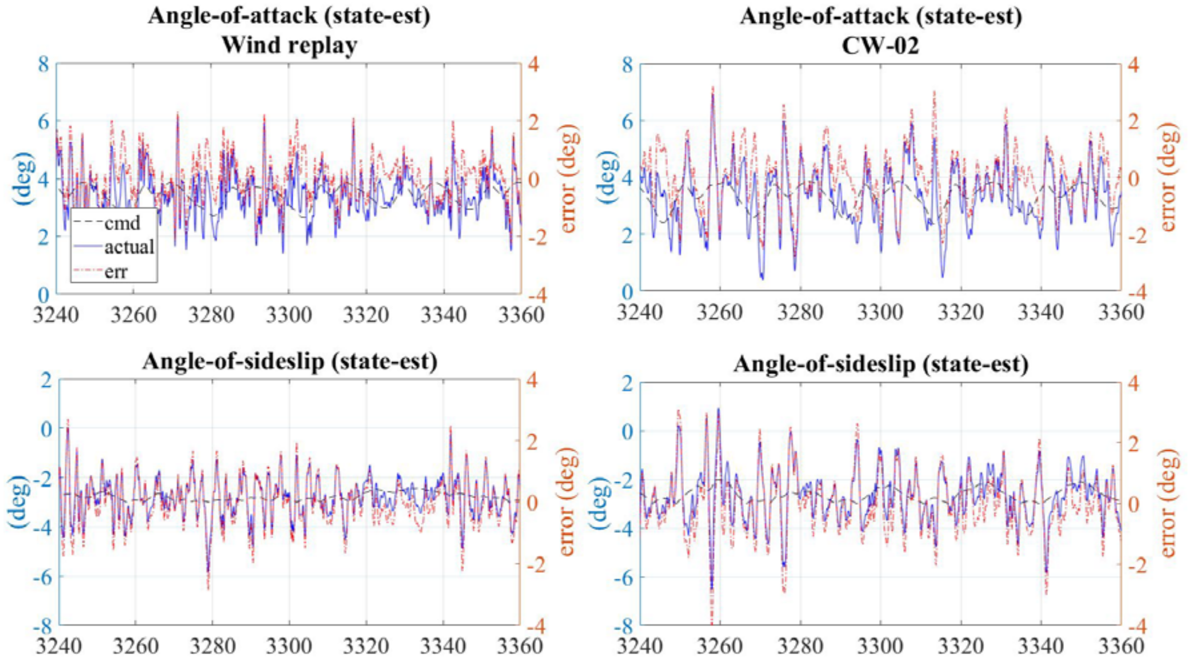


Wind Replay - Aerodynamic Angles

Overall, larger amplitudes in flight test.

- Max aoa error:
  - Flight: 3 deg.
  - Sim: 2 deg.
- Max aos error:
  - Flight: 3 deg.
  - Sim: 2 deg.
- What is the source for the ~0.5 Hz dynamics in the aero angles?

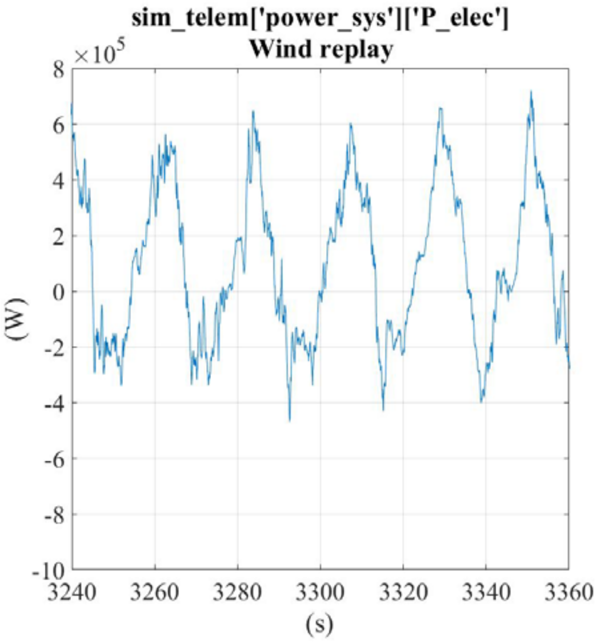
→ Is it a tether mode?

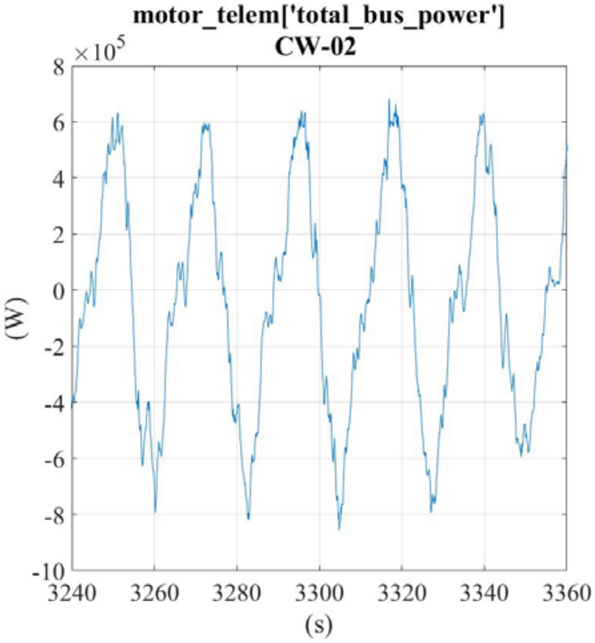


Wind Replay - Power

- The power generated during the downstroke is predicted reasonably well by the Sim.
- However, the power consumed during the upstroke is largely underestimated by the sim.

Bug 122981385





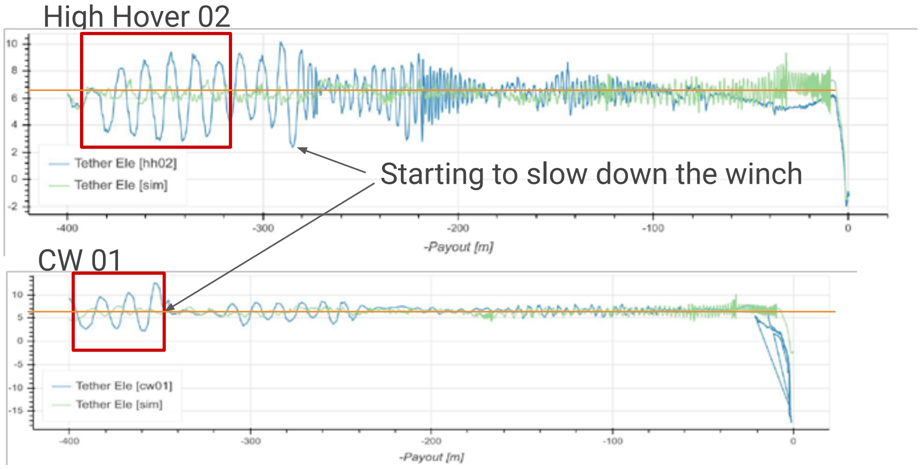
Tether Elevation in Pay Out/Reel-In

The target matches.

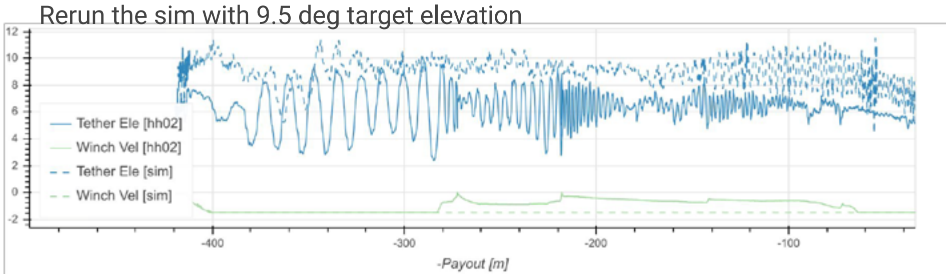
Sim is:

- Under-damped near perch
  - Could be because of missing damping from un-modeled levelwind
- Over-damped near full payout.

Yet it does show the same mode.



Starting to slow down the winch



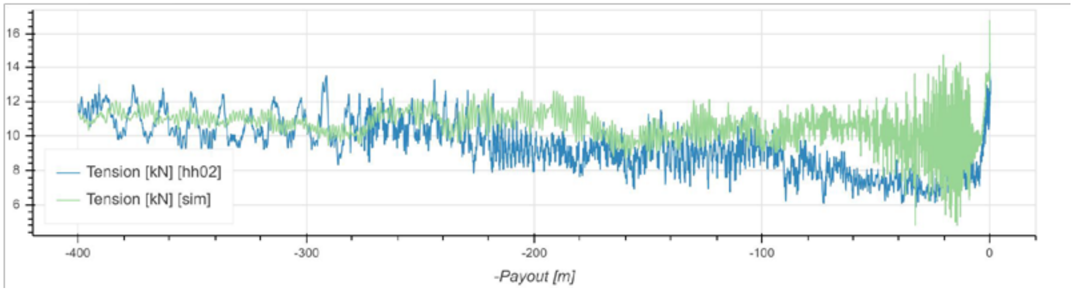
Rerun the sim with 9.5 deg target elevation

Tether Tension in Pay Out/Reel-In

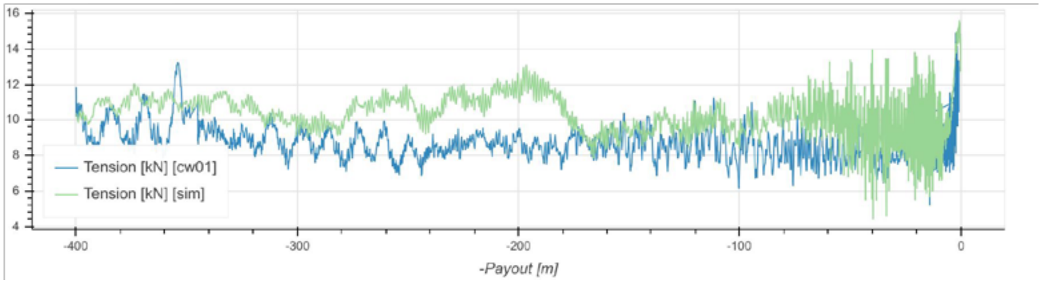
Sim has:

- Sometimes 2-4 kN more tension than the real.
- More oscillation near perch
    - ○ Could be because of missing damping from un-modeled levelwind
- Less oscillation at long payout

High Hover 02



CW 01

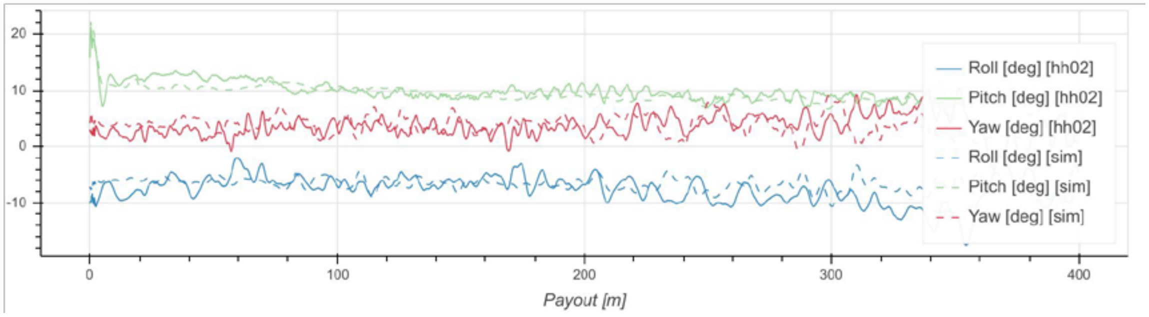


Hover Angles in Pay Out/Reel-In

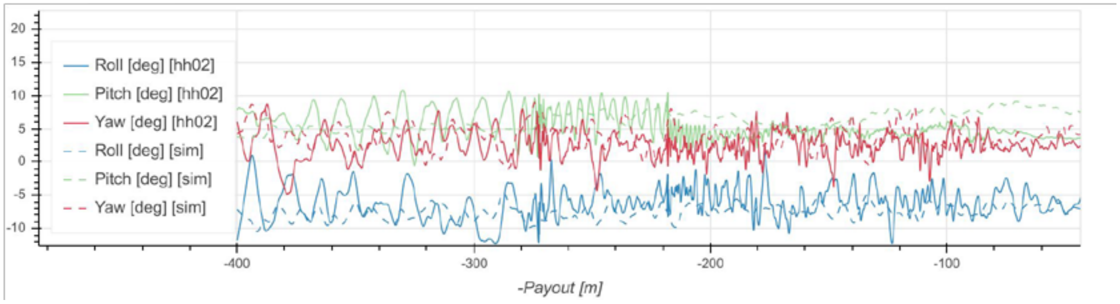
Sim has:

- Similar disturbance in hover angles during HoverPayOut
- Much less disturbance / oscillation during HoverReelIn

High Hover 02 HoverPayOut



High Hover 02 HoverReelIn



Dynamic Replay Analysis

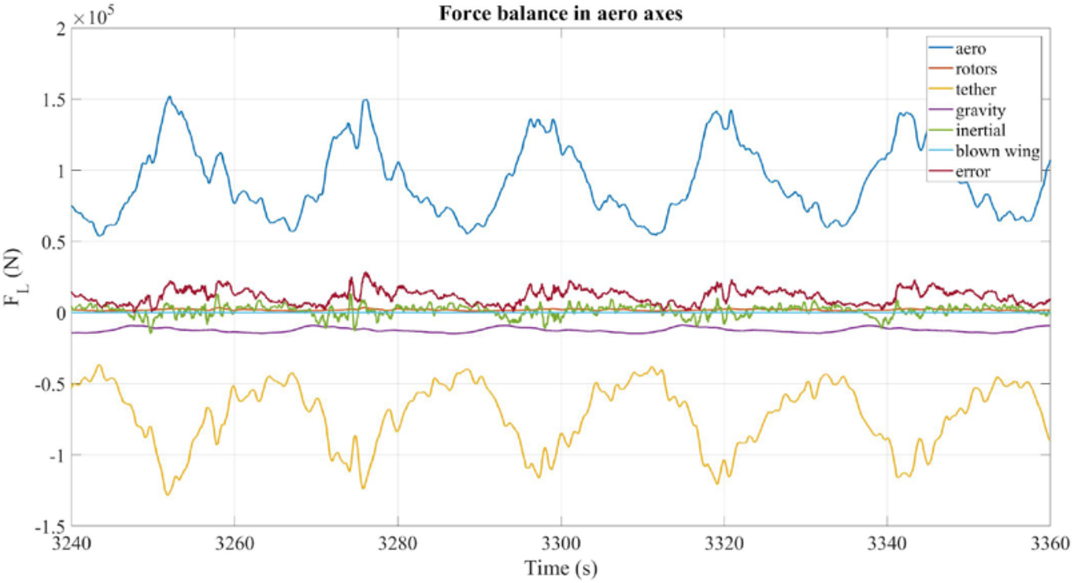
- Error force residual is always positive:
  - Assume tether force measurement is accurate (see AME slide)
  - Assume error is in aero database

⇒ The lift force is OVER-estimated in the aero database.

This is consistent with tension being over-estimated in the C-Sim.

- Error force residual is NOT constant.
  - It's maximum near the bottom of the loop.

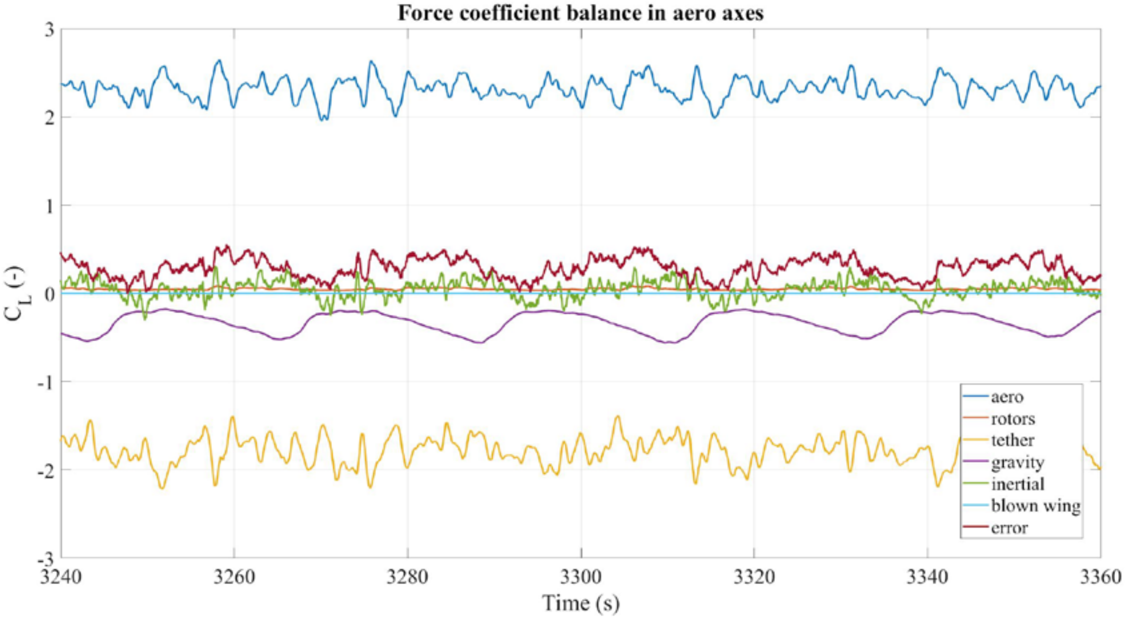
Forces in body axes transformed into aero coordinates.



Dynamic Replay Analysis

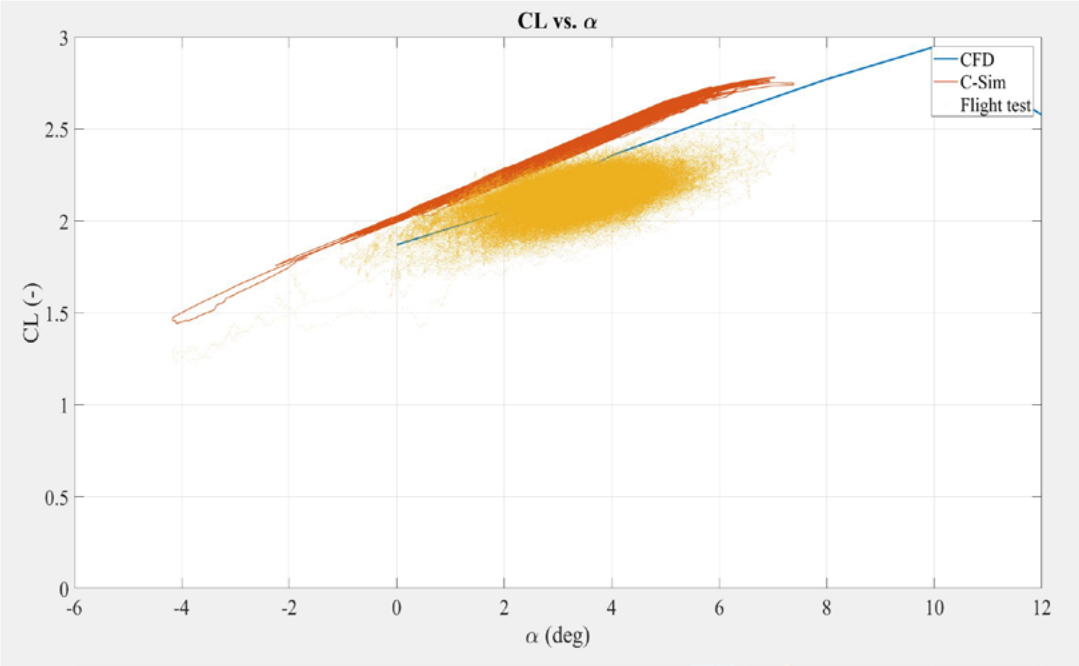
Non-dimensionalize the previous data...

- The CL error is not constant and maintains its period consistent with loop period.
  - Is it f(alpha)? No, see next slide.
  - Is it a CL_0 offset? No, see next slide.



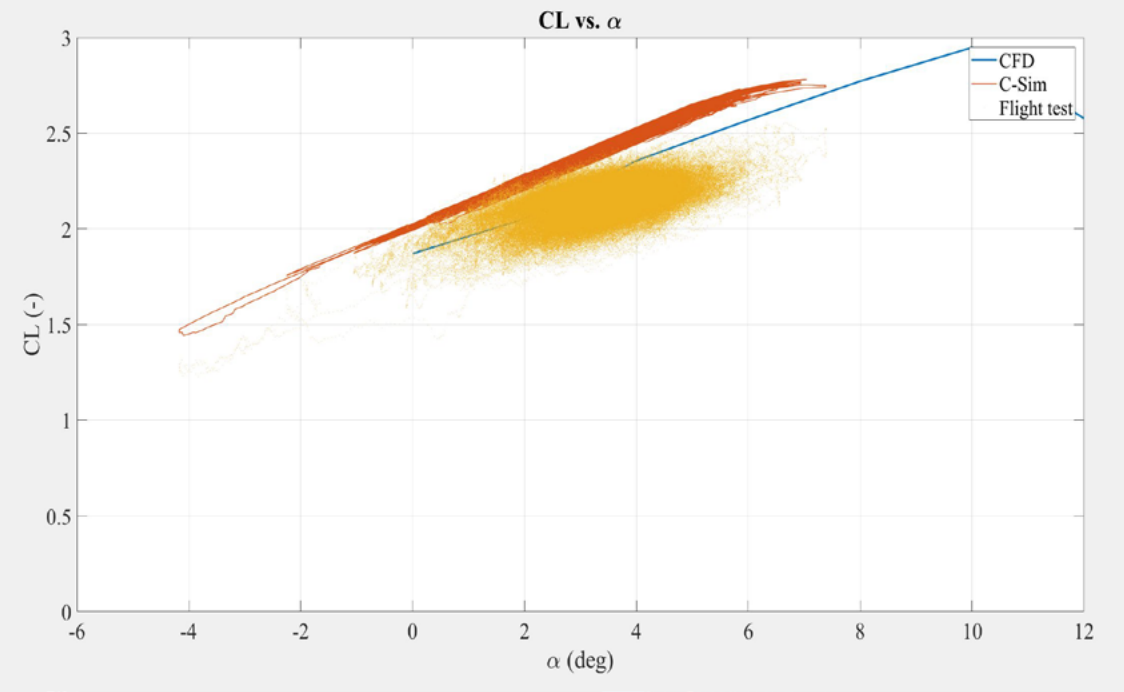
Dynamic Replay Analysis

- C-sim is the aero body force coefficients transposed into the lift vector with the flap contributions removed based on aswing database.
- The flight test is the same data with the residuals or error subtracted.
- The net CL can vary wildly depending on the CL_aero to CL_error ratio for a given alpha.
- Plots not shown here show trends up and to the right indicating correlation between error and airspeed, error and inertia, and error and alpha.
- The following bullets have not yet been substantiated but serve as my hypothesis..



Dynamic Replay Analysis

- This multifaceted correlation is why we see a blob and not a cone. For example if it were solely correlated with alpha then at high alpha we would have more error than at low alpha, ergo cone.
- At low alpha we have high airspeed so still large error.
- At low airspeed we have high alpha so still large error.

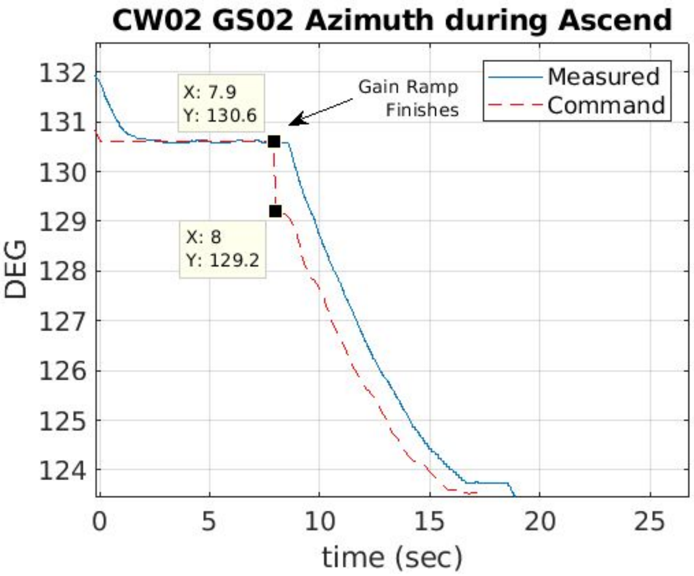


Major Observations By Flight Mode

New Flight Modes

Ascend

- Port hook always lifts off first (we knew this already)
    - Trim hover yaw attitude is positive (port wing high) because of pylon lift.
    - This is required by force balance for zero lateral acceleration.
- Starboard hook slides very slightly before lifting off.
- Azimuth tracking by ground station is good.
    - Error < 1 degree at all times in CW01 Ascend
- CW02 reveals an interesting thing: Kite slides to starboard during gain ramp
    - During gain ramp, azimuth target for ground station is locked
    - Kite motion during gain ramp (rotating and sliding) gives a 1.4 degree azimuth error while the ground station is locked

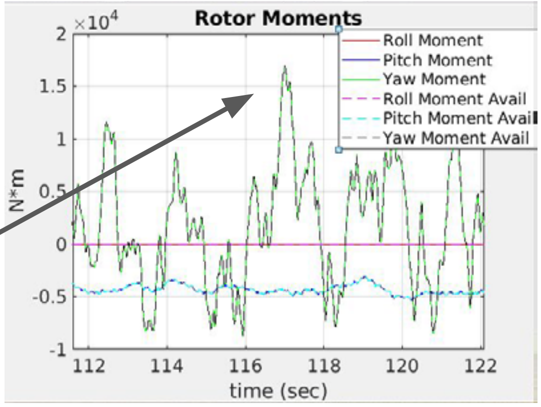


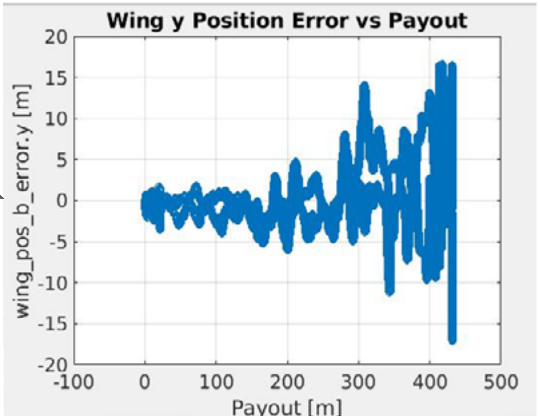
Pay Out

- Tether Oscillations are present here but are less severe than during Reel In

- Lateral Position Control needs to put on a Cat Stevens record and chill out.
    - Large amplitude yaw moment commands are a symptom
    - Trying to track the downwind position very aggressively
    - Lateral position error is worse at full length where the same angle command is acting on a longer arm
    - This problem has been with us in RPX and C-sim for a long time

Bug 120178512
50840 hover: Filter the kite azimuth command [internal ref]
ECR 382 [internal ref]





Descend

- CW01 was under Pilot Control
- CW02 was autonomous
- Ground Station azimuth tracking was good in both flights
- We have never missed a hook laterally
- The two times we have missed the panel the hook missed longitudinally
    - First time was a typo in the flight control code when moving a test day change to master
    - Second time was a timing issue between the winch motors and winch brake
    - Fixed both problems

Transform Up / Transform Down

- Discussion with whoever is qualified to talk about it in the meeting.

Reel-In

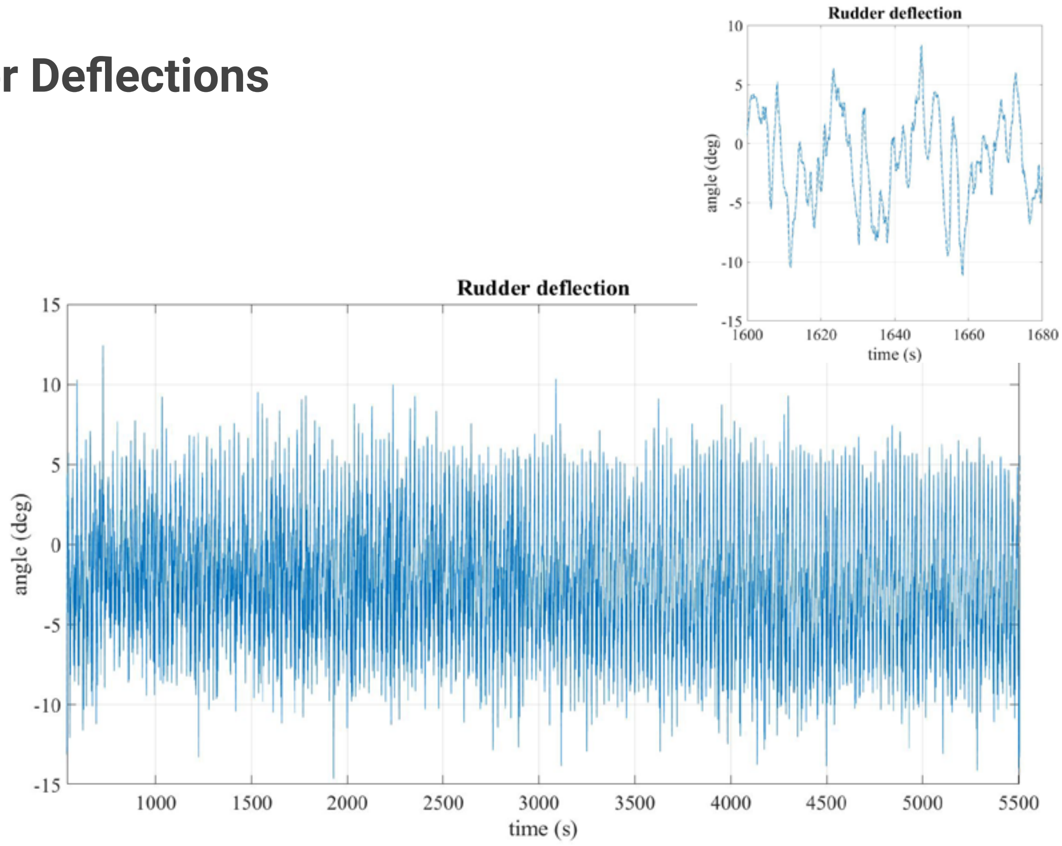
- Tether oscillations were demonstrably worse here than during pay out
    - Discussed elsewhere
- Saw GPS trouble in this flight mode
    - Discussed elsewhere

Major Observations By Flight Mode

Old Flight Modes

Crosswind : Rudder Deflections

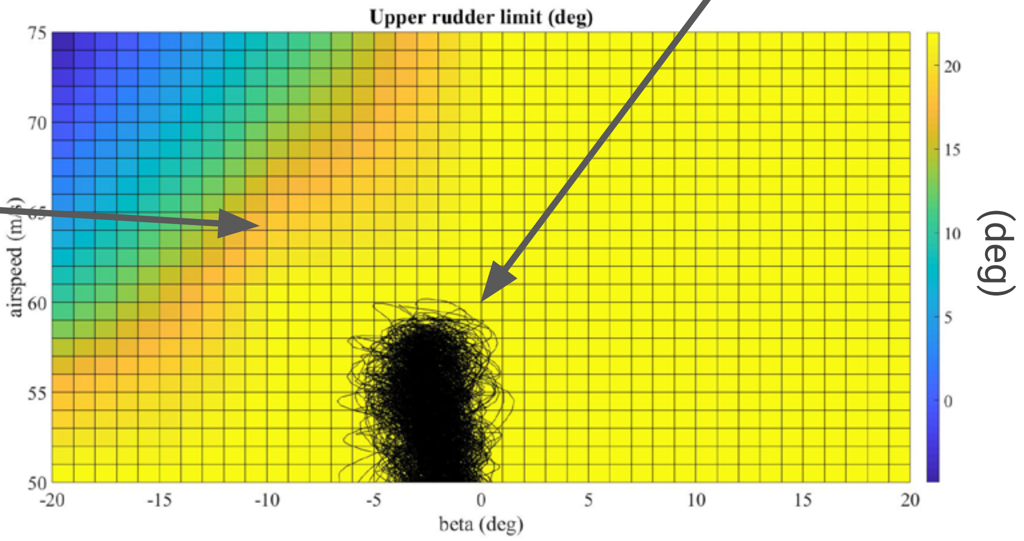
- Max rudder deflection limits are +/- 22 deg
    - limits are reduced at high airspeed and high beta
- We had good margins against these limits throughout the flight.



Crosswind : Rudder Deflections

We never entered the loads limited regime

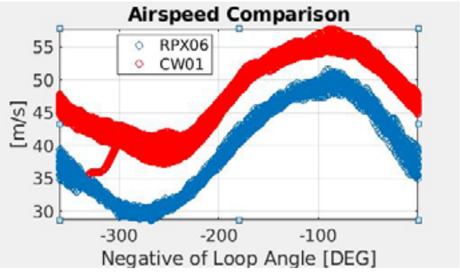
- We have reason to be afraid of this cliff
    - The resulting “control law” is unstable
    - It says: “If beta is too small, move the rudder to make beta smaller.”
    - Should fix this



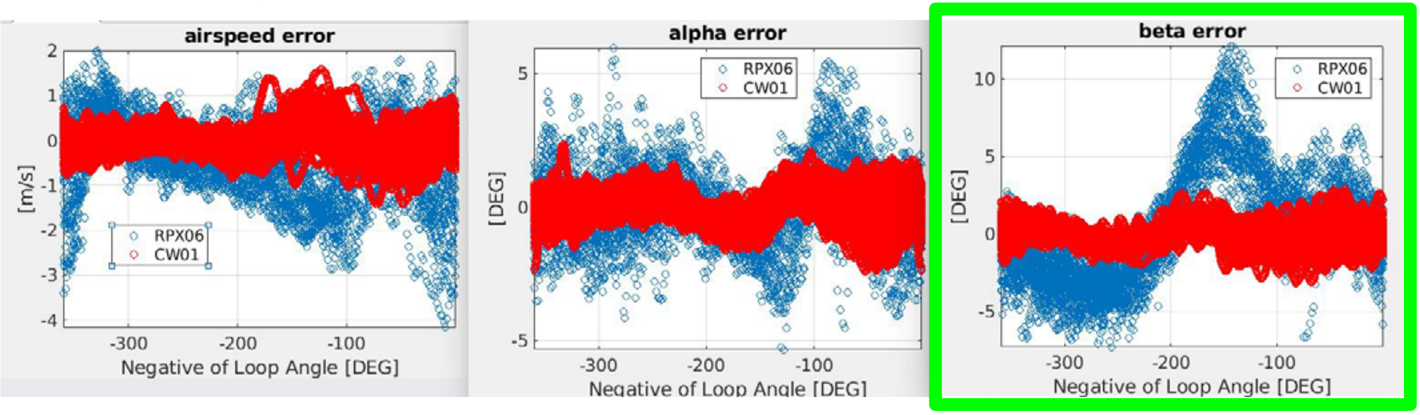
CW-02

Crosswind : Angle of Attack & Sideslip Control

- **Sideslip Control is greatly improved** compared to RPX flights
- Airspeed Control is also slightly improved
- Angle of Attack still has some unwanted excursions but also is improved

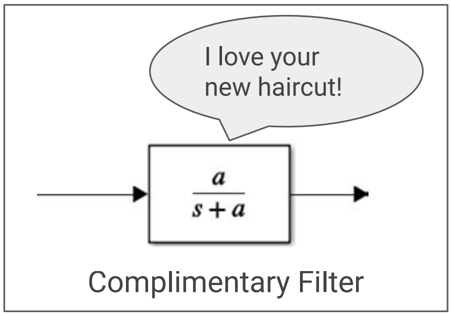


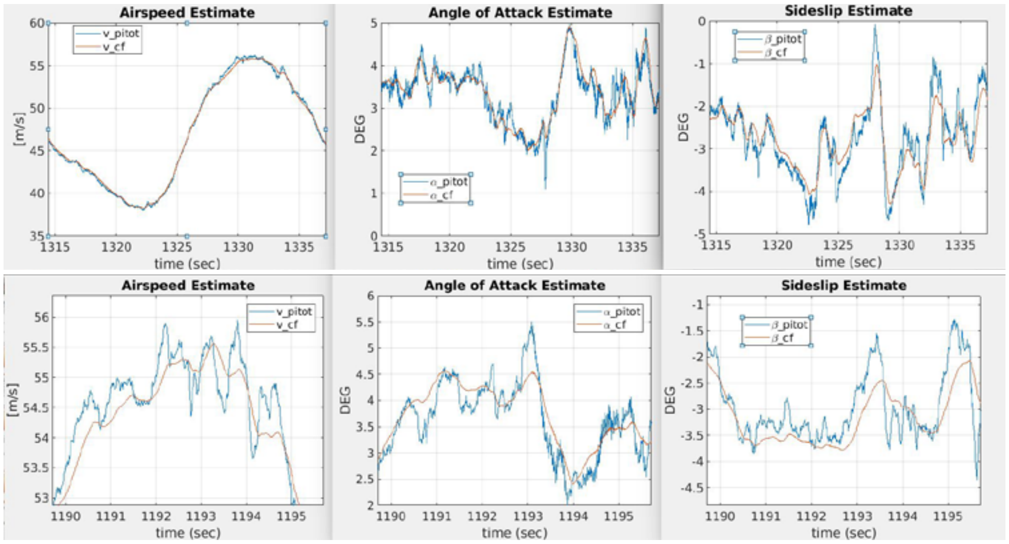
Plots compare CW01 to the most similar loops from RPX06:
Big Radius RPX06 was flying slower than CW01

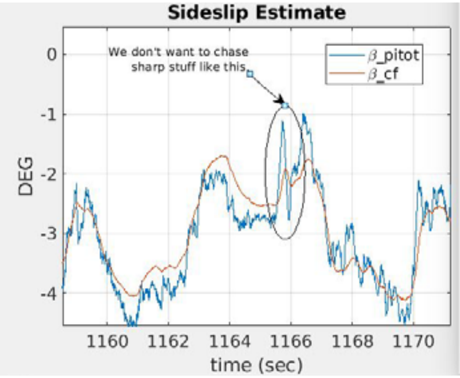


Crosswind : Complementary Filter (ECR 337)

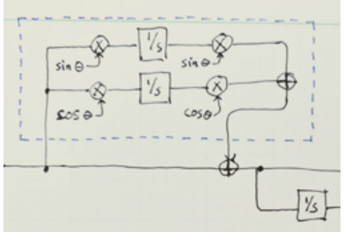
- New Feature: Combines pitot and inertial measurements.
- Definitely attenuates gusts!
- Seems to be working as intended.



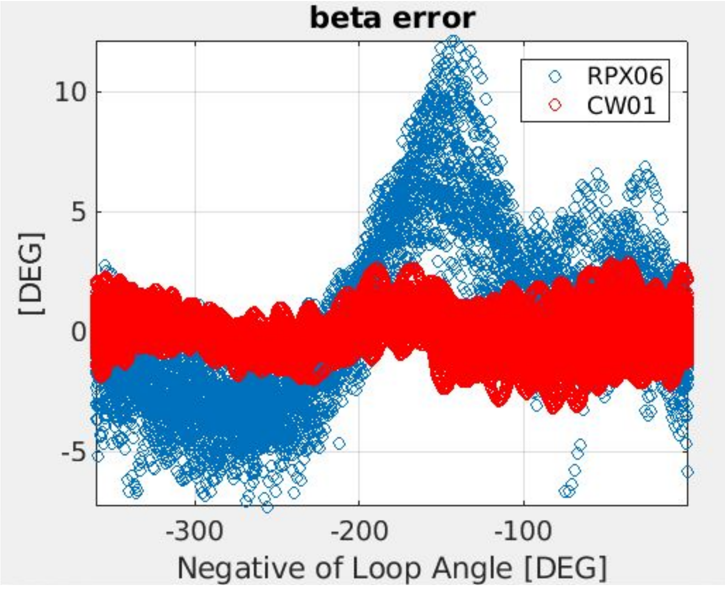


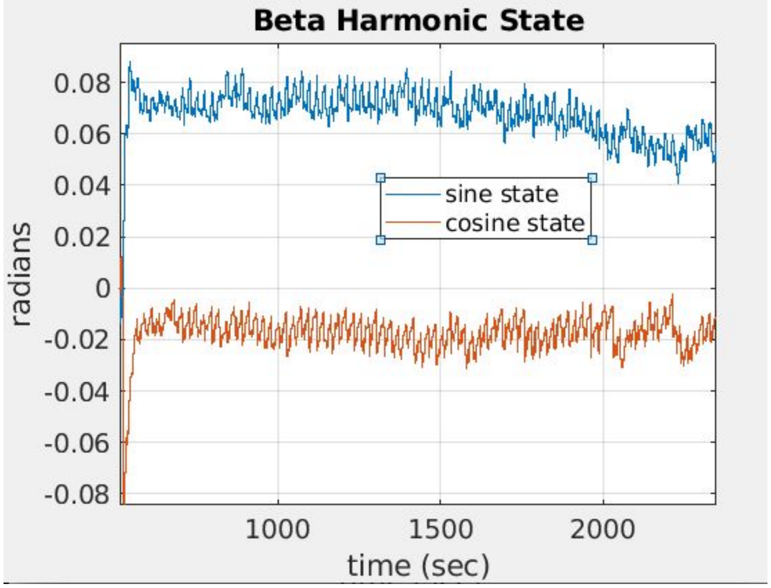


Crosswind : Harmonic Control (ECR 310)



Total success!





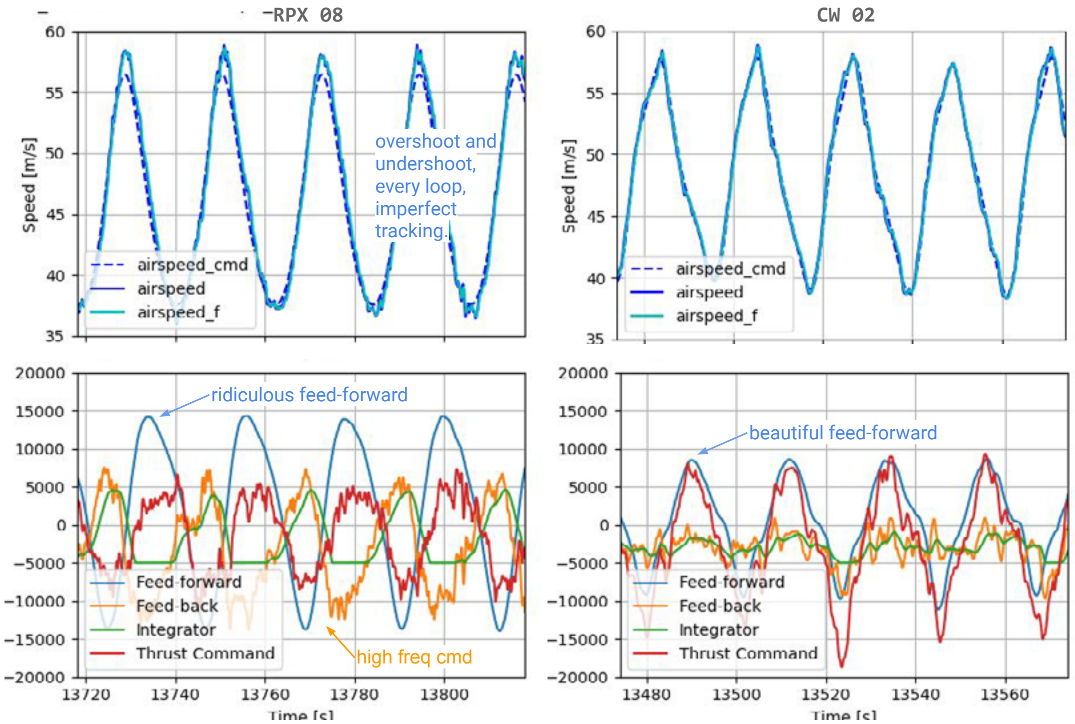
Crosswind : Airspeed Control (ECR 307)

Airspeed control improved via:

1. Achievable commands.
2. Complementary filter.
3. Kinematics-based feed-forward.

Next steps:

1. Reduce the gain?
2. Add propulsive lift feed-forward?



overshoot and undershoot, every loop, imperfect tracking.

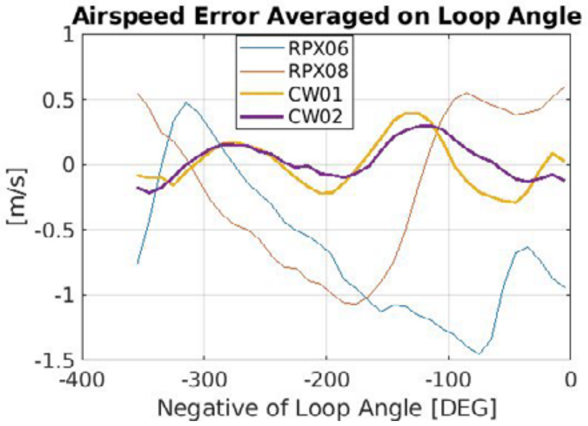
ridiculous feed-forward

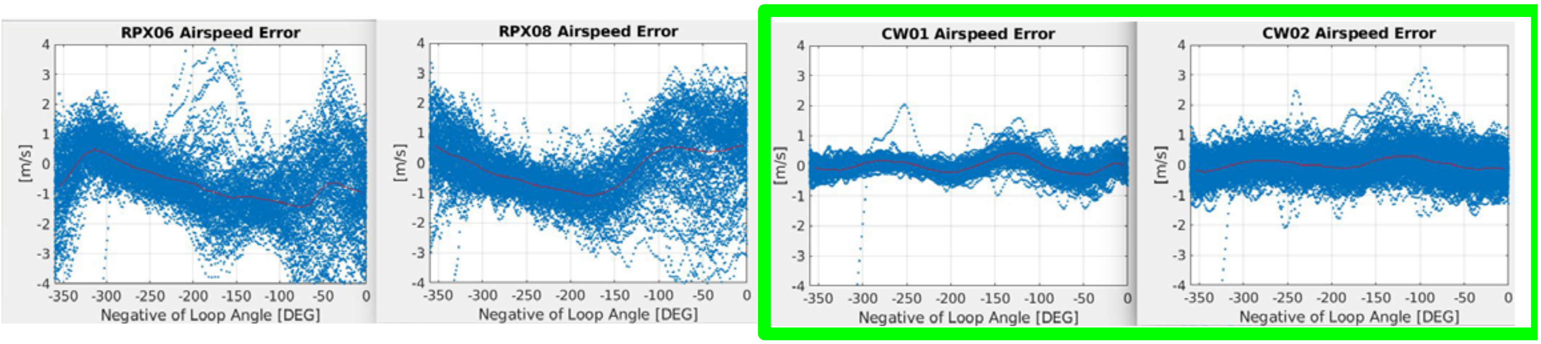
high freq cmd

beautiful feed-forward

Crosswind : Airspeed Control

- Airspeed Control was generally very good
  - CW02 a bit worse (faster wind)
- Average error < 0.5 m/s at every loop angle (both flights)
- Worst excursions were about 3 m/s
  - During downstroke



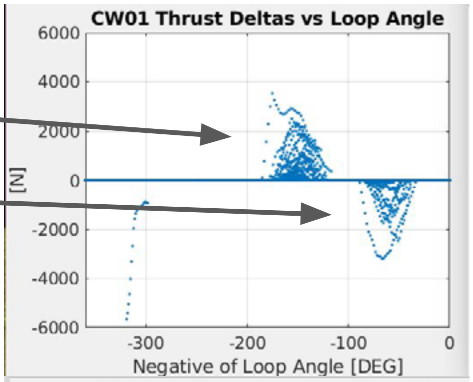


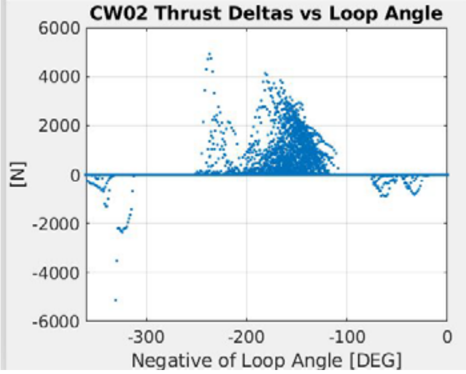
Crosswind : Airspeed Control & Rotor Saturations

When rotor saturations occur, the result usually is:

- Too much thrust (not enough drag) on the downstroke
    - Usually advance ratio limit
- Not enough thrust on the upstroke
    - Usually motor torque limit

CW02 (higher wind speeds) shows more trouble on the downstroke than on the upstroke.



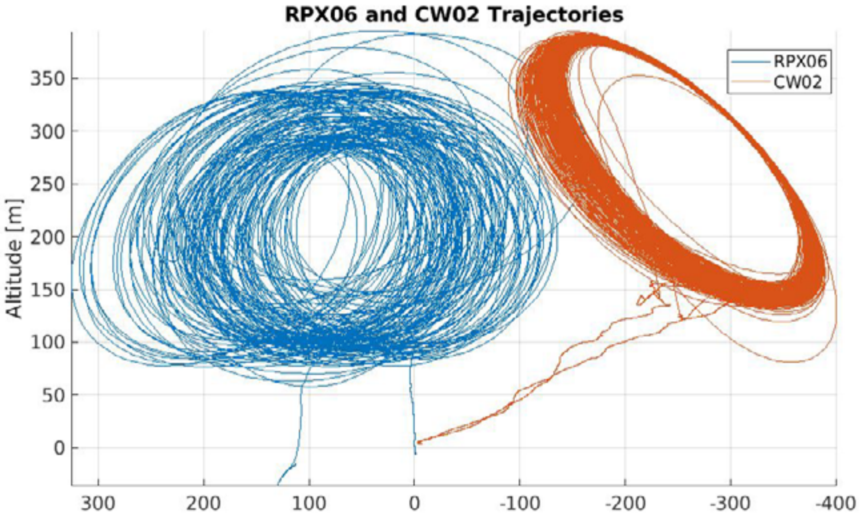


Crosswind: Path Center Slewing Is Much Calmer

- The path controller had a more steady target in these flights compared to RPX
- Mostly due to the aggressive filter used for the Playbook wind direction input
    - Also Playbook azimuth saturation
- Unclear how much blame/credit to award here

Also worth noticing:

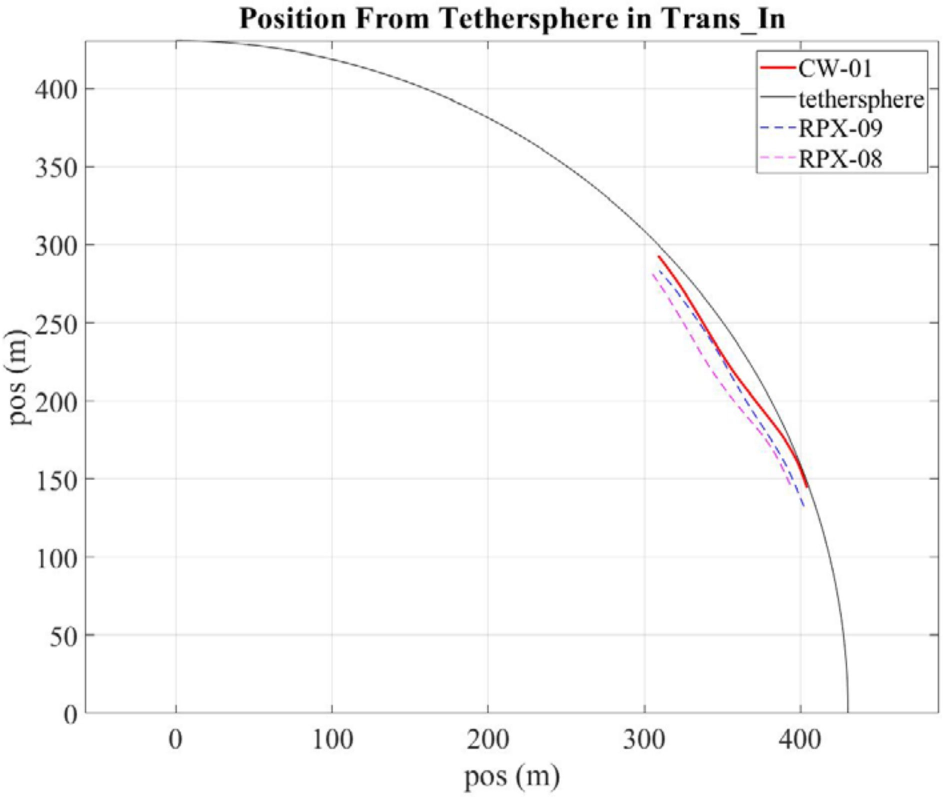
- CW01 and CW02 loops are bigger and higher than RPX in general
    - Also contributes to improved flight quality



Hover Accel / Trans-In

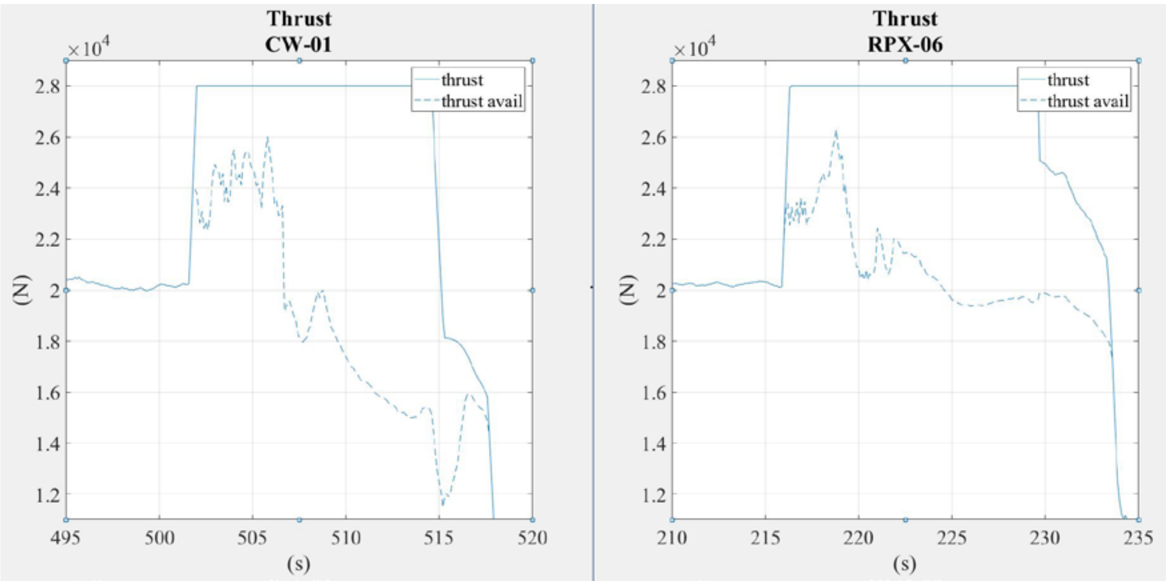
Question: Does the increased tension set-point in hover and in low winds affect Trans-In negatively?

- The higher tension meant that HoverAccel started closer to the tether sphere.
- The TransIn path was less circular, the pitch forward was more pronounced.



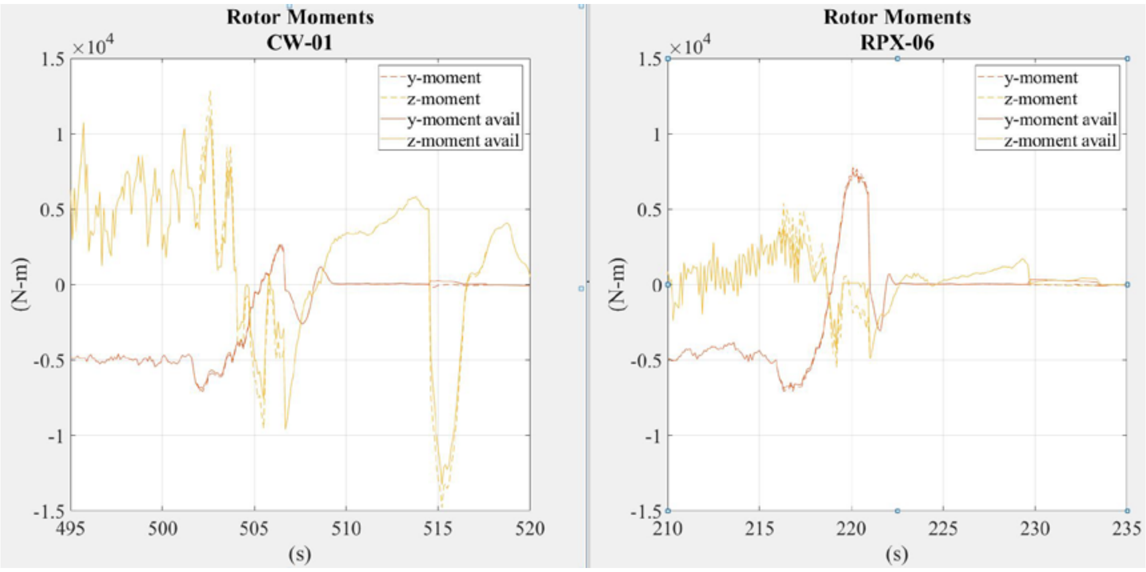
Hover Accel / Trans-In

- We had less thrust available at the end of HoverAccel and beginning of TransIn.
- The duration of HoverAccel + TransIn was similar as RPX-06 (12.9 s vs. 13.7 s)



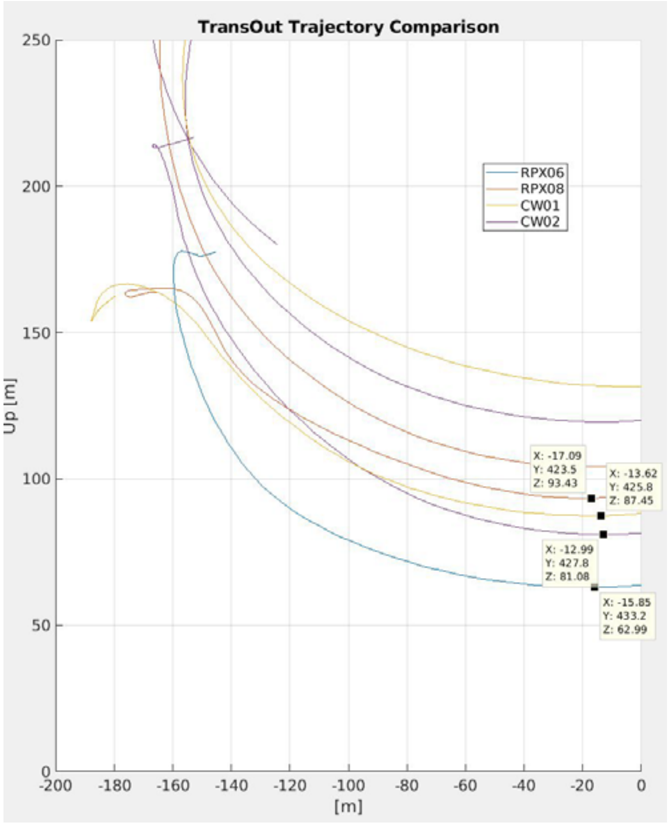
Hover Accel / Trans-In

- The Trans-In pitch forward maneuver required less rotor pitching moment.
- There was a large swing in rotor yawing moment at Crosswind entrance because we are now using motor steering (another discontinuous command)



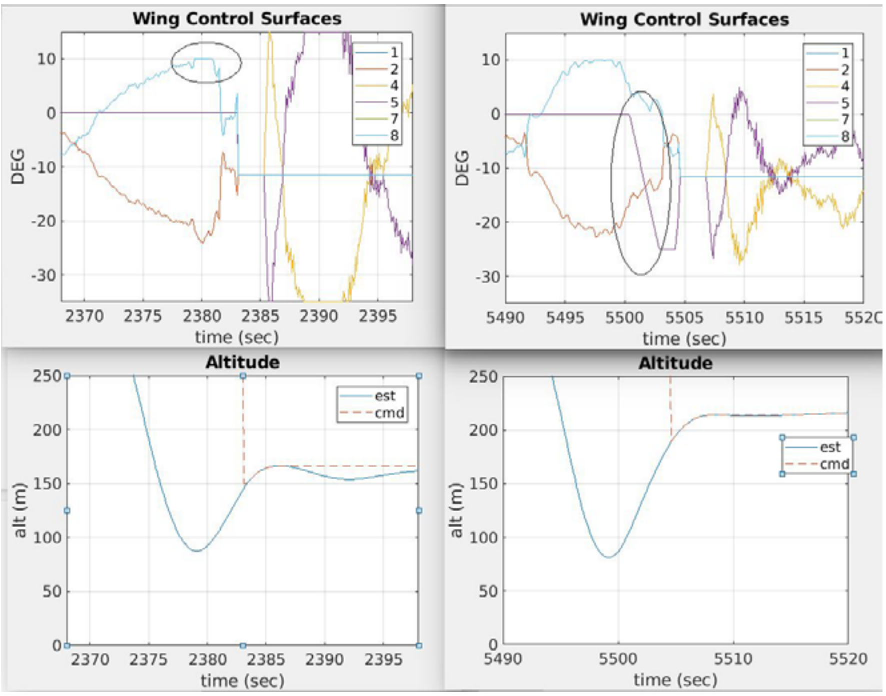
TransOut Performance (ECR 325)

- CW02 looked GREAT!
  - “That was gorgeous.”
  - “Parked it.”
  - Best TransOut since RPX06
  - Kite flying vertically when flare occurs
  - No altitude loss
  - Higher than other recent TransOuts
    - High hover is okay if on the sphere
- CW01 had a somewhat sideways flare
  - Currently blaming it on aileron saturation during upstroke
- Both flights were acceptable
  - No worry about tether ground clearance
  - Did not strike the pylons with the bridles



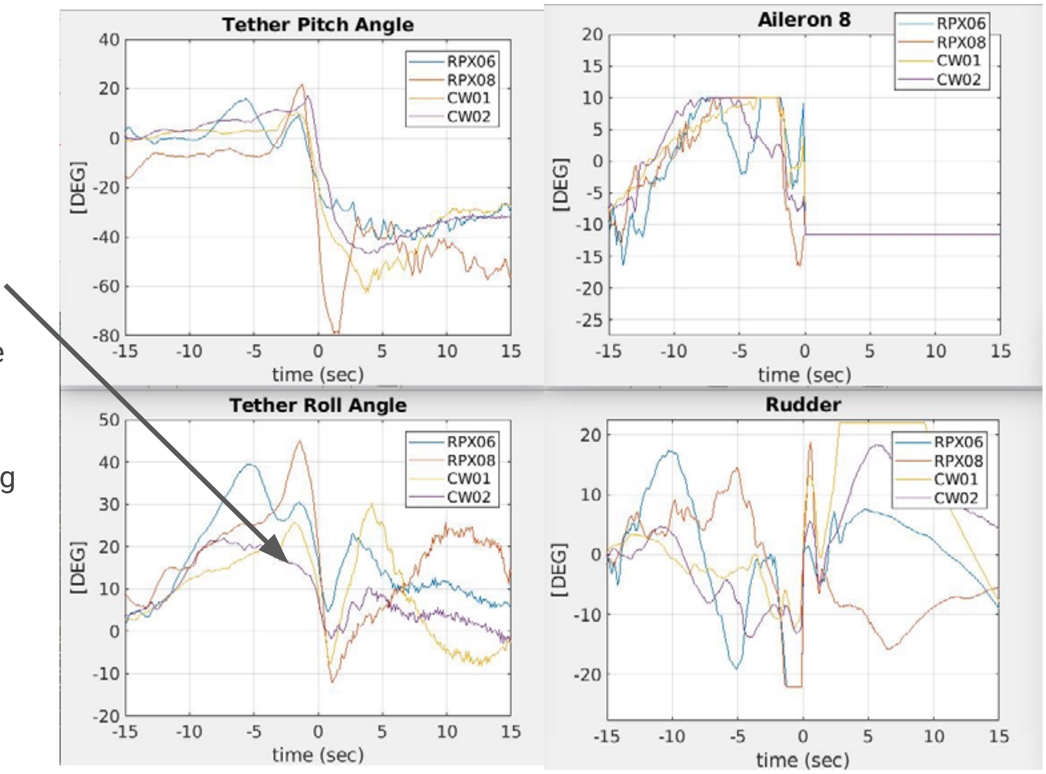
Trans-Out Performance (ECR 325)

- **CW01 ailerons saturate on the upstroke** for more than 1.5 seconds
    - Affects the path near flare
- **CW02 ailerons briefly saturate on the downstroke**, are not saturated on upstroke
    - Vertical flare
- **CW02 spoilers deploy** during final upstroke (deceleration)
    - CW02 was overspeeding a bit on the final loop
    - This plus a more vertical attitude during the flare lead to a higher hover than CW01



Trans-Out Trends

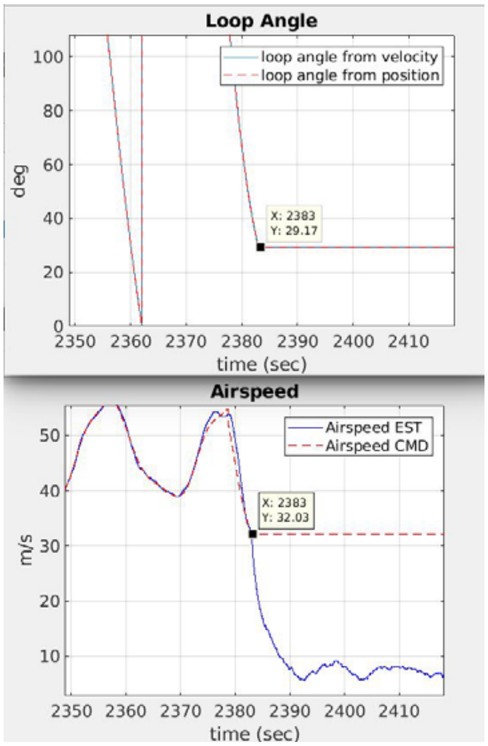
- CW02 has a lot of good qualities.
    - Looks like what TransOut should be
- Flare occurs with a small tether roll angle
    - Kite path has become mostly vertical
    - Leads to smaller bridle moments during the flare
    - Kite motion is more longitudinal
- Rudder not saturated!

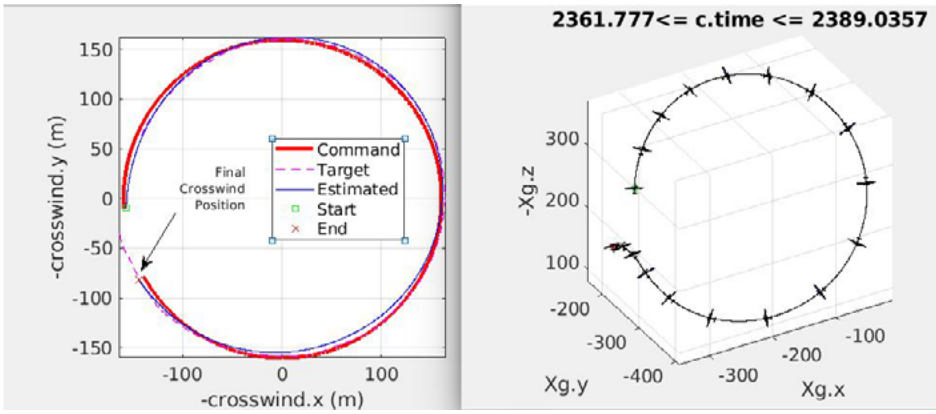


Vertical Trans-Out Trajectory (ECR 371)

Is the vertical trans-out path effective at helping the kite slow down without beginning a new loop?

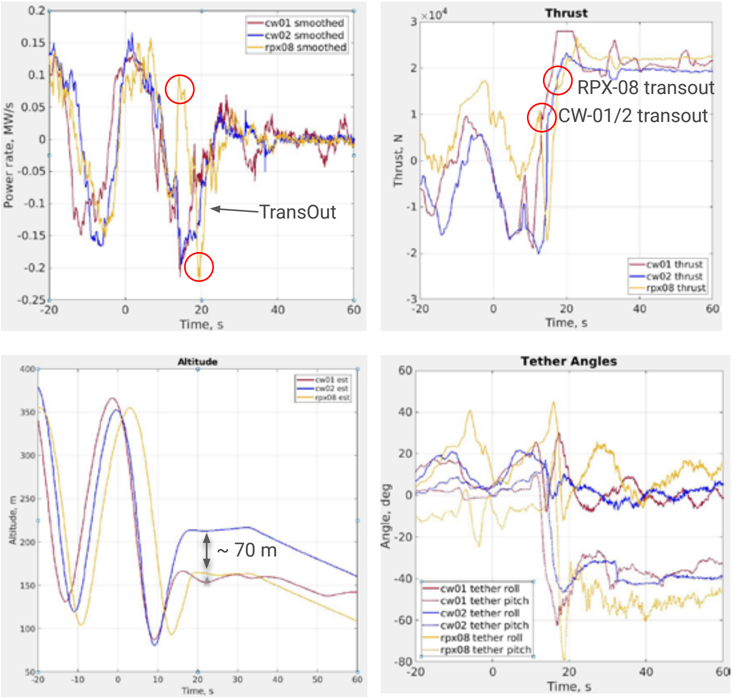
Don't know. Kite entered Hover before the 9 o'clock position in both CW01 and in CW02. CW01 shown here.





Power Jumps at Trans-Out (ECR 361)

- Power jump at transition to TransOut in CW-01/02 is ~ 0.2 MW/s, well below the ~1 MW/s that the simulation predicts without the change. Very similar to values observed RPX-08. RPX-08 had a large swing in the positive direction before transOut due to airspeed tracking errors.
- CW-01/02 command a lower initial thrust vs. RPX08 due to a 20% reduction in velocity delta.
- A smoother thrust profile provides smoother tether angle swings than during CW-01 and especially during RPX-08.
- CW-02 had a high hover altitude, despite similar thrust and airspeed, due to a more vertical thrust orientation during transOut.
  - Aileron saturation contributed to the vehicle flying more sideways in prior flights



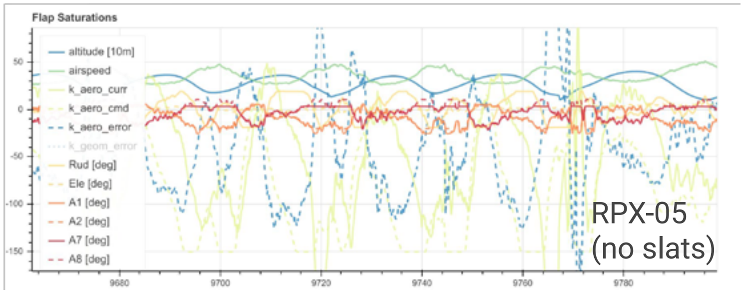
Crosswind : Curvature Error Saturations (ECR 306)

Compared to RPX-09 and RPX-05, curvature error in CW01/02 is

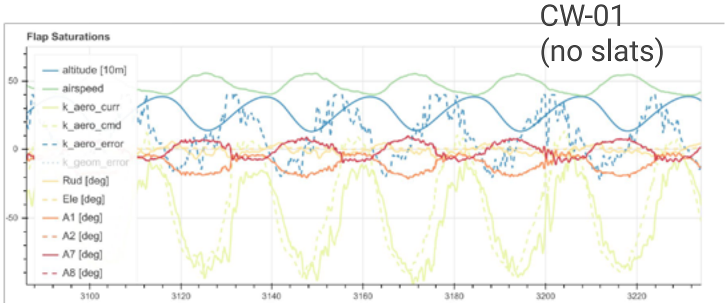
- Significantly reduced at downstroke
- Slightly more at upstroke, and saturated there.

Contributing factors:

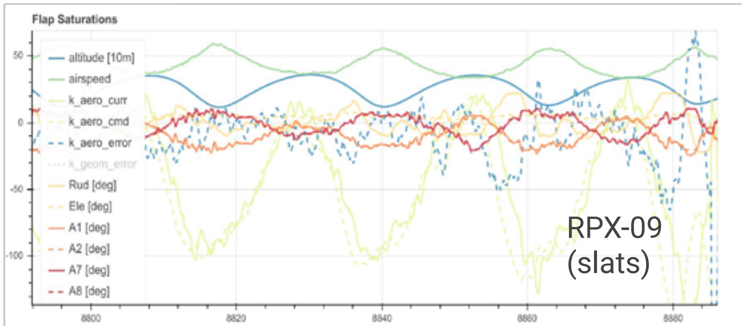
- Larger rudder → Need less roll to help with yaw → Less rudder/aileron saturation → Better tracking
- More flyable playbook schedule (azimuth, beta/alpha cmd)



RPX-05
(no slats)



CW-01
(no slats)



RPX-09
(slats)

Crosswind : Curvature Error Saturations (ECR 306)

Aero Curvature Error
Error is larger on the downstroke as wind increases from 9 m/s (CW-01) to 11 m/s (CW-02). If the trend continues, the controller will ask for more ailerons and then saturate longer there, like RPX05/09

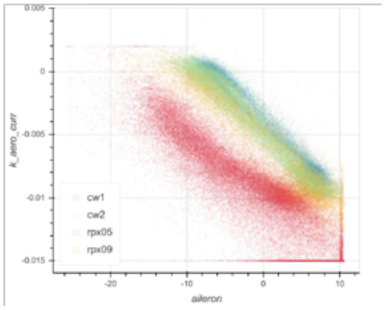
Aero Curvature Cmd
We command less aero curvature (in magnitude).

Correlates with aileron saturation, but not consistent (due to varying tracking quality)

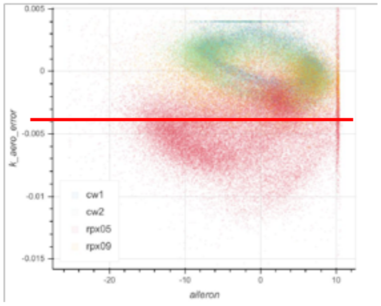
Aero Curvature Flown
Seems a better, more consistent indicator about when ailerons saturate.

Correlate with how much bridle force to fight?

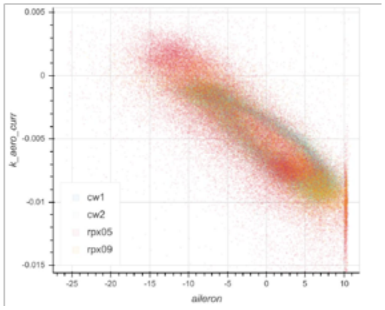
K_aero_cmd vs A8



K_aero_err vs A8



K_aero_curr vs A8

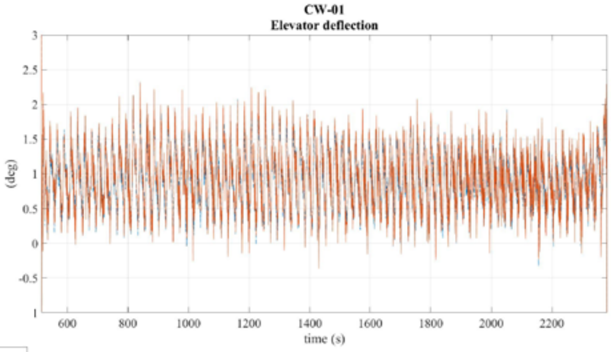


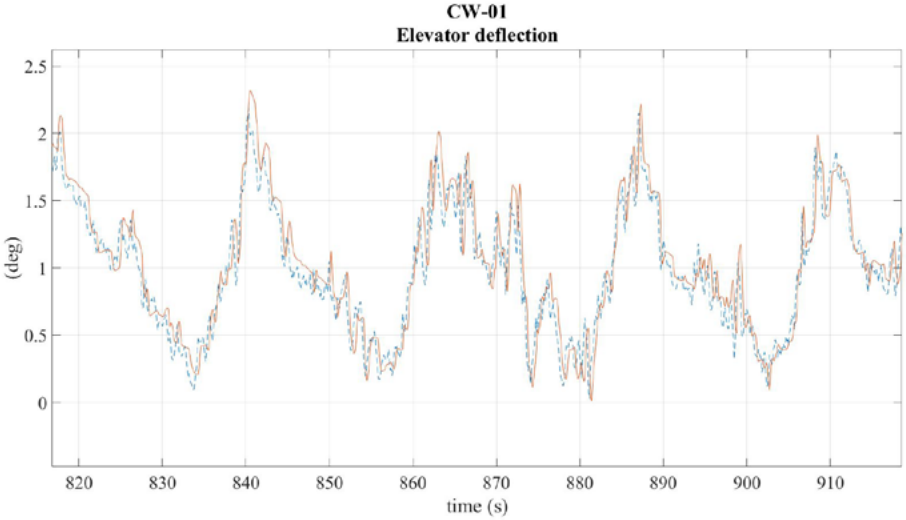
Past Investigations

- Saturate aero curvature cmd
- Saturate aero curvature error
- Saturate geom curvature

Crosswind : Elevator Deflections

- Very little use of the elevator in Crosswind, as usual.
- Mild 1 Hz oscillations in the elevator angle (amplitude < 1 deg).





Crosswind : Pitch Rate Command (ECR 350)

- Alpha command following is a little better,
- but it is not obvious how much the pitch rate command is contributing.

Crosswind : Aileron Deflections

- Talked about this in Topics of Interest
- We will probably redefine "zero aileron deflection" to be the center of each flap's throw

Outlook

- Generally positive
    - Some things we tried hard to fix are largely fixed
    - Crosswind was boring
    - Our understanding is enhanced
        - Problems encountered in these flights are (mostly) NOT mysteries or surprises!

- The kite is flying better now while not making much power than it used to while not making much power
    - We tried big, high loops before but the sideslip issues were always with us
    - Perhaps the better flight quality will continue as we fly more power-focused Playbooks

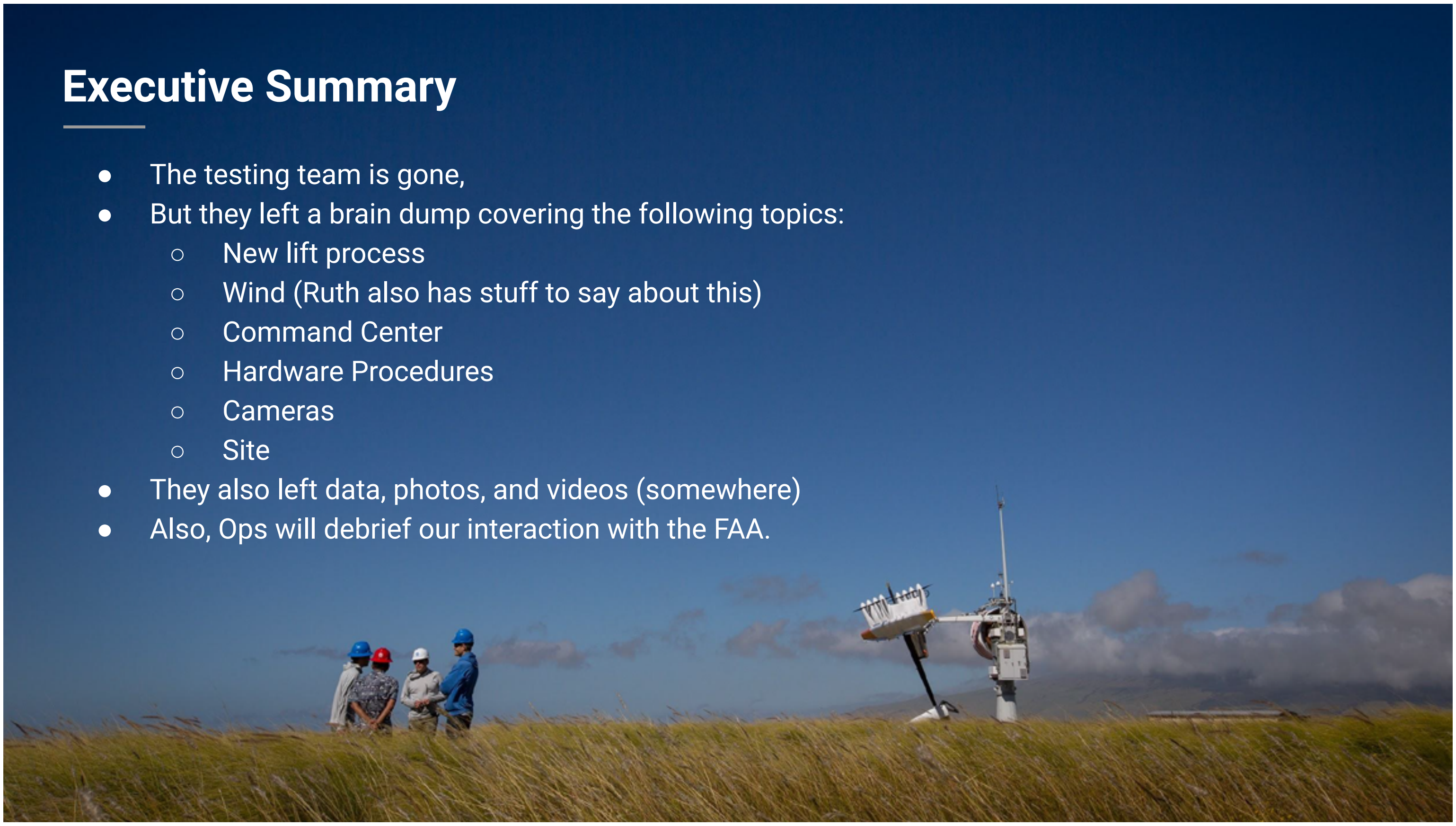
- Need to move on to a more focused comparison with C-sim (Dynamics Replay in particular)

- Would be "Go!" to fly again in January with a few code changes
    - Some already have ECRs!

MAKANI

Flight Testing
CW-01/02 Learnings Review

December, 2018



Executive Summary

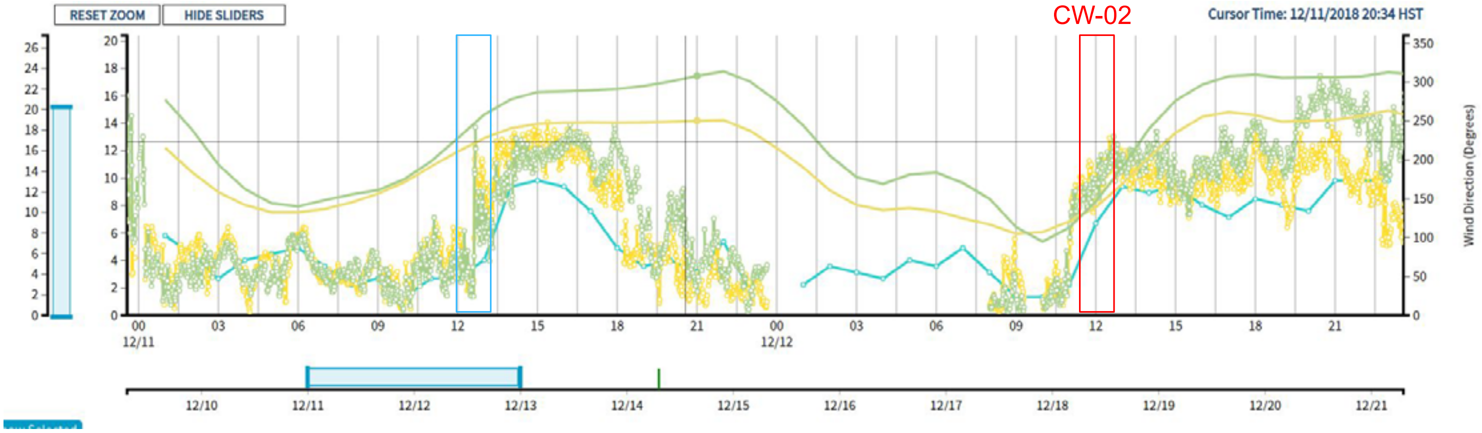
- The testing team is gone,
- But they left a brain dump covering the following topics:
  - New lift process
  - Wind (Ruth also has stuff to say about this)
  - Command Center
  - Hardware Procedures
  - Cameras
  - Site
- They also left data, photos, and videos (somewhere)
- Also, Ops will debrief our interaction with the FAA.

New Lift Process

- Kite survived ~20 m/s on perch without tail tie down (but will be great to have one)
- Need to simplify lifting setup - mostly slat bracket guy wire installation
- Kite hangs very pitched forward from slat brackets, (robbiesu: we knew it would, because design assumed we had to clear installed slats. if we aren't using slats, can we redesign lug to move the attachments +Z?)

Wind

- Lidar in CC will be big help, having the raw data allowed us to justify launching in > 8 m/s despite a 0.1 shear forecast, *was critical to us flying for the FAA*
    - Preferably filling in live on the vaisala dashboard
- Morning forecast inaccurate, common to see strong NE wind forecast but really it's light and variable until it fills in quickly



Planned Improvements to Wind Data Availability and Quality

- Real-time lidar feed into CC (for shear, wind at elevation)
  - UDP feature is enabled (thanks, Rooster), but not yet connected to our network
  - Live data processing scripts still need updating
- Forecast retraining (for improved forecasting)
  - Vaisala now has > 3 months of lidar data, BUT almost NO night/early morn data
  - Will want to retrain again, after we collect 24/7 data
- Lidar scan geometry
  - Wood did analysis of VAD vs ARC scan. Wind at site has significant vertical component, therefore, we must do VAD scan to get vertical WS
  - Switching to 6-beam VAD scan (from initial 15-beam scan)
  - New scan geometry will enable us to get indicative TI (6 samples/min vs 1/min)
- Lidar 24/7 data collection
  - New battery pack on order — should get us mostly there
  - Timing to get connected to grid power still uncertain

In the Command Center

- Great to have a full CC for first flights to have full coverage and training, but need to cut #s
- Monitors had lots of distracting false warnings/errors, let's be less tolerant and try hard to get it all green/grey when all is well
  - FAA lights, motor HetGood warnings
- Move more telemetry from PLC to AIO
  - Goal is to get rid of the PLC laptop in the long run

At the Kite

- Pitot covering is a pain
- Some hardware procedures need better documentation
    - Bridle junction pin install has no documentation, took 2 engineers 1.5 hrs morning of a flight
    - Loads logger had no instructions, didn't know we needed to replace SD card. Didn't know about license expiration.

Cameras

- We should prioritize robust onboard cam solution that requires no lift operations (preferably with remote download/quick turnaround)
- As soon as we can cut cameras from certain spots, we should.

Site

- The site infrastructure still isn't finished so some of our work will get a little easier once we aren't camping quite so much.
- Will need to add lights [internal ref] or other see-in-dark hardware to allow night flight, might as well start now.
- We may want person-lifts with higher wind rating (the Magni may satisfy this).

GS02

- Time to take a step back and fix things! [internal ref]
  - We might be on borrowed time on some issues.
- GS02 code has to be migrated locally, and we need to adapt the same standards regarding reviews as we do with AIO code.

Makers and Breakers
CW-01/02 Learnings Review

December, 2018

Executive Summary

- Working in an incomplete site is an adventure
- Deferring work to the site is a delicate balance

Learnings

- GS assembly
    - The general re-assembly went well, it was nice to have the same people put it back together who took it apart.
    - Organized and clearly labelled GS tools and hardware made them easier to find once in PR
    - We had a lot of electrical issues on first power up. It's hard to say if that was because of the move or not, but maybe we should take extra care to packing the electrical cabinets for the move.
    - Do not leave the antenna mast up without lightning cables attached - It will vibrate!

Takeaway:
Organized and labelled hardware made it much easier to find on arrival, making the general reassembly go much smoother. However, moving can be rough on the hardware and we should provision for more debugging time after reassembly.

Learnings

- Working on two kites is a shuffle
    - One kite always had priority, slowing down progress on the other
    - Some work could happen in parallel but personnel would get pulled in different directions
    - Dedicated a crew to SN4 finishing to deconflict with SN1 hover support
    - Could only power one kite on at a time
    - GS HITL requires a kite and caused a lot of moving/swapping

Takeaway: Things take longer as we juggle tasks between multiple kites that have to be flight ready. More personnel are required onsite to keep up. This may go away as SN5 is to act as a "spare" and can be given more time to complete assembly.

Learnings

- SN1 and SN4 assembly without tent
  - Assembling outside, in real wind is challenging
  - Keeping track of tools and hardware was hard
  - Racing trailer organically became a really useful mobile shop

Takeaway: (Especially relevant for Norway) Getting ahead on having tools and space to organize things is extremely valuable.

Learnings

- Rushing SN4 out added some tension
  - Tasks deferred to site
    - Landing gear mount bonding
    - Fairing work (Canoes, Pylon root, nose cowl, slat bracket)
    - Much cable restraining
    - Mass balance tube assembly
    - Loads monitoring setup
    - Light nodes

Takeaway: There is a balance to be made of assembly detailing and testing/validation before shipping out of ALM. Some simple items can be deferred to the site as they need attention during reassembly anyway (i.e. root fairings).Major assemblies requiring validation should be prioritized early or held back (i.e. mass balance tube, lights). Still need more thorough validations on some (Ozone swaps). More detailed assembly-for-flight checklists have been made to help track progress and make these decisions/tradeoffs.

Open Bugs: Kite

- Pylons getting wet: bug 117175455
- Leading edge tape on rotors: bug 120991142
- SBO PTO cap boxes: bug 121161444
- Servo Boxes getting wet: bug 118445497
- DAQ license upgrade: no bug, [internal ref]
- Fuselage My strain gauge: no bug

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Power Systems
CW-01/02 Lessons Review

December, 2018

Executive Summary

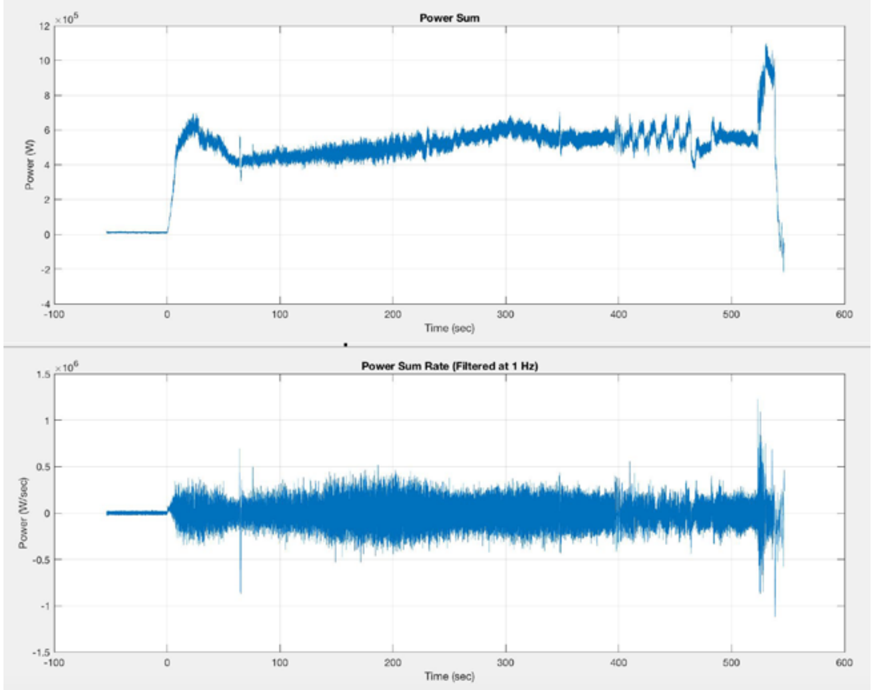
- Drivetrains nominal
    - Some comments on control and modeling
- Servos nominal
    - Rudder extension doesn't seem to be an issue
    - LV loads appear (mostly) within primary MVLV capacity
- MVLV nominal
    - Thermals appear acceptable; future improvements
- Batteries nominal
- Ground power performance significantly improved
    - Some significant problems still pending
- FAA lights
    - Tentative success
- Many planned improvements underway

What's New?

- MVLV upgrade - improved controller, better isolation.
- PR ground power setup
    - Switchgear
    - Satcon control through Ground Power AIO node
    - Better Satcon data throughput
    - Loadbank control through Ground Power AIO node
    - 1.5 MW diesel
    - Crowbar… mostly
- Aluminum battery box
- New MV Harness design
- Slip ring isolation issues -> new slip ring
- Larger rudder -> higher torque on servos?

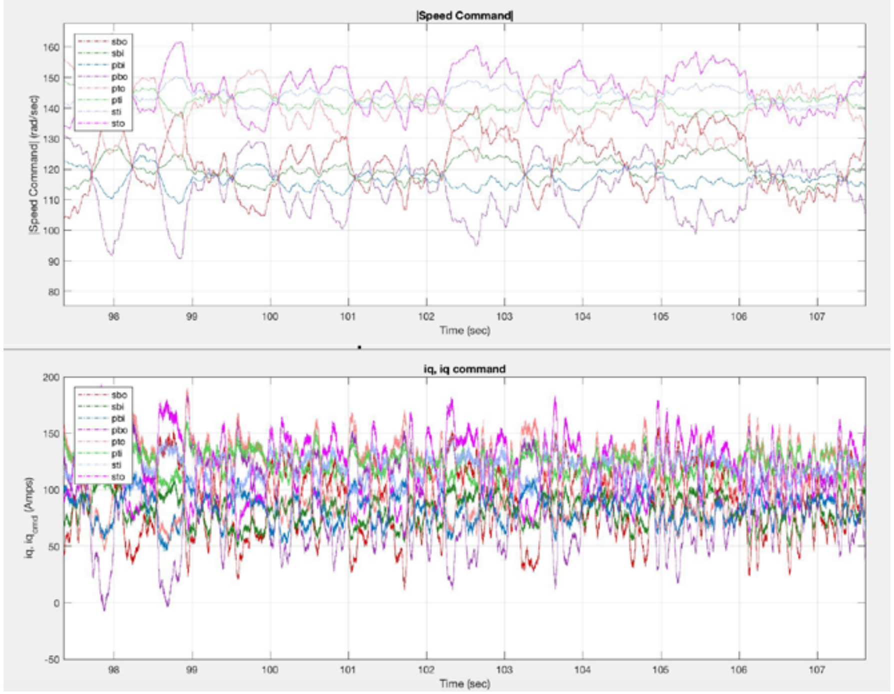
Hover Power Usage

- Some concern over 600+ kW hover numbers. Longer term this can start to drive subsystem cost and deplete revenue (increased launch cost).
- Slew rates occasionally reaching 1 MW/sec



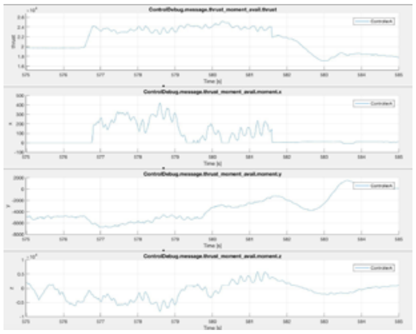
Hover Commands

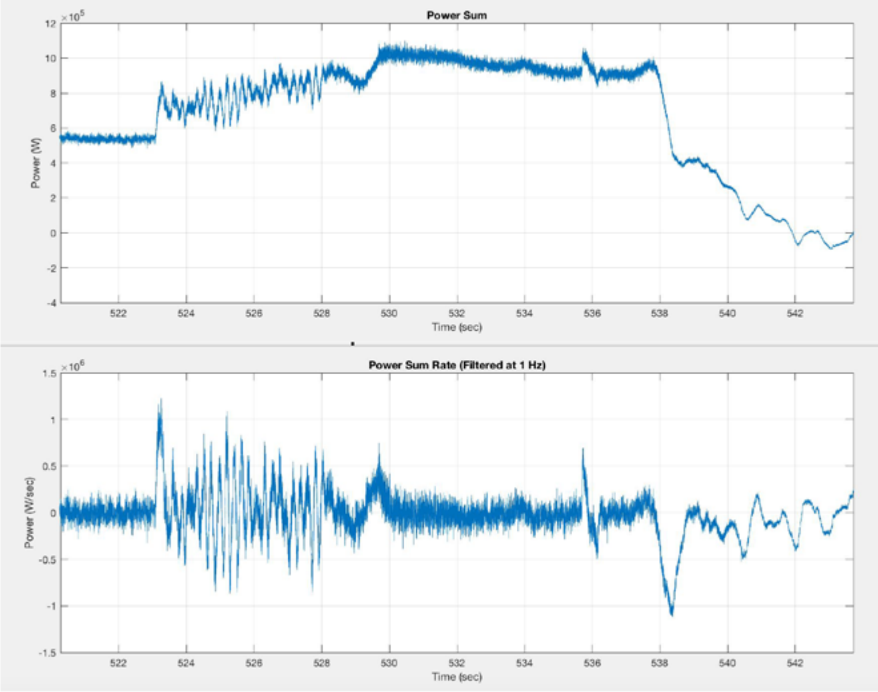
- Very active commands with lots of frequency content.
- Lots of gain at high frequencies -> huge torque fluctuations.



Trans-In Power Usage

- Higher frequencies (~5 Hz) in moment commands decrease total power available for thrust.
- High rate of change at beginning and end - short duration so likely non-issue.

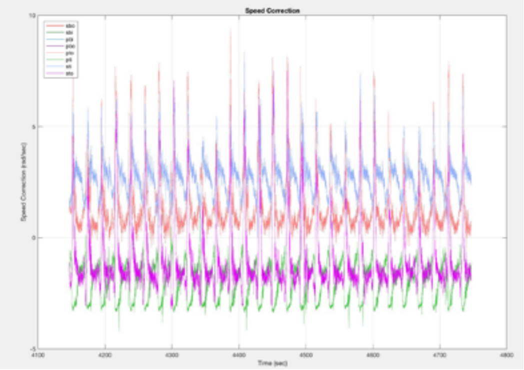




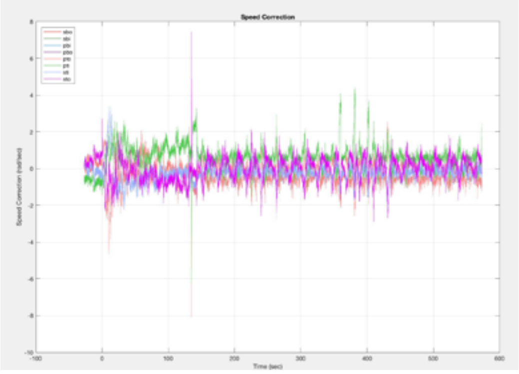
Crosswind Corrections

Seeing some speed corrections:

- Not huge, but last time we saw these, we found pitot measurement issue.
- Need further investigation to see if we are violating advanced ratio limit.
- Also, some steady state correction is being applied. Implies some airflow estimate error. Noticeably worse than RPX-08. (New props? airflow?)



CW-02



RPX-08

MixRotors?

- Slight discontinuities in commands at limits of generator / advance ratio limit.
- Jumps cause torque spikes.
- Not critical yet.

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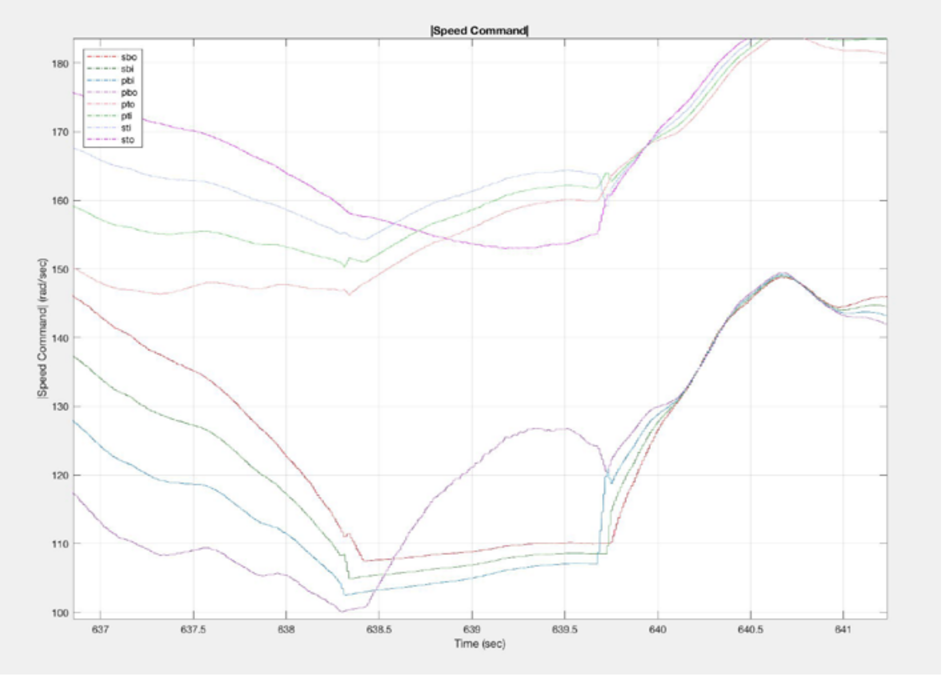

Variable Power

- Just a reminder that 1 MW to -600 kW is not ideal

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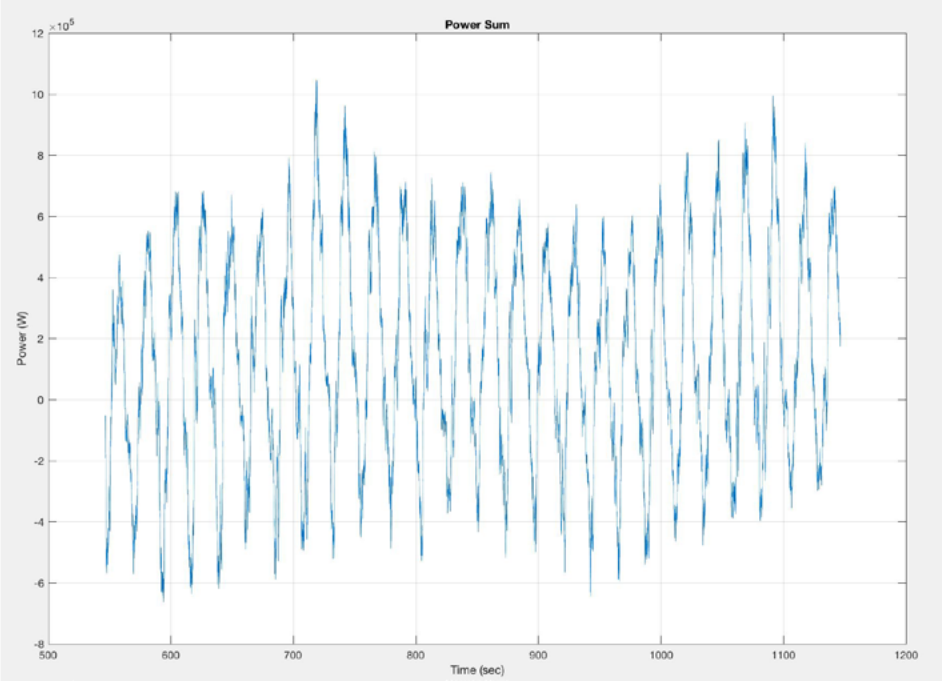

Servos

- Very crude analysis so far: More power consumed in hover than in crosswind.
- Movement is still main source of torque.
- No sign of higher aero torques (but wouldn't expect to see at these speeds?).

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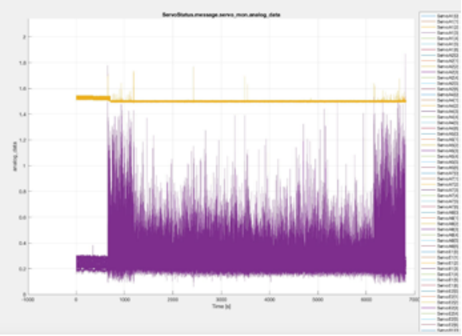
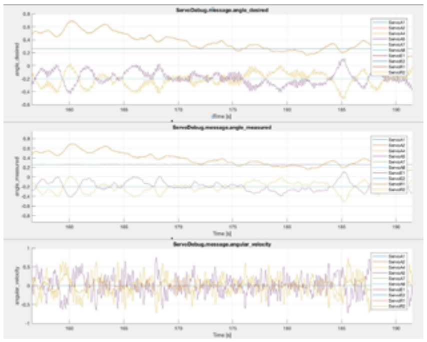
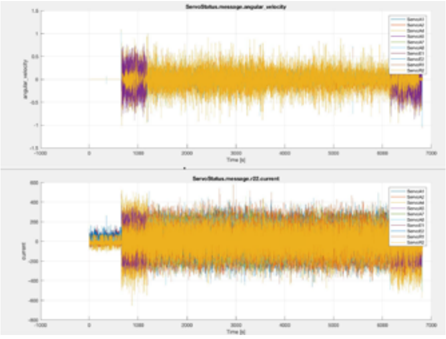






MVLV

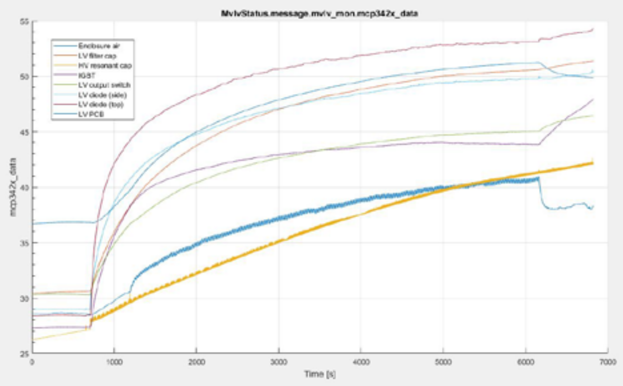
MVLV operated normally without problem.

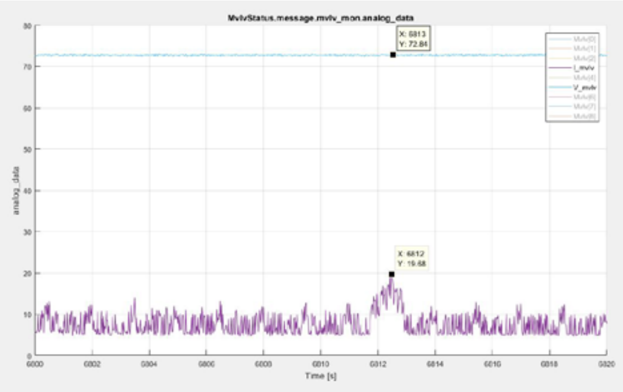
Thermal performance:

- CW-02 close to thermal steady state.
- MVLV enclosure had better cooling during cross wind.
- Major semiconductors (IGBT, Diode) ran cooler during cross wind.
- Thermal margin > 30C

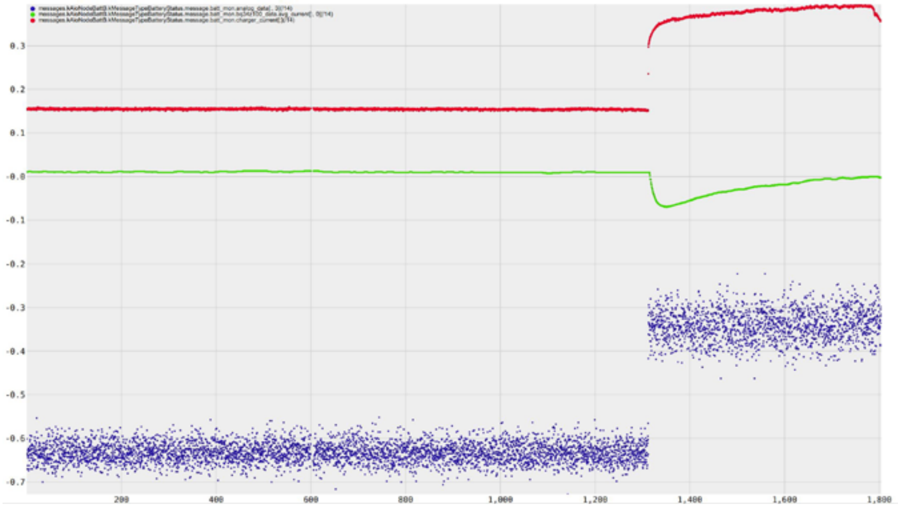
Electrical performance:

- No LV drop out → new CPLD code handles peak current well.
- Peak current (19.7A) occurs when arm/disarm servos.
- Spectrum analysis of MVLV current shows peak at 0.667Hz caused by FAA light (indirect indicator of FAA light status).
- Current measurement is noisy. Low pass filter should be implemented to filter out switching noise.





Battery Currents Before vs. After Umbilical Disconnect



- Red: charger current (hall sensor; this one has ~0.1A offset)
- Blue: battery output current (bigger hall sensor; this one has ~-0.6A offset). Start of plot is 0A output because connected to umbilical supply. After umbilical disconnect, jumps 0.3A because of LV-12Vs' quiescent current draws.
- Green: Average net battery current (charge minus output). Resistor sensor; no offset. See charge current rise to meet quiescent draw after launch.

Battery

- Small battery box is backup for MVLV
- Small battery box shows 0.3A output after disconnection from umbilical -- motor LV-12V converters have small quiescent draw on secondary bus. Battery charger runs to keep batts at full state of charge.
- MVLV appears sufficient to address power needs

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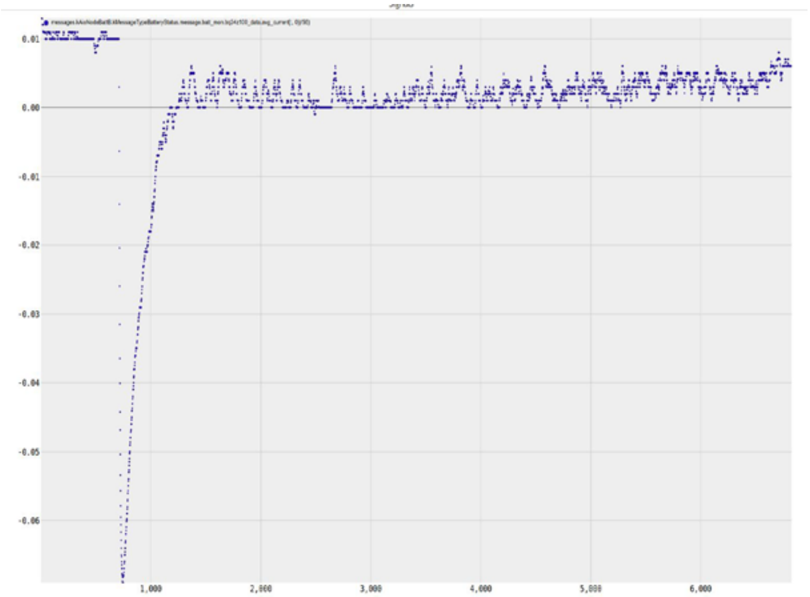


Ground Power Progress: Annotated

WHEN	SATCONS	LOADBANK	GENSET
RPX program	Slow reporting, no native control client, clunky startup	PLC driven, slow, crappy control, long dropouts (risking flight)	Clunky 2MW (because we thought we needed it)
CW-01	6x faster reporting, native operator scripts for control, more robust startup, crowbar (almost)	AIO node driven, 6x faster, more stable, code under normal review process, still some 5 second dropouts	Modern 1.5MW (re-did step load testing with improved loadbank control)
CW-02		Reduced dropouts to 0.5 second (not a flight risk), some crazy outliers	
“The Future”	Automated isolation fault detection, fix crowbar circuit	Filter outliers, Backup data source from wing power measurement	

FAA Lights

Preliminary success!

Conspicuity: unknown, pending night time FAA observations, but looks promising

Functional issues:
- Software bugs can blow up the lights :(
- Water ingress needs work
    - Lights were made for horizontal fixed-wing aircraft, M600 is not that
- Better design for tail light drive box
- Sync to GS FAA beacon
    - Known solution
    - Requires tiny wiring mod to GS
    - Run GS sync application on GS GPS node, drive FAA beacon sync input
- Lack of direct strobing indicator (frequency domain analysis of MVLV current shows light status)

Strategic issues:
- Build procedure is unsustainable at scale
- Need to reach out to Whelen, or “Roll our own”

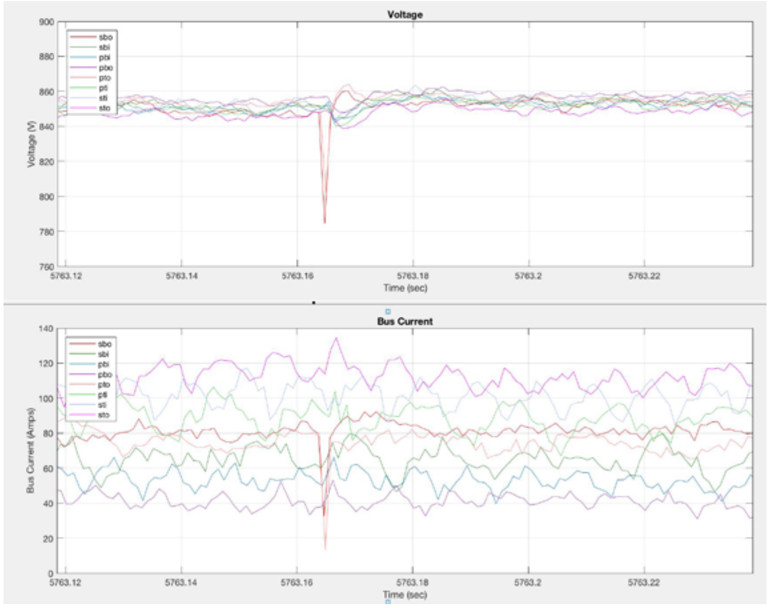
Changes / Improvements in The Pipeline

- 140 rad/sec software fix.
- 17 cell battery - SN5 with option to backfill SN4
- Higher tether voltage - higher power from motors
- MVLV higher voltage - next quarter if prioritized
- Short stack - next quarter if prioritized
- Airbrakes

- Waterproofing?

Open Bugs

- Bus voltage ticks in SBO-PTO stack level
- Loadbank comms glitches
- Bootloading lights

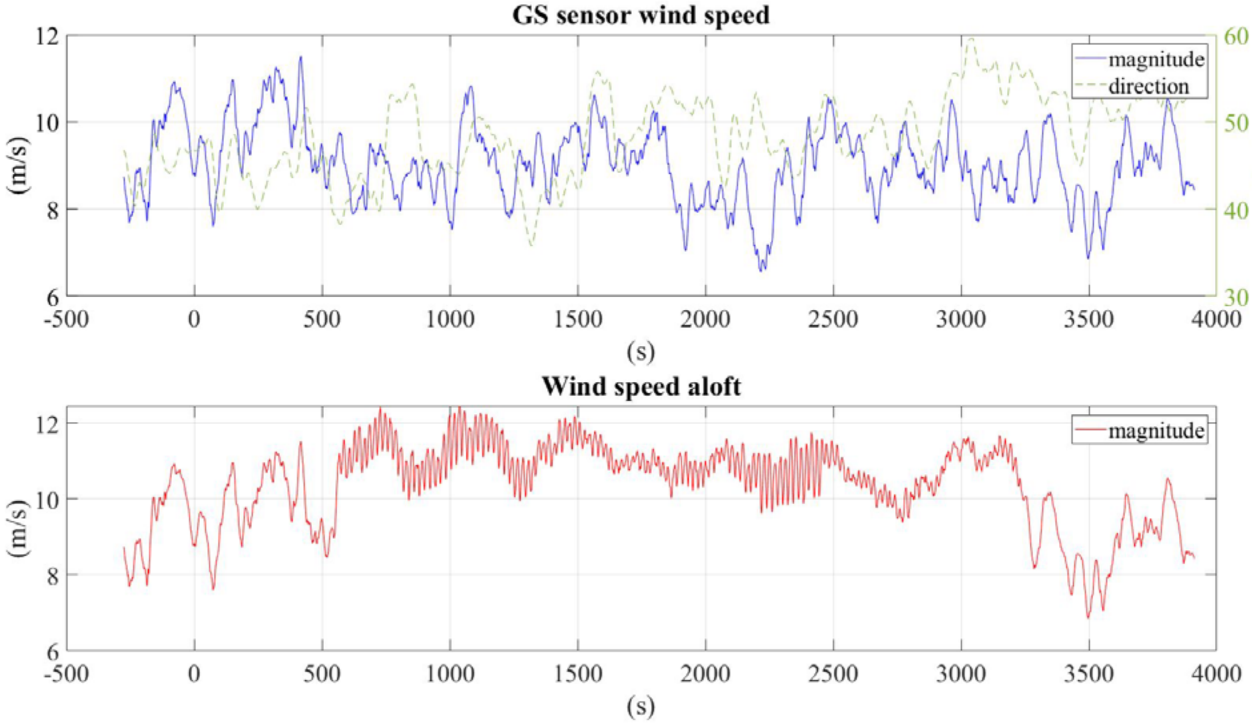


Controls CW-05/06 Learnings Review

April 2019

CW-05

Wind



SN4 Flight Test Statistics

Flight	Total Flight Time (min)	Number of Loops	Crosswind Average Wind Aloft [m/s]	Crosswind Average Power [kW]	Launch to Crosswind Duration [min]	Crosswind Duration [min]	TransOut to Perch Duration [min]
CW01	61	81	9.7	-98	8.6	31.1	21.6
CW02	103	222	10.1	-53	8.9	82.8	10.8
CW03	92	185	9.6	-99	11.7	69.1	10.9
CW04	42.2	47	5.0	-255	9	21	12.1
CW05	64.7	130	11.0	26	9.3	44.5	10.85
Sum	362.9	665				248.5	

Power

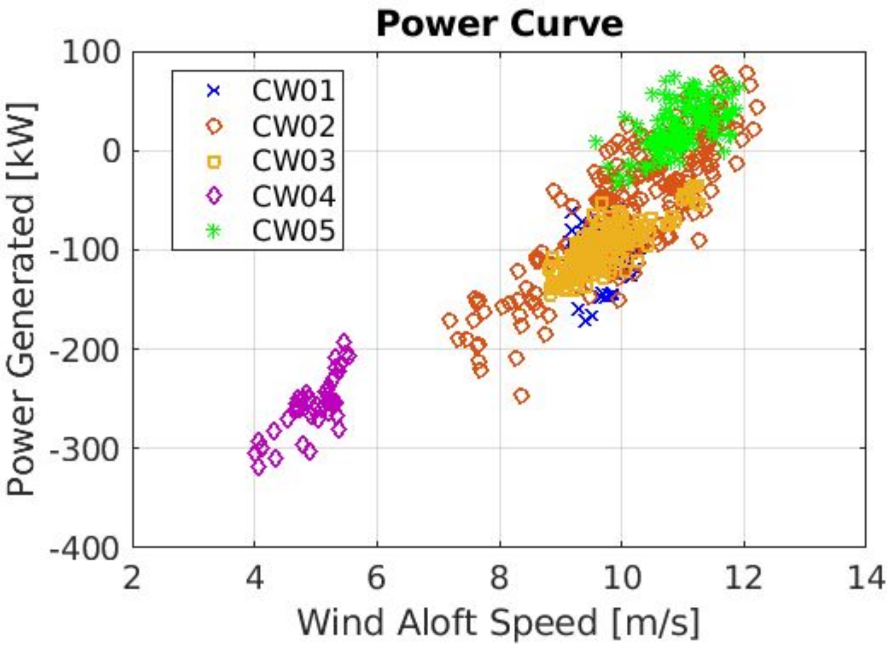
Slightly more power than CW02 at similar wind aloft speeds.

Crosswind average: +26 kW

Best loop: +75 kW

(this was not a TransOut loop)

Worst loop: -34 kW



Scores

Scoring function report [internal ref]

Scoring function	Severity	Score	Value
Selected Crash scoring functions of interest			
-Crash- HoverTransformGsUp Tether Elevation [2] [deg]	5	0	[6.0, 8.44]
-Crash- HoverTransformGsUp Tether Elevation [3] [deg]	5	0	[6.81, 8.16]
-Crash- HoverTransformGsUp Tether Elevation [0, 4] [deg]	5	0	[7.32, 7.36]
-Crash- HoverTransformGsDown Tether Elevation [2] [deg]	5	40	[4.3, 8.77]
-Crash- HoverTransformGsDown Tether Elevation [3] [deg]	5	30	[4.39, 6.97]
-Crash- HoverTransformGsDown Tether Elevation [4] [deg]	5	0	[6.91, 6.91]
-Crash- Crosswind - Max Wing Bending Failure Index [-]	5	0	0.32
-Crash- Crosswind - Max wing-fuselage Mx moment [kN-m]	5	0	[-5.33, 1.98]
-Crash- Crosswind - Max wing-fuselage My moment [kN-m]	5	0	[-33.21, 11.96]
-Crash- Crosswind - Max wing-fuselage Mz moment [kN-m]	5	0	[-41.98, 18.85]
-Crash- >20[m] AGL, CrosswindNormal Max. Tether Sph Dev (mean tension = 100 kN) [m]	5	0	0.42
-Crash- HoverTransOut Tether Pitch Range (tension > 50 kN) [deg]	5	0	[-7.0, -7.0]
-Crash- HoverTransOut Tether Roll Range (tension > 1 kN) [deg]	5	0	[-20.96, 18.49]
-Crash- >20[m] AGL, CrosswindNormal Max Airspeed [m/s]	5	0	59.39
-Crash- >20[m] AGL, CrosswindNormal Max Tether Tension [kN]	5	0	139.53
-Crash- >20[m] AGL, CrosswindNormal Gsg Yoke Range [deg]	5	0	[-34.76, -8.13]
-Crash- >20[m] AGL, CrosswindNormal Gsg Termination Range [deg]	5	0	[-15.33, 10.5]

Scores

Scoring function report [internal ref]

Scoring function	Severity	Score	Value
Flight quality Hover scoring functions			
Hover - Perch to CW Max Rotor Speeds [rad/s]	2	0	[166.87, 172.71]
Hover - CW to Perch Max Rotor Speeds [rad/s]	2	0	[161.79, 174.99]
Hover - Perch to Transform Min Tether Tension [kN]	4	0	6.23
Hover - Transform to Perch Min Tether Tension [kN]	4	0	5.77
>5[m] payout, Hover - PayOut Tether Elevation Oscillations [deg]	4	0	0.93
>5[m] payout, Hover - ReelIn Tether Elevation Oscillations [deg]	4	0	0.77
Hover - Perch to Accel Tether Pitch Range (tension = 0 kN, duration = 1 s) [deg]	4	0	[-17.0, -17.0]
Hover - TransOut to Perch Tether Pitch Range (tension = 0 kN, duration = 1 s) [deg]	4	0	[-17.0, -17.0]
Hover - Perch to CW Hover Roll Period [s]	4	0	7.46
Hover - CW to Perch Hover Roll Period [s]	4	0	7.98
HoverDescend Duration [s]	1	0	74.69
HoverPrepTransformGsUp Duration [s]	1	12	76.09
HoverPrepTransformGsDown Duration [s]	1	25	108.69

Scores

Scoring function report [internal ref]

Scoring function	Severity	Score	Value
Flight quality Crosswind scoring functions			
>20[m] AGL, CrosswindNormal Main Wing SSAM AoA (w/o initial transients) [deg]	3	109	[0.6, 7.17]
>20[m] AGL, CrosswindNormal Side-slip (w/o initial transients) [deg]	3	0	[-3.12, 5.81]
>20[m] AGL, CrosswindNormal Angle-of-attack Error (w/o initial transients) [deg]	3	75	3.5
>20[m] AGL, CrosswindNormal Sideslip Error (w/o initial transients) [deg]	4	78	5.33
>20[m] AGL, CrosswindNormal Min Airspeed [m/s]	4	0	35.81
>20[m] AGL, CrosswindNormal Airspeed Error [m/s]	2	0	2.1
>20[m] AGL, CrosswindNormal Crosswind Radius Error [m]	1	6	[-26.58, 22.84]
>20[m] AGL, CrosswindNormal Tether Pitch Range (tension > 1 kN) [deg]	1	0	[-11.54, 10.73]
>20[m] AGL, CrosswindNormal Tether Roll Range (tension > 200 kN) [deg]	2	0	[7.15, 7.15]
>20[m] AGL, CrosswindNormal Min Tether Tension [kN]	3	0	26.42
>20[m] AGL, CrosswindNormal Max Rotor Speeds [rad/s]	2	0	[196.01, 224.18]
>20[m] AGL, CrosswindNormal Acceleration [m/s^2]	0	0	[-27.54, 0.71]
>20[m] AGL, CrosswindNormal A1 % Saturated [% time]	4	0	0
>20[m] AGL, CrosswindNormal A8 % Saturated [% time]	4	22	0.54
>20[m] AGL, CrosswindNormal Ele % Saturated [% time]	4	0	0
>20[m] AGL, CrosswindNormal Rud % Saturated [% time]	4	0	0
>20[m] AGL, CrosswindNormal Min Kite Height Above Ground Level [m]	3	0	88.4

Scores

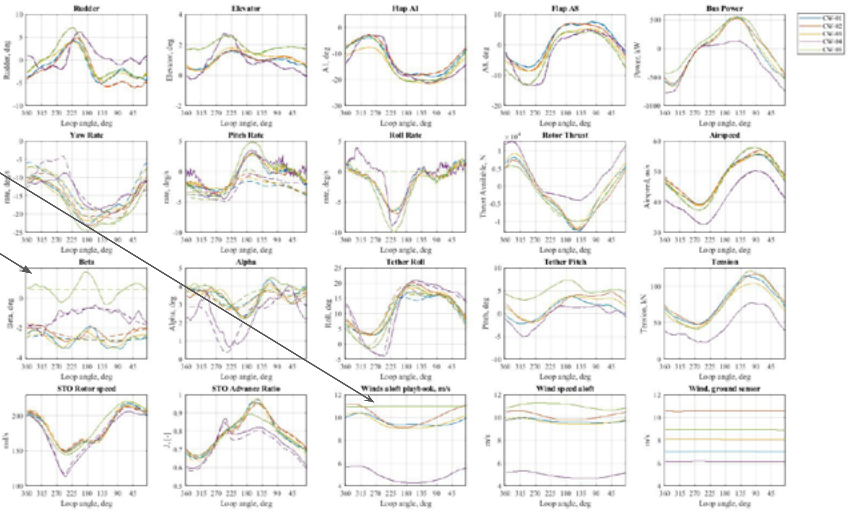
Scoring function report [internal ref]

Scoring function	Severity	Score	Value
Flight quality CrosswindPrepTransOut scoring functions			
CrosswindPrepTransOut Duration [s]	1	0	23.69
CrosswindPrepTransOut Max. Tether Sph Dev (mean tension = 100 kN) [m]	4	0	0.23
CrosswindPrepTransOut Main Wing SSAM AoA [deg]	2	42	[1.74, 5.83]
CrosswindPrepTransOut Side-slip [deg]	1	0	[-1.56, 2.6]
CrosswindPrepTransOut Crosswind Radius Error [m]	2	0	[-4.75, 7.73]
CrosswindPrepTransOut Rud % Saturated [% time]	2	0	0
Flight quality TransOut scoring functions			
HoverTransOut Duration [s]	1	0	24.79
HoverTransOut Max. Tether Sph Dev (mean tension = 100 kN) [m]	4	0	4.49
HoverTransOut Pitch Rate [rad/s]	1	0	0.46
HoverTransOut Tether Pitch Range (tension = 0 kN, duration = 3 s) [deg]	1	319	[-65.98, -20.0]

- A high altitude TransOut led to large and sustained tether pitch angles. The last score reflects poor roll stiffening action from the bridles during this moment.

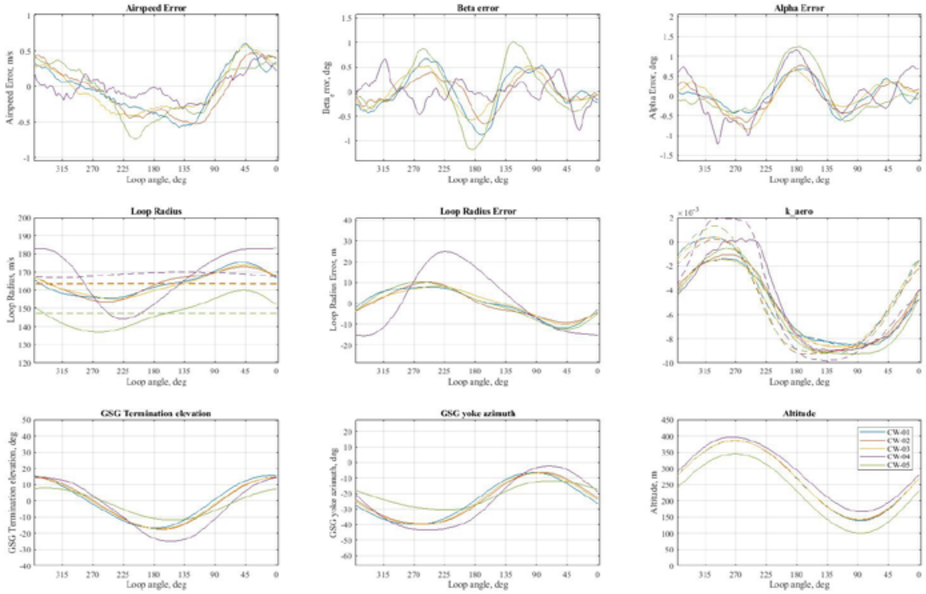
Average Loop Comparisons

- The wind speed the playbook uses no longer varies with loop angle
- Beta error seems larger
- Roll rate error seems larger
    - Could this be due to not retuning the feedforward gains?
- Most of the difference in power is in not consuming power on the upstroke
- Average power in crosswind is +25 kW



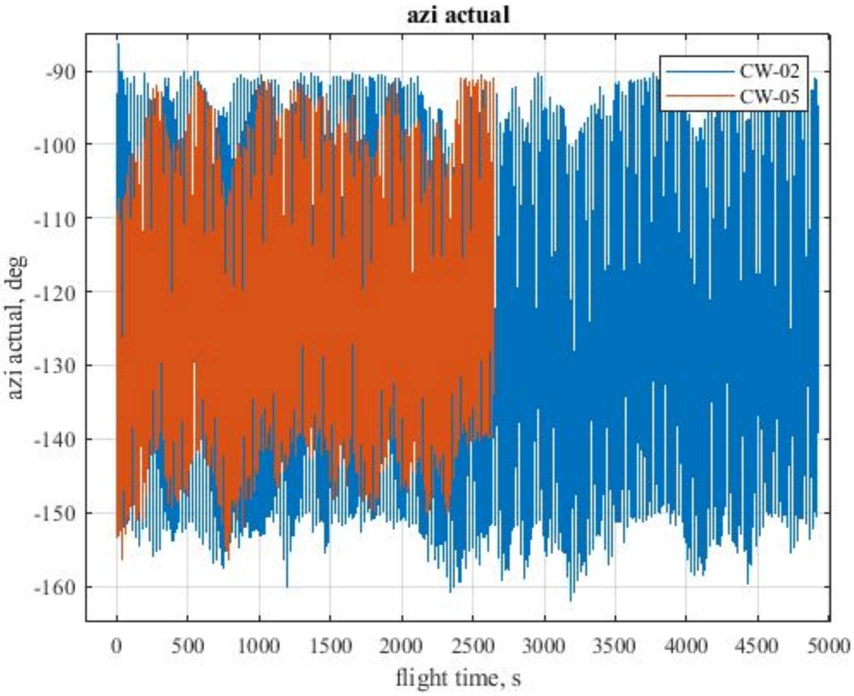
Average Loop Comparisons Errors

- Beta error seems larger
- Other errors are still similar
- Loops are smaller and lower



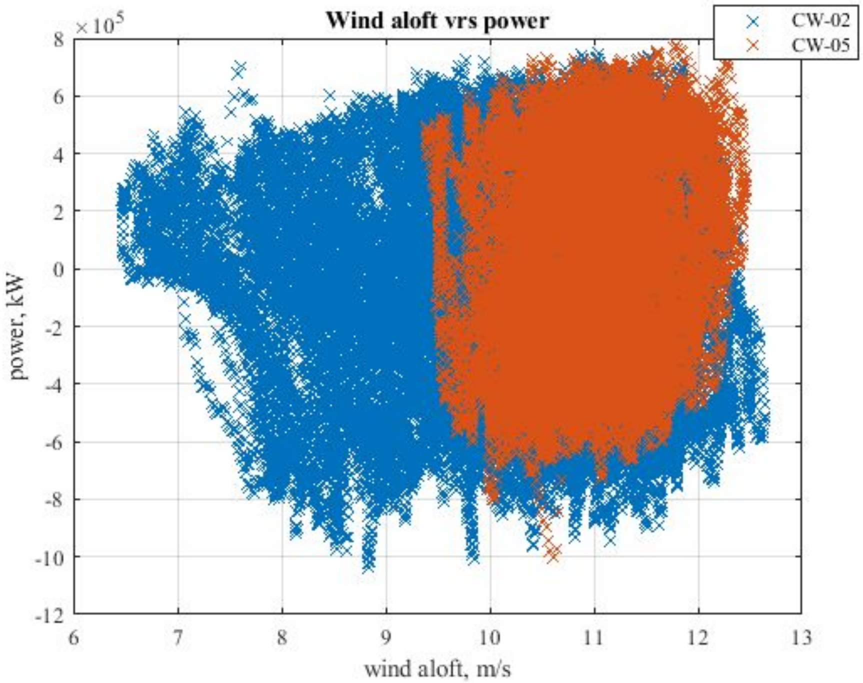
V1/V2 Playbook Playbook Observations - Azimuth

- Azimuth is within limits
  - Now we are saturated less
  - Azimuth range is less with the decreased loop sizes



V1/V2 Playbook Observations - Power Range

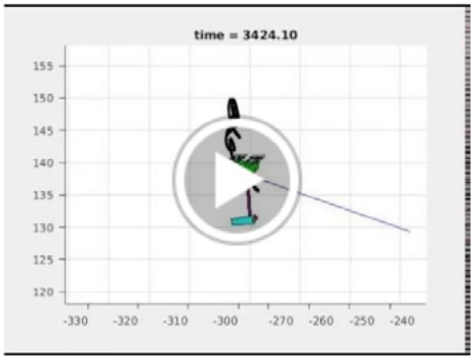
- Still a large range between min and max power but min power increased slightly

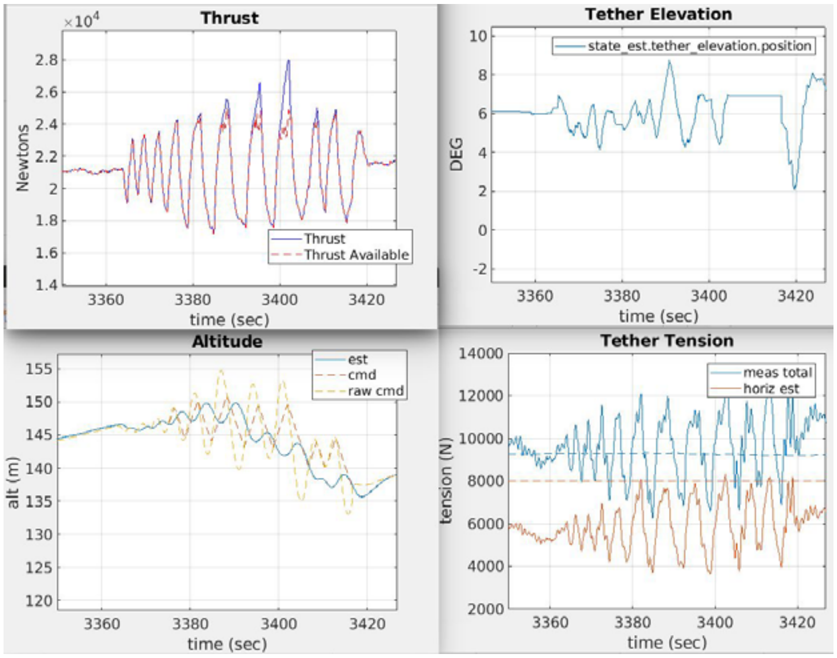


Hover Instability Showed Up Again During Transform Down

- We knew this risk existed
- Feature being removed in ECR 421

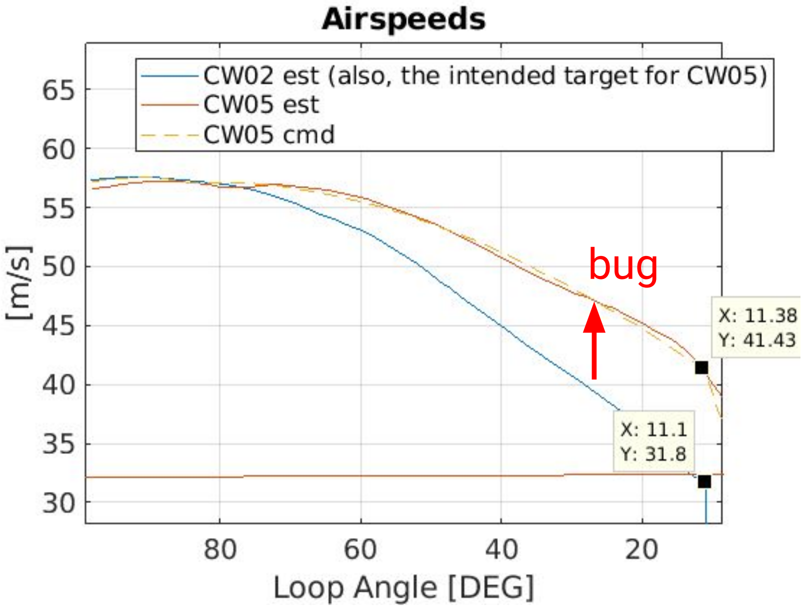
See video “20190409 CW-05 - Animation - Tether Oscillations During TransformDown” on YouTube playlist
Recommend 2x Playback Speed





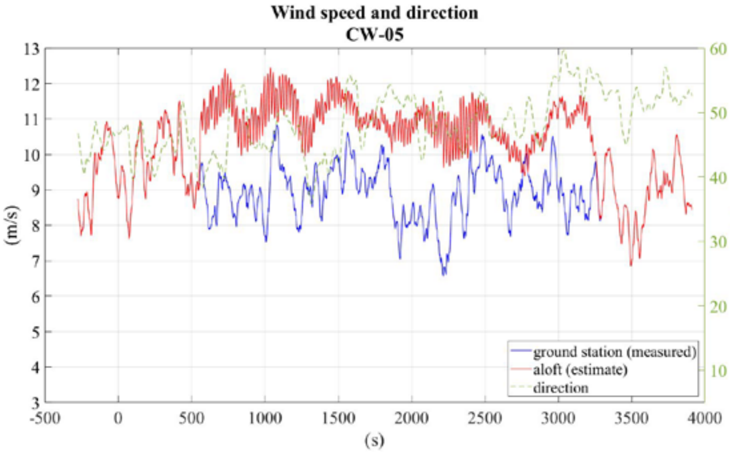
Bug In the TransOut Airspeed Command Code

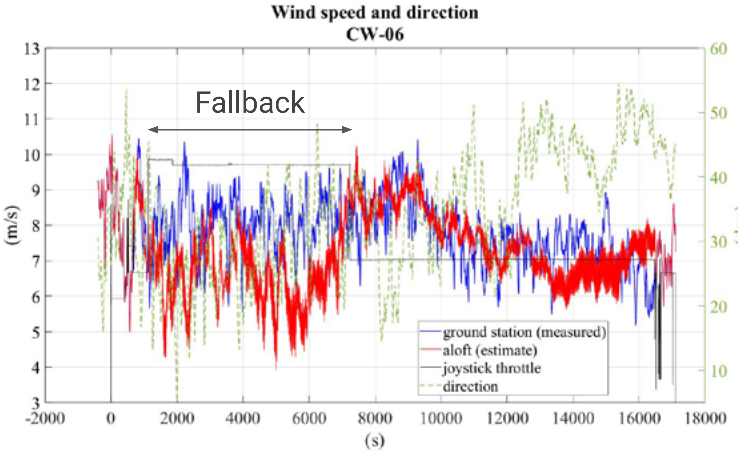
- Typo Bug in ECR 406 code
- Causes faster airspeed cmd than intended
    - Therefore higher HoverTransout
- Batch sims showed good performance even with this bug in place.
- This cl [internal ref] fixes the bug.
    - 50 m lower in HoverTransOut



CW-06

Wind

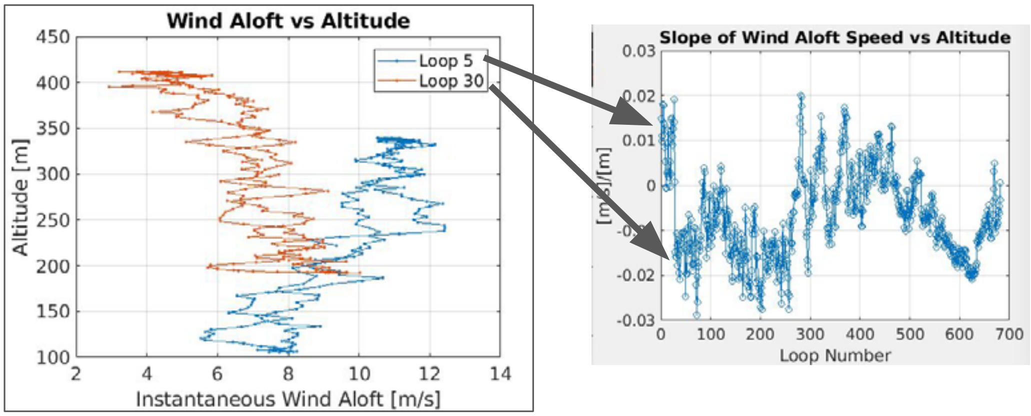


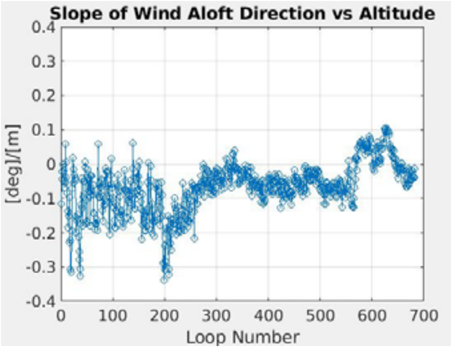


- The wind speed, particularly aloft and in the first 1000 seconds of flight, was significantly lower in CW-06 than 05, dipping down to 5 - 6 m/s.
- The 5 m/s wind speed aloft (this is the lower end of the wind envelope) seems to be a limit that we shouldn't break with the V1/V2 playbook.
- Recall that the limits of the Min Airspeed scoring function were re-adjusted after flying too slowly in CW-04, but the playbook wasn't.

Shear and Veer as Measured by the Pitot

- Big changes in shear across this flight
- Veer seems to settle down around Loop 257



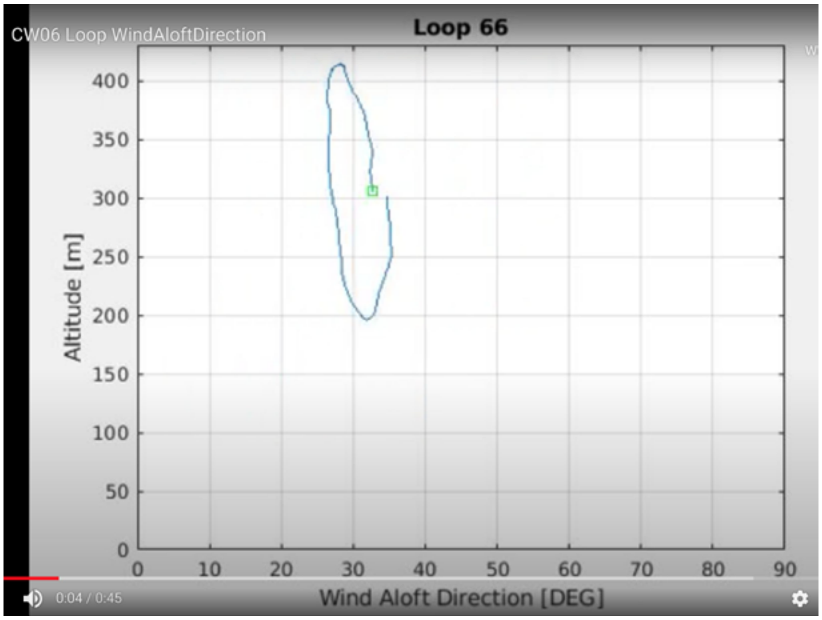


Wind Aloft Direction - Strange Looking Veer

The data suggests that sometimes the wind direction depends on the kite’s azimuth position! (Loop 18, 19)

Pause the video “20190418 CW-06 - Animation - Observing Wind Veer in Crosswind” and then use . and , to move one frame forward or backward. (YouTube playlist).

Green square indicates the start of the loop (9 o’clock)



Animation of Wind Aloft Estimate - View From Above

See video “CW06 Wind Aloft TopView” [internal ref]

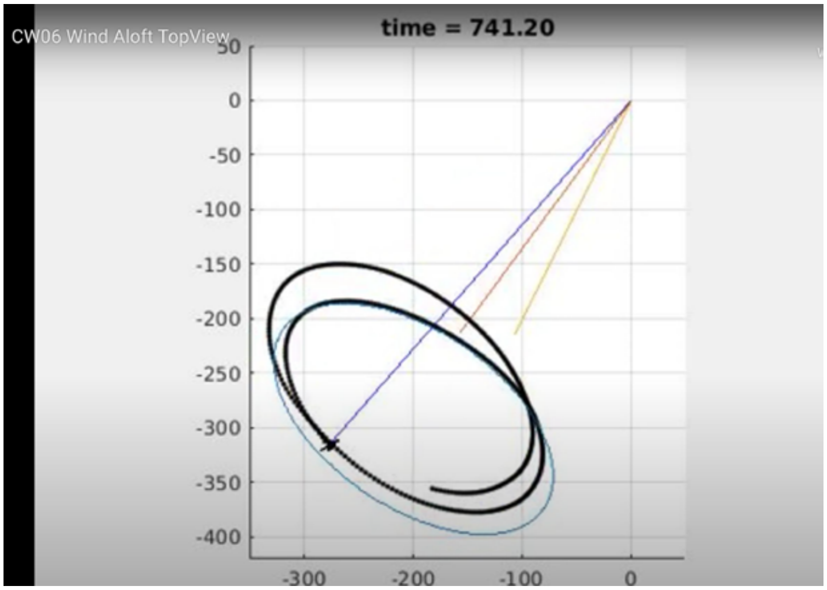
Blue: Tether

Yellow: wind_aloft_g.vector_f

Red: wind_aloft_g.vector_f_slow

Wind vector length is multiplied by 30 to make it visible.

Notice the huge direction swings between upstroke/downstroke.
How much of this is real?



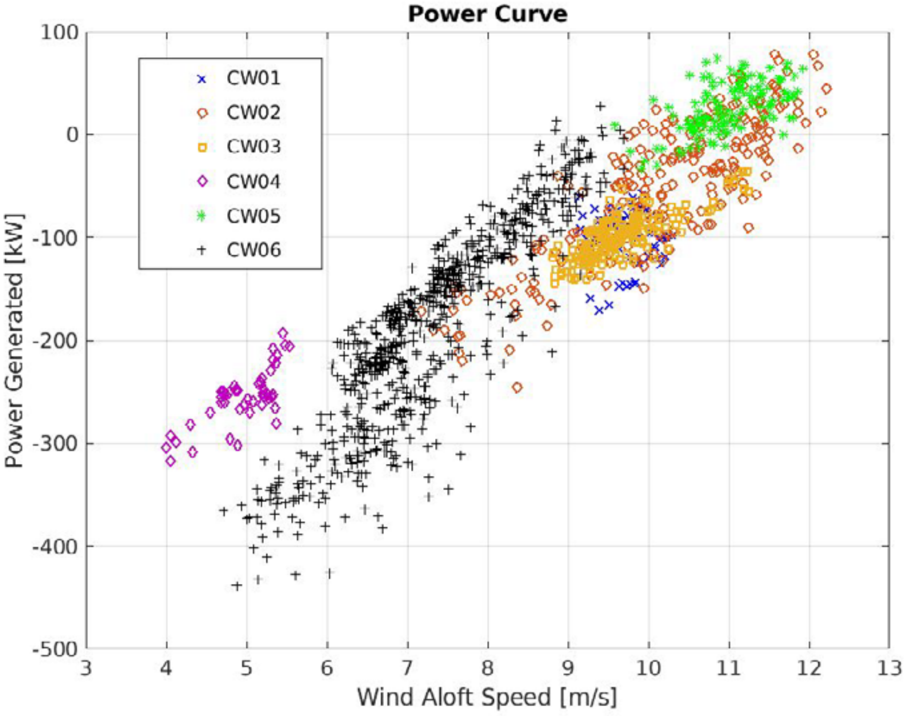
Power Curve

More power produced than CW02 at wind speeds between 7 and 9.5 m/s

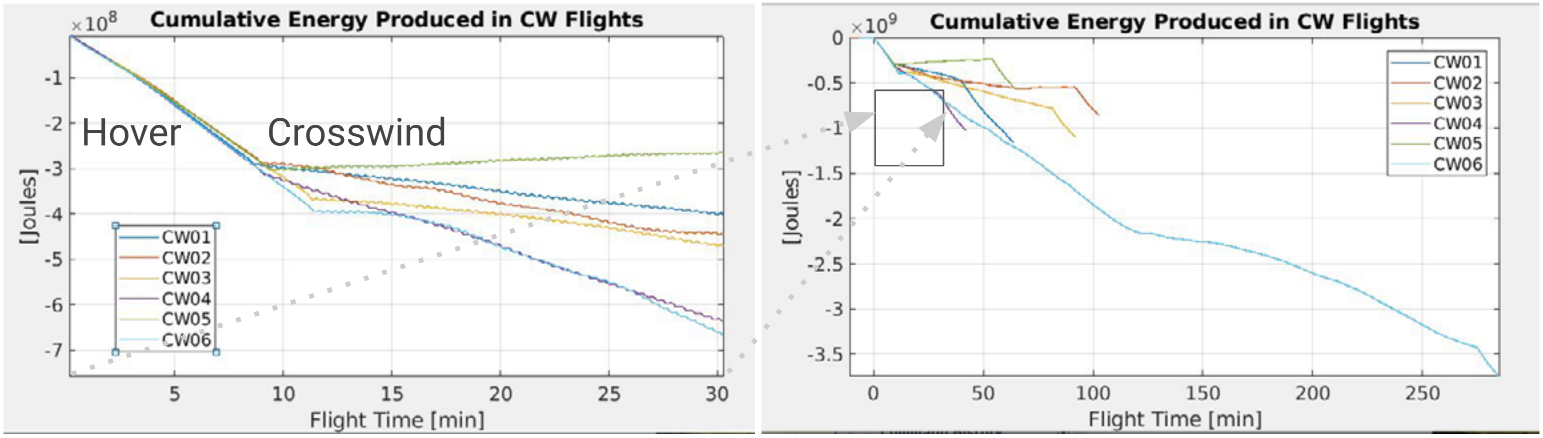
- This is a positive effect of V2/V1 Playbook merge (we assume)

Less power than CW04 at low wind

- Because we had to switch to Fallback Playbook (there was bad flight quality)
- Perhaps V2/V1 Playbook is more dangerous at low wind?



Cumulative Energy Produced (The Carbon Neutral? Plot)



Detail of 1st Half Hour

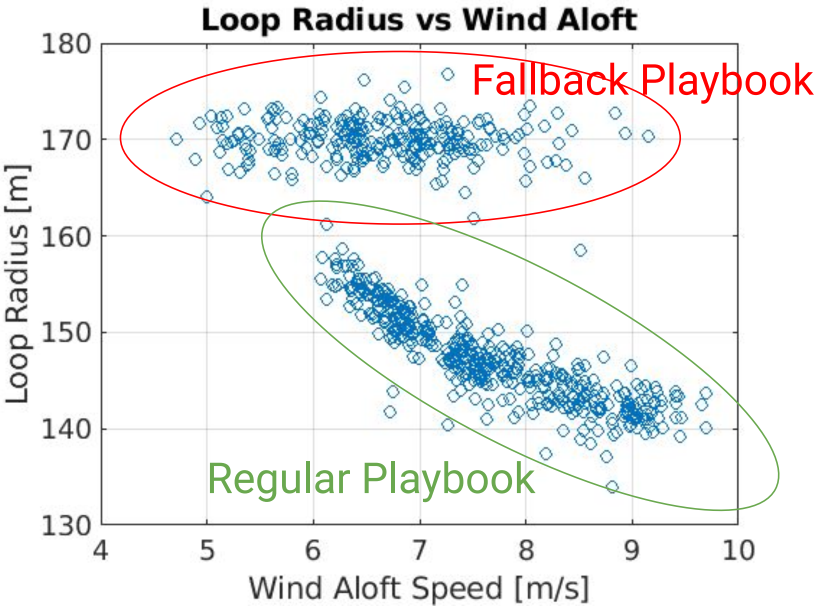
Full Flight Records

Flight Statistics

Flight	Total Flight Time (min)	Number of Loops	Crosswind Average Wind Aloft [m/s]	Crosswind Average Power [kW]	Launch to Crosswind Duration [min]	Crosswind Duration [min]	HoverTransOut to Perch Duration [min]
CW01	61	81	9.7	-98	8.6	31.1	21.6
CW02	103	222	10.1	-53	8.9	82.8	10.8
CW03	92	185	9.6	-99	11.7	69.1	10.9
CW04	42	47	5	-255	9	21	12.1
CW05	65	130	11	26	9.3	44.5	10.85
CW06	285	682	7.23	-192	11.4	263.7	9.9
Sum	648	1347				512.2	

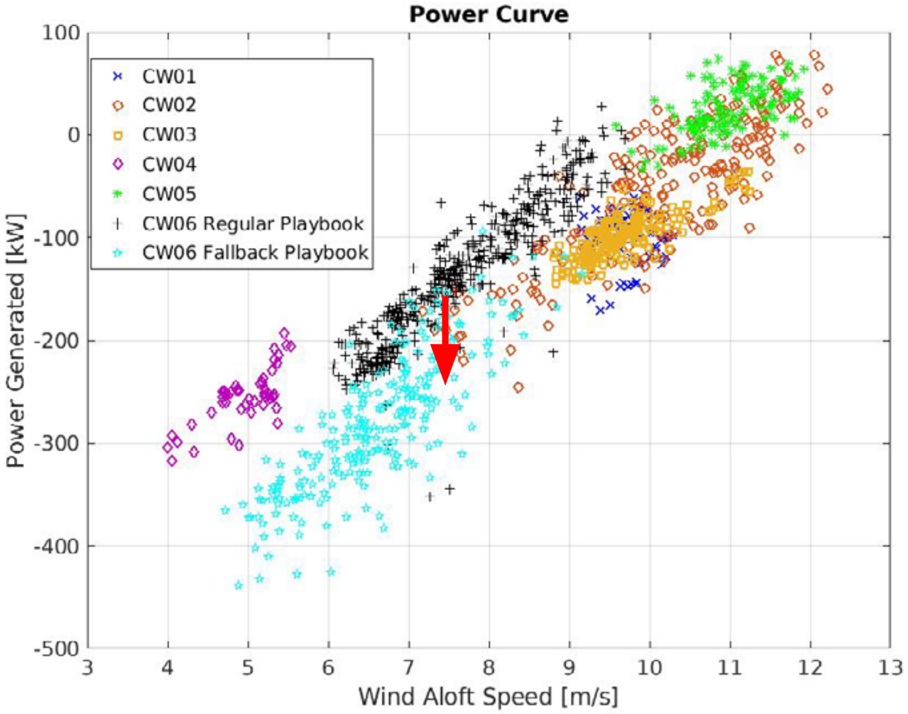
Switched to Fallback Playbook Due to Poor Flight Quality

- Fallback Playbook is supposed to be safer
    - Larger loop radius
    - Higher loop elevation
    - Constant alpha, beta
- We only have Fallback loops at wind aloft <6 m/s
    - There is overlap at higher wind speeds



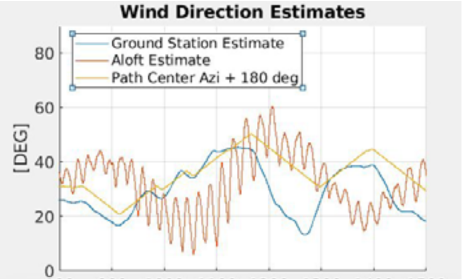
Fallback Power Curve

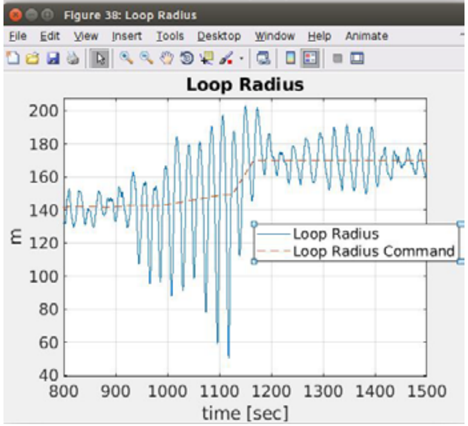
Switching to Fallback seems to cost between 50 and 100 kW



Worst Flight Quality of the All Modes Program So Far

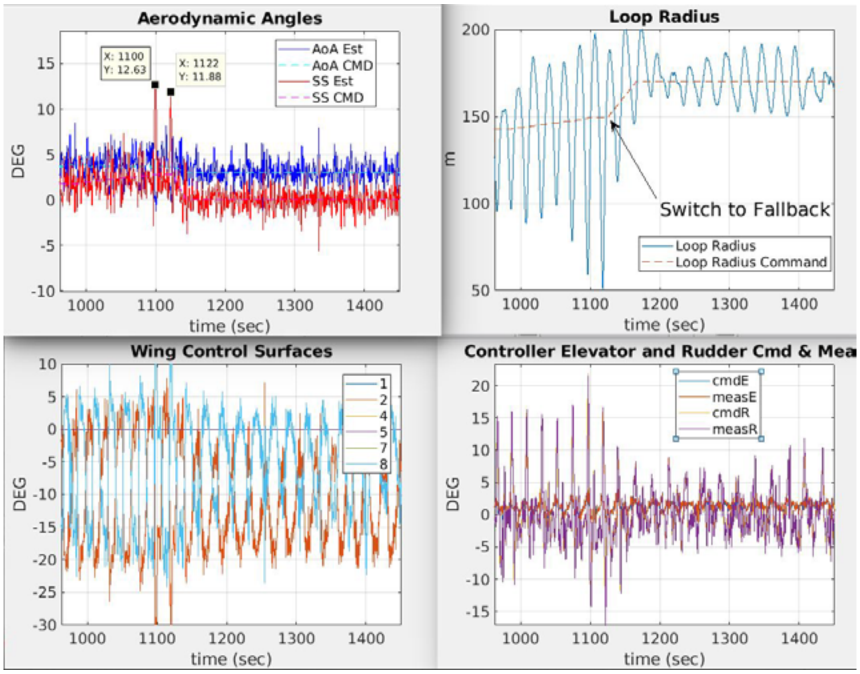
- Switched to Fallback after observing scary loops
    - Huge path tracking errors
    - Kite was “cutting the corner” near 12 o’clock
- Hypothesis: This has to do with
    - Shear + Veer + Path Being Not Downwind
    - Have not shown this to be true, however
    - MUST have to do with wind conditions (the control laws are deterministic!!!)
- C-sim does NOT show this behavior when using wind replay (does not include veer)
    - Still working on reproducing it manually.





Example of Poor Flight Quality Prior to Fallback Switch

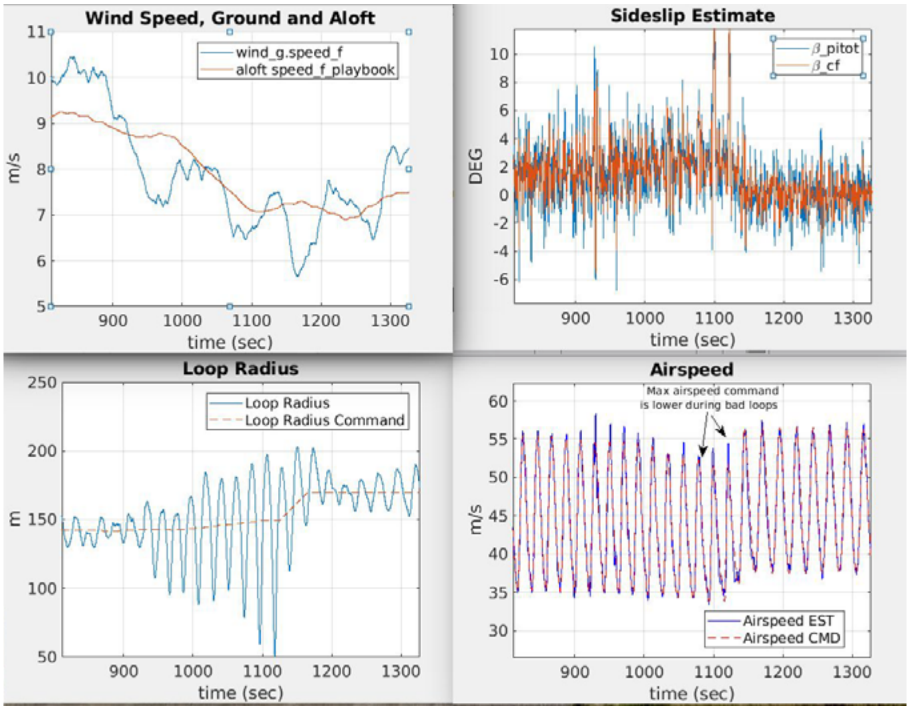
- Sideslip excursions beyond 10 degrees!
- Saturated ailerons!
- Path errors near 100 m!
- Huge rudder use!



Flying Slower Doesn’t Help Us Fly Well

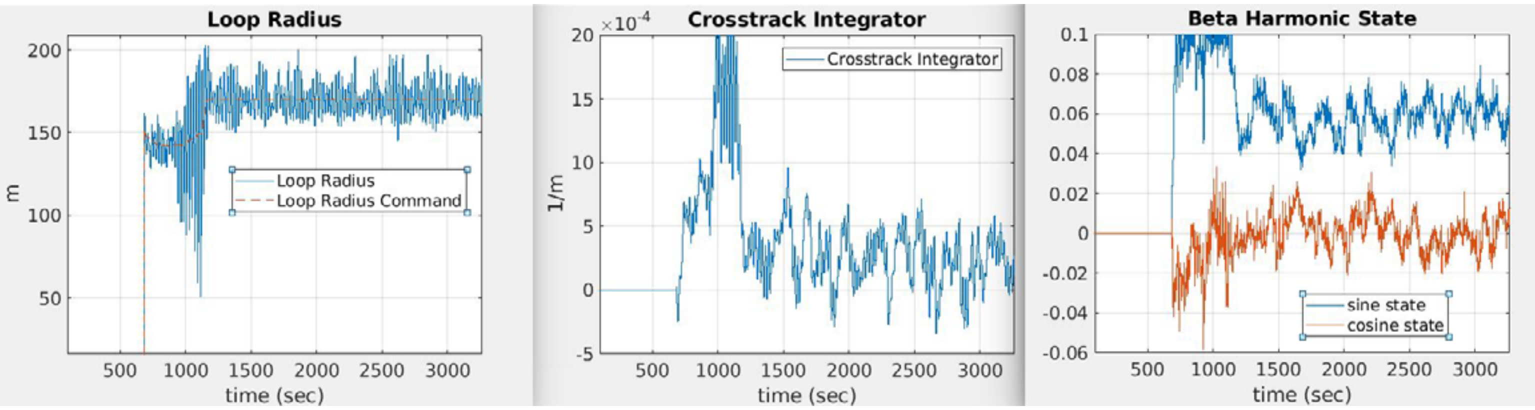
Worst loops were also the loops with the lowest max airspeed command.

This decrease in max airspeed command seems to come with the decreasing wind aloft speed estimate used in playbook.



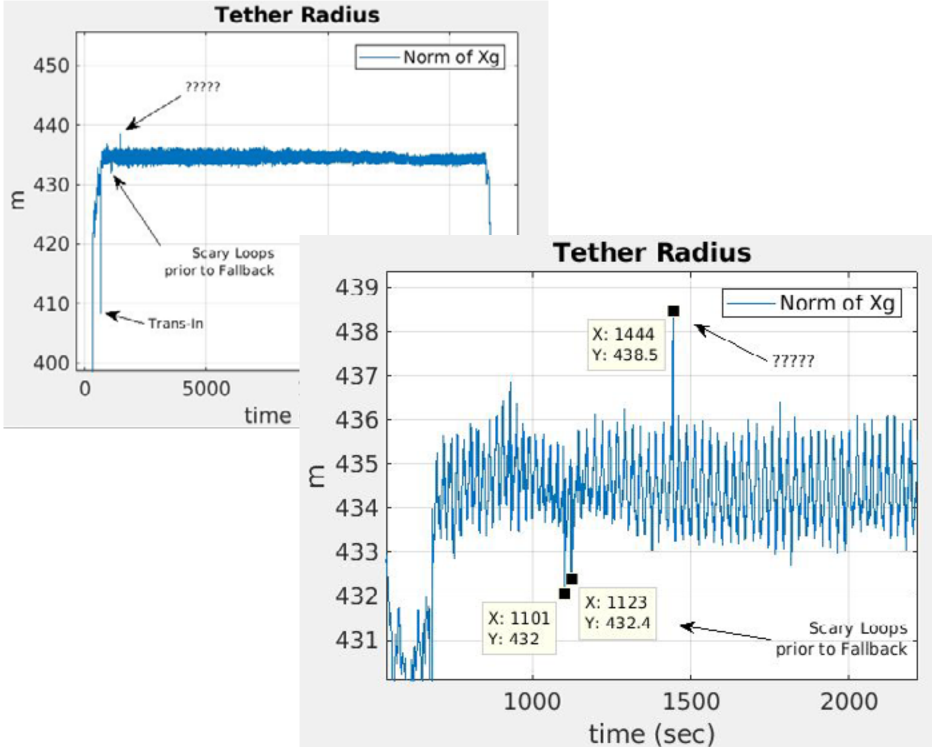
Our Crosswind Controls “Patches” Saturated

Both the Harmonic Gain for Sideslip and the Crosstrack Integrator saturated during our poor flight quality at the start of the flight.



Tether Sphere Deviation

- Worst sphere deviation is about 2.4 m below the Crosswind mean.
- (RPX09 crash was nearly 8 m below)
- No idea what the strange increase in radial position is about. ???
    - UPDATE! Solved. GPS trouble

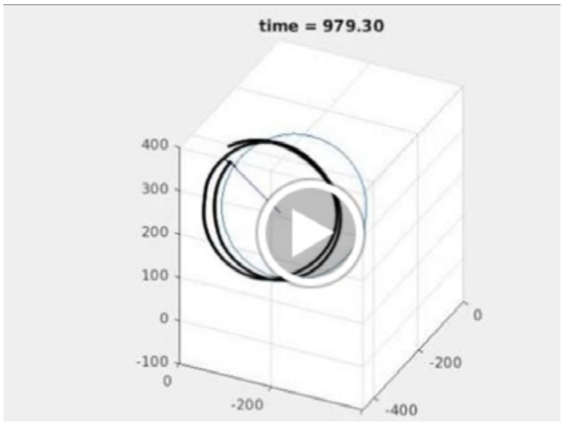


Crosswind Is Harder to Fly During Positive Azimuth Slews

- Bottom of the loop requires the most turning effort (fighting gravity)
- Paths that slew negative effectively increase the radius in this part of the loop (easier)
- Paths that slew positive decrease the radius in this part of the loop (harder)
- Our worst CW06 loops are during positive azimuth slews

Recommend 2X playback speed.

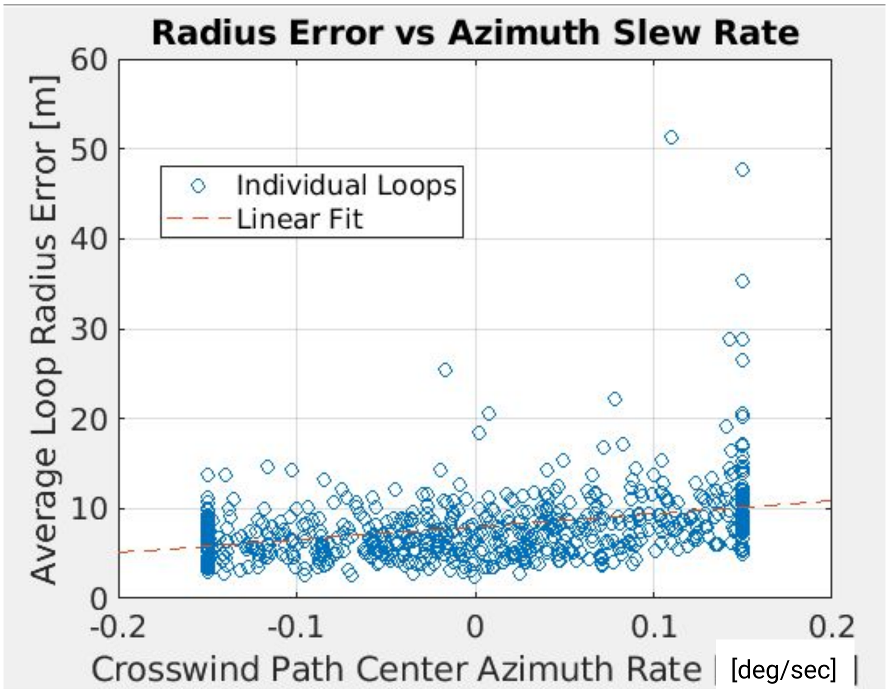
Positive azimuth slew direction ⟶



(video “20190418 CW-06 - Animation - Kite Motion During Crosswind” on YouTube playlist)

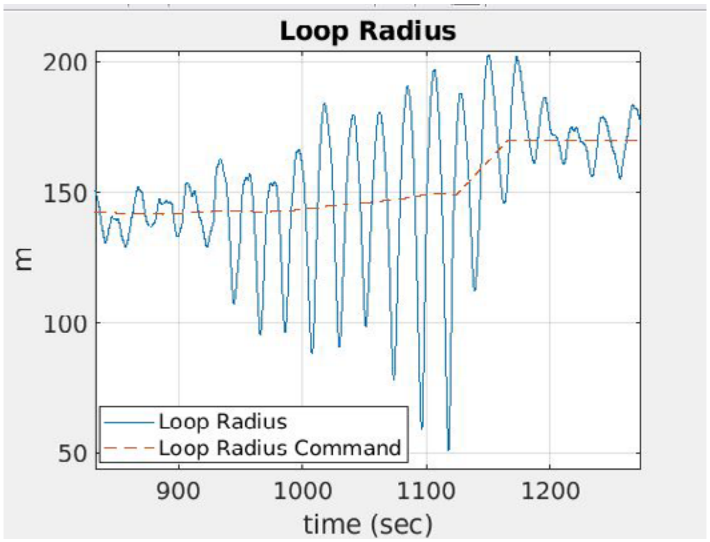
Radius Errors vs Crosswind Path Azimuth Rate

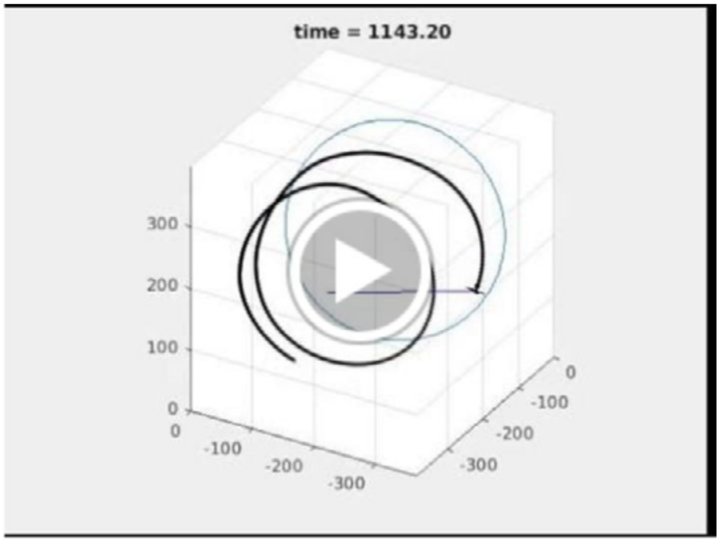
Our worst loops are during positive slews.



Transitioning Into and Out of Bad Flying Quality

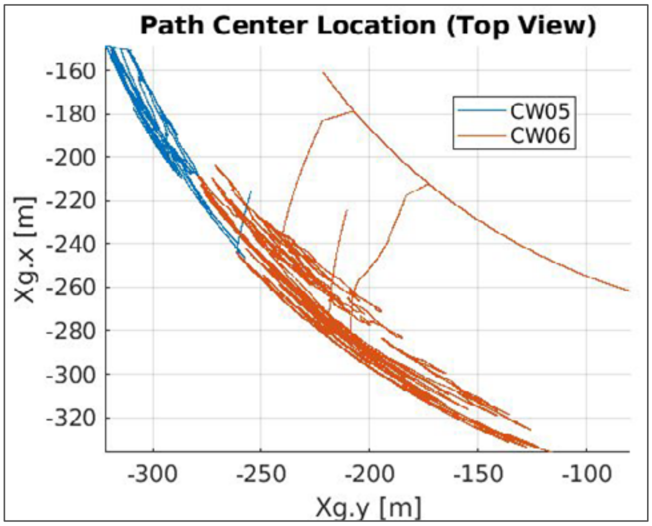
This much-faster-than-realtime animation [internal reference] shows the kite entering poor flight quality as the path slews right then recovering on the switch to Fallback

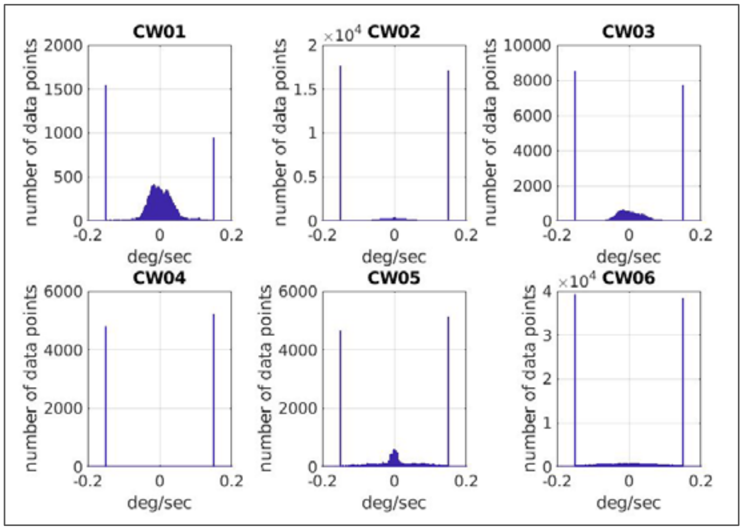




CW06 Had More Path Slewing Than CW05

Histograms of azimuth slew rate show some flights spend all their time on the rate limit



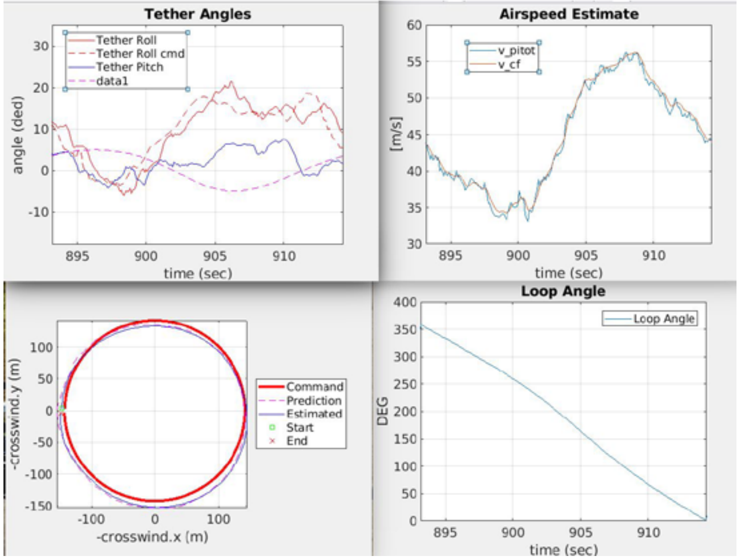


Flying a Bad Circle Distorts Our Outer Loop Commands

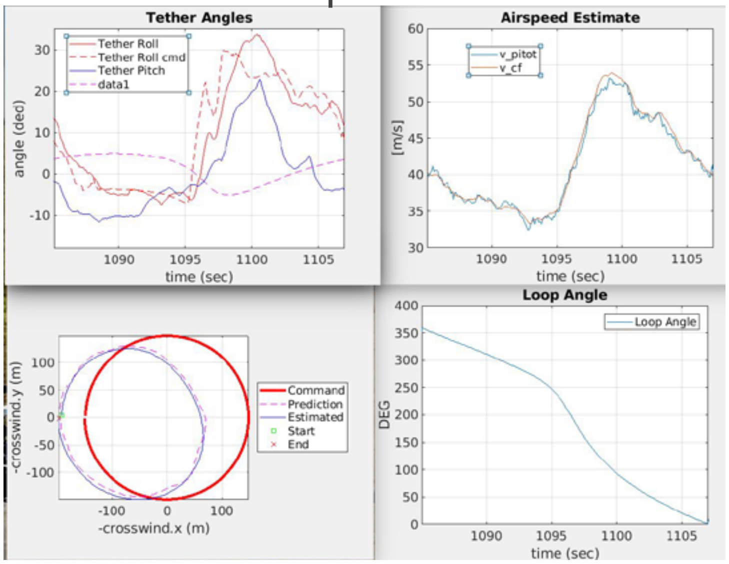
- Things which are scheduled on loop angle:
    - Airspeed CMD
    - Alpha CMD
    - Tether Roll Feedforward CMD
    - Detwist
- Loop angle is calculated based on kite position relative to the *commanded* circle center
    - Changed from velocity-based calculation after RPX05 due to worries about discontinuities in GPS velocity estimates (“rabbit hops”)
- When the kite cuts across the circle, the loop angle gets distorted and so do these commands
    - Velocity-based angle may be what we want in these cases!

Example of Loop Angle Distortion When Flying a Bad Circle

Loop 10

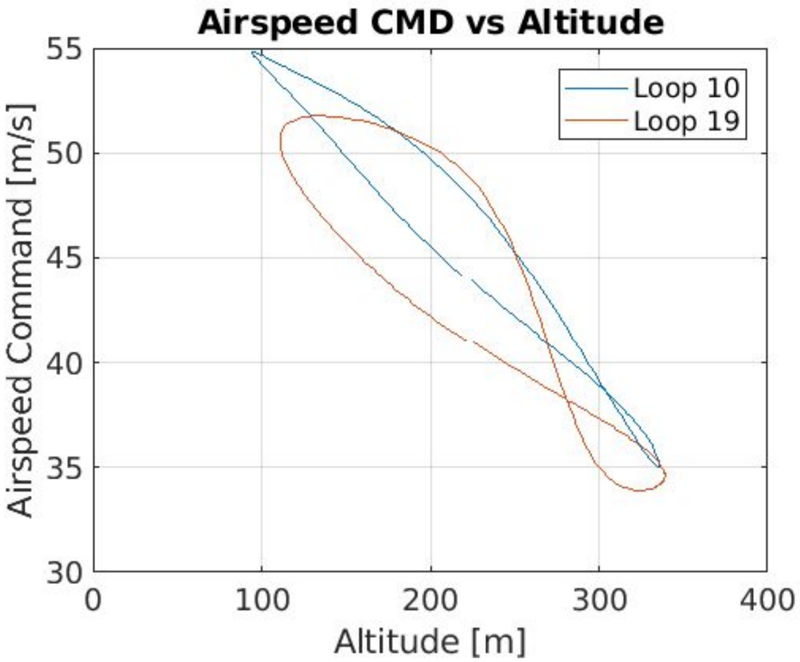


Loop 19



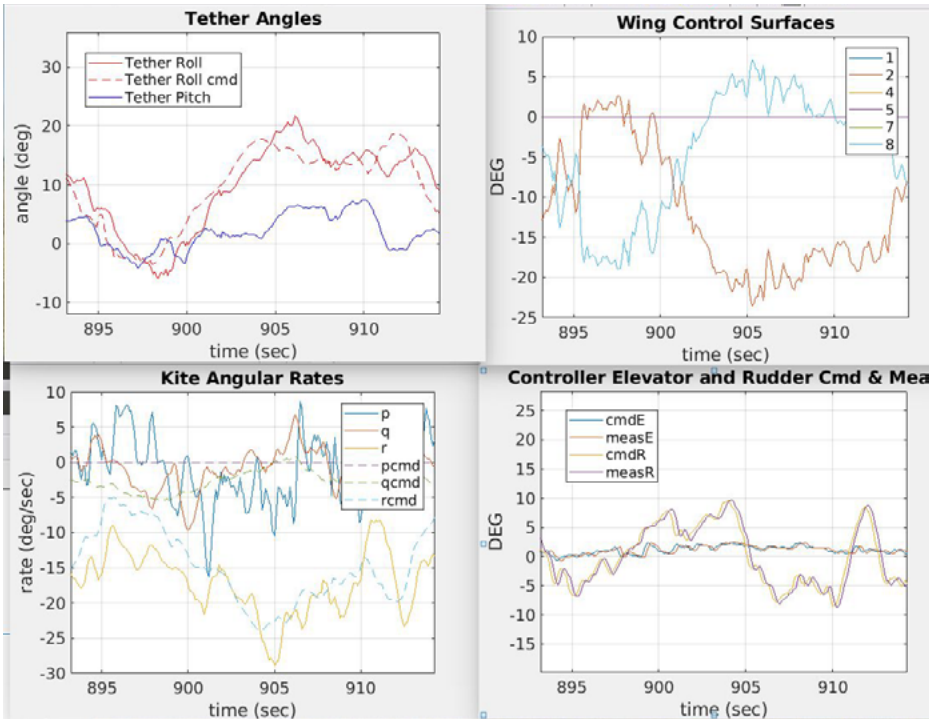
Airspeed Command vs Altitude is getting Badly Distorted

- The airspeed command vs altitude is much more important than airspeed vs loop angle



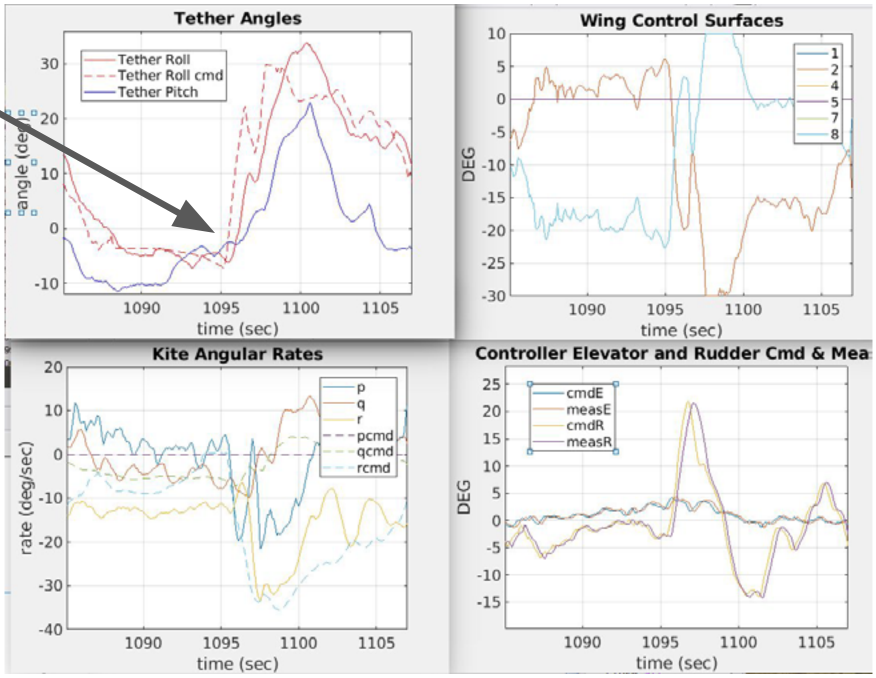
Good Flight Quality: Loop 10

- Things look okay here.
- This is the regular playbook before we had trouble.
- Contrast this with the next slide.



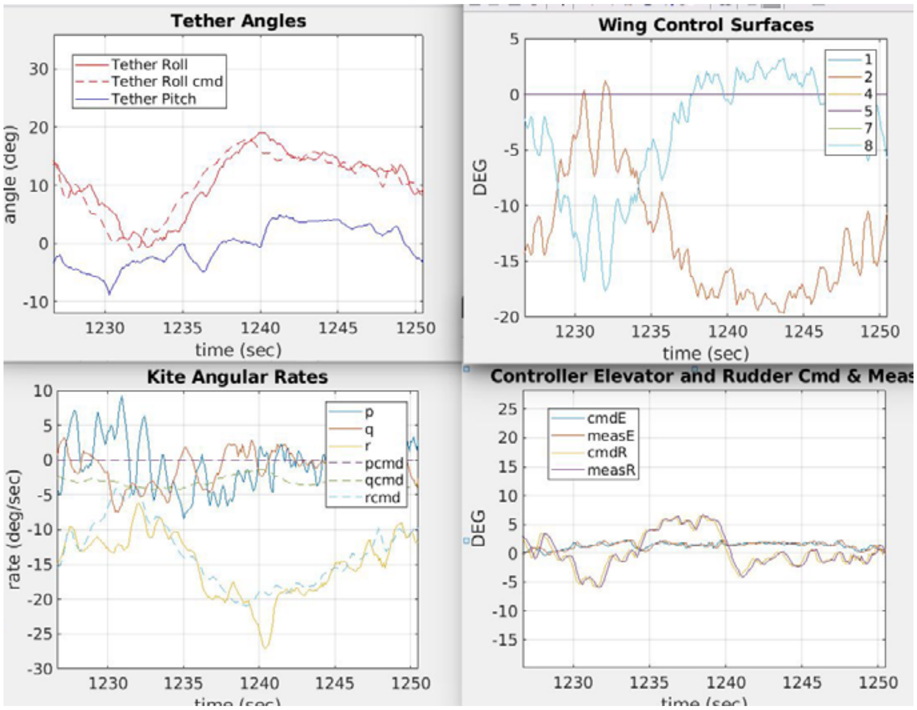
Poor Flight Quality: Loop 19 (Ridiculous Roll Rates)

- Tether roll command has an extremely sharp corner
    - Big roll rates are hard for our inner loops
    - CNp term in particular
- Finding a way to calm the tether roll command time history will help improve flight quality



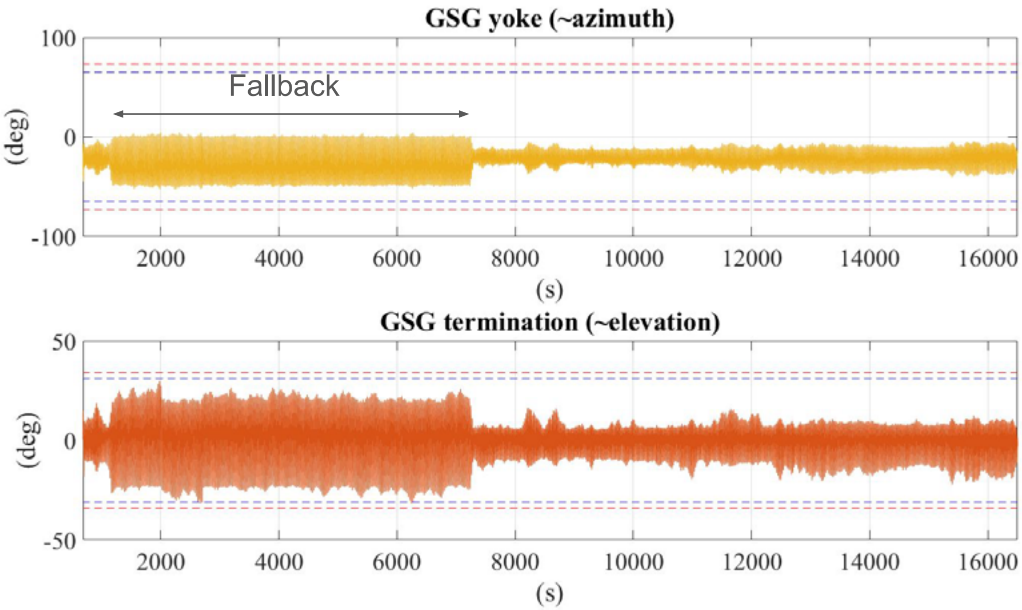
Good Flight Quality: Loop 25

- Contrast this good loop with the previous slide
- This is Fallback



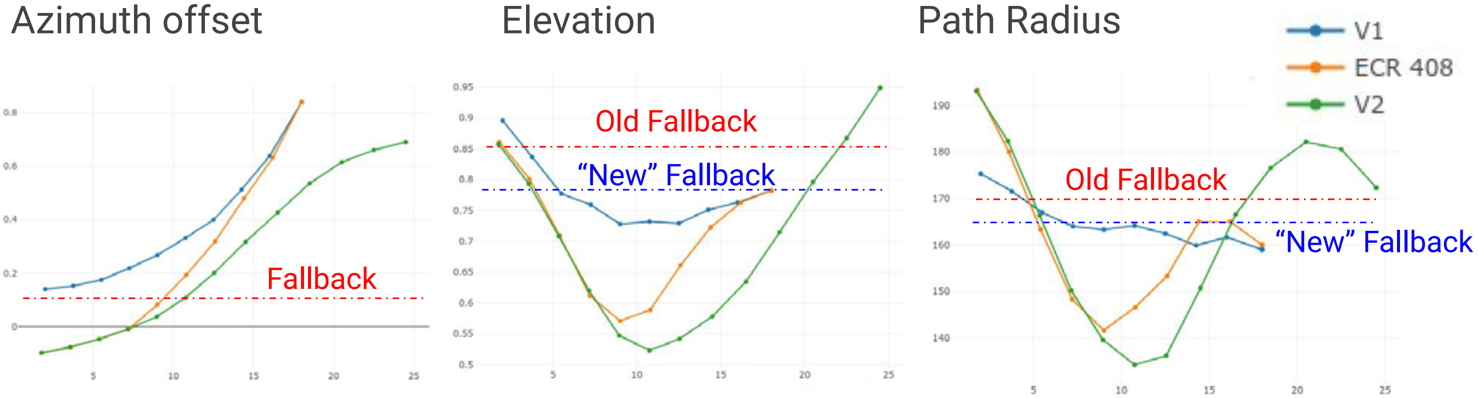
GSG Angles in Crosswind

- The GSG termination warning limit was exceeded a couple of times while flying on fallback.
- Recall fallback parameters:
  - Path radius target: 170 m
  - Loop center elevation: 50 deg (0.87 rad)
  - Azimuth offset from downwind: 5.7 deg (0.1 rad)
- Can we increase our GSG termination angle margins by modifying the fallback outer-loop parameters? (bug 130882010)



Merged Playbook Parameters

(from ECR408: Playbook V1/V2 merge)


Azimuth offset

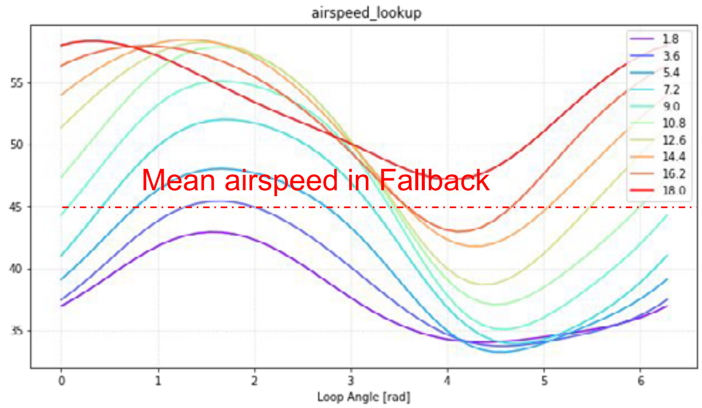
Elevation

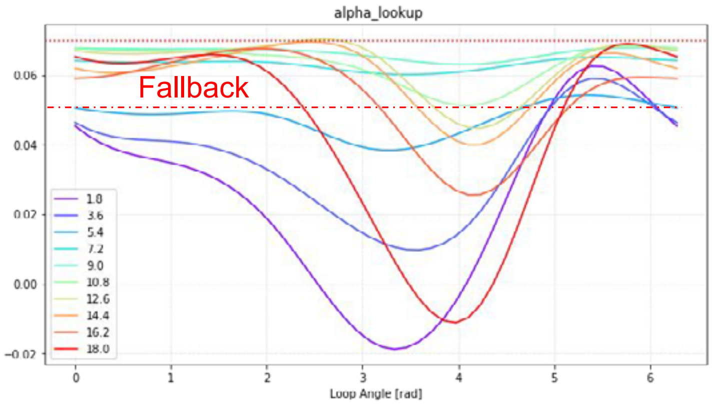
Path Radius

- The fallback parameters are currently independent of wind speed. We must find a combination of parameters that is safer than Playbook at all wind speeds.
- For instance, by decreasing the loop elevation and radius of fallback by 5 degrees (0.09 rad) and 5 meters respectively, we lose the ability to increase these parameters in case of poor flight quality in low winds (< 5 m/s) and high winds (> 14 m/s). Note that the current wind envelope is 5 to 12 m/s.
- Note also how we lose the azimuth offset when switching to Fallback in high winds.

Merged Playbook Smoothing Comparisons

(from ECR408: Playbook V1/V2 merge)

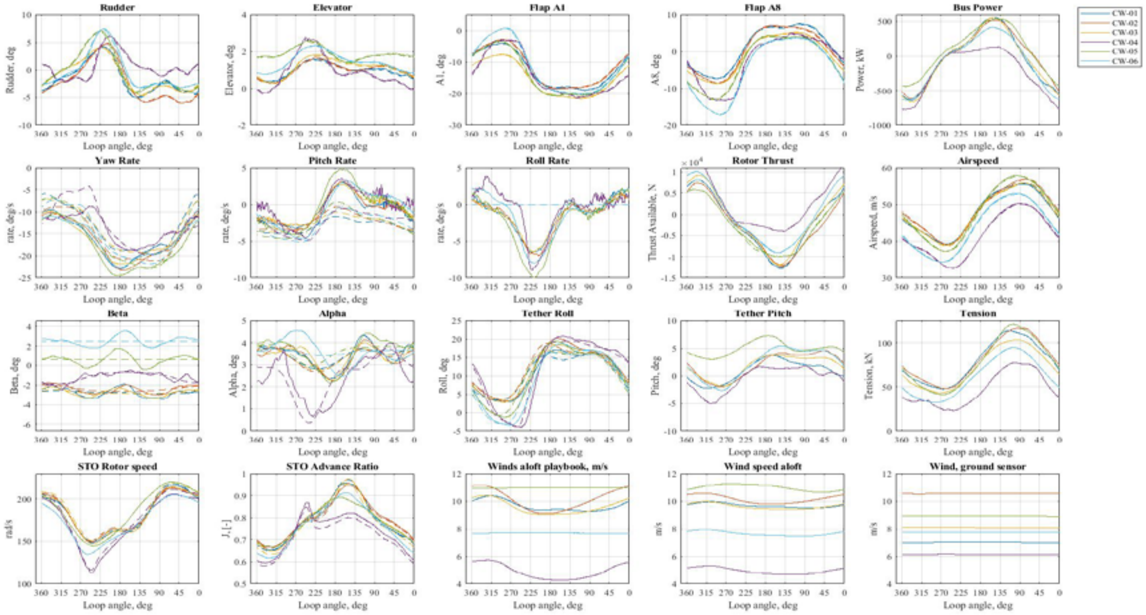




- The mean airspeed command in fallback is higher than the mean airspeed command in winds less than 9 m/s. This should be enough to improve flight quality in low winds, without changing the loop radius or path elevation.
- Removing the ability to increase the loop radius or the path elevation with Fallback in high winds remains a problem.

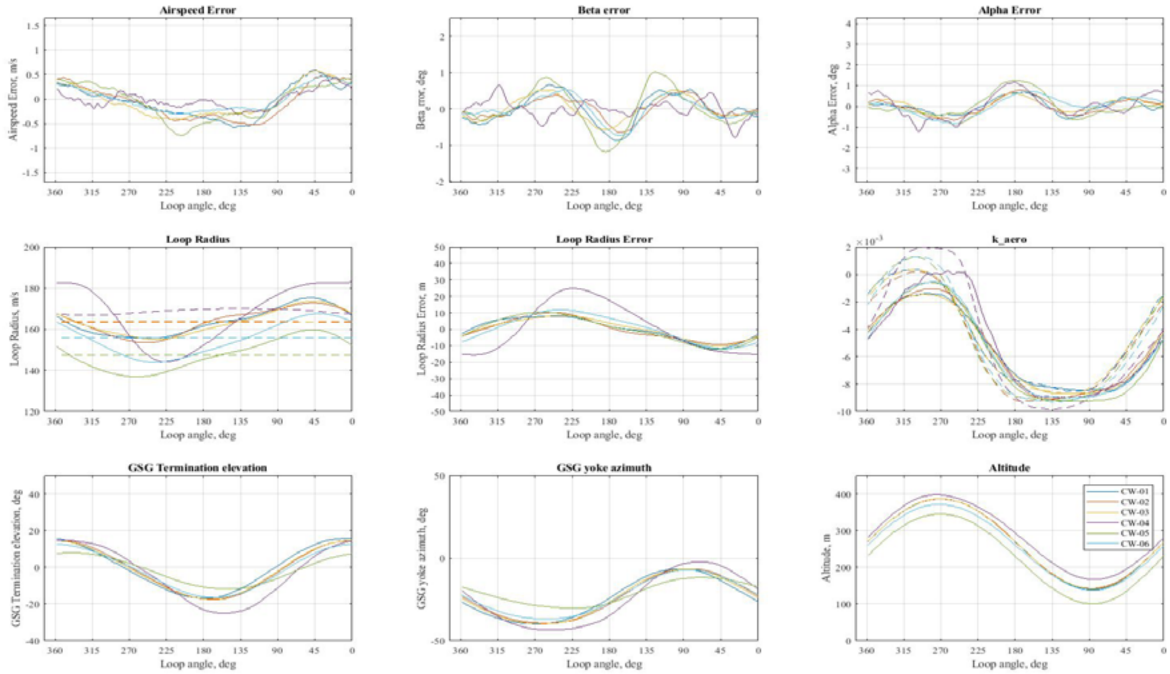
Loop Averages

Only playbook shown for CW 06

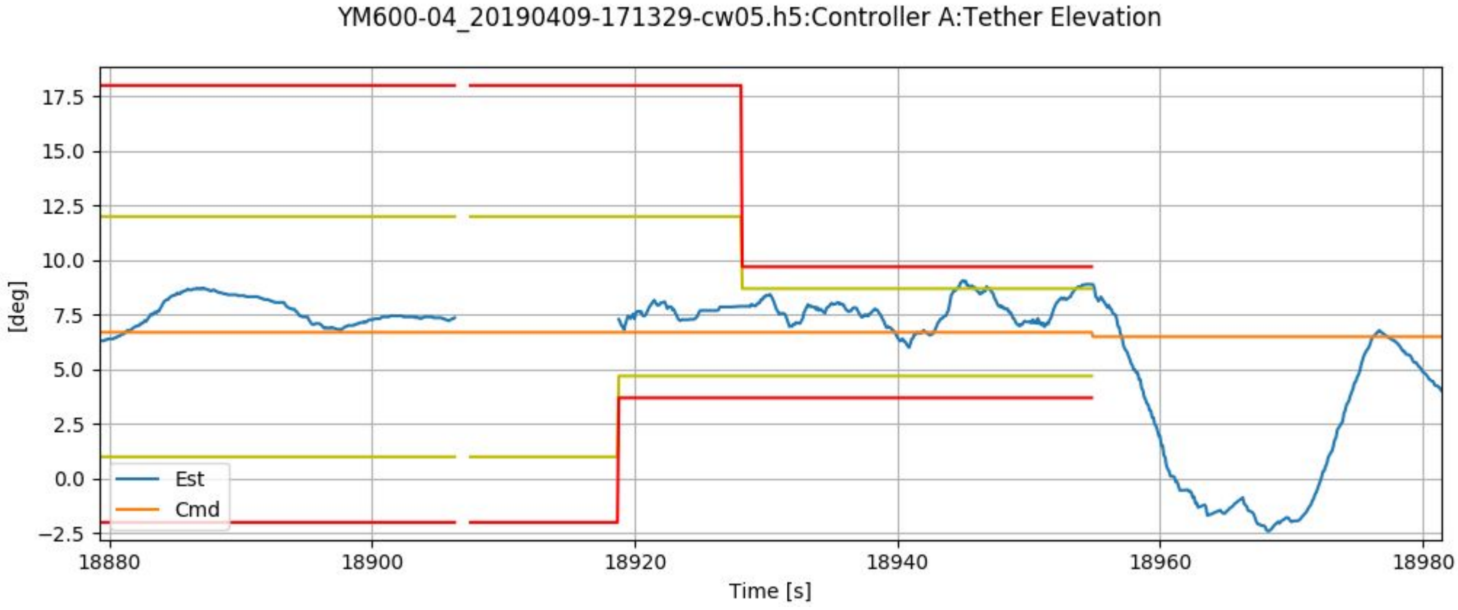


Loop Averages - Errors

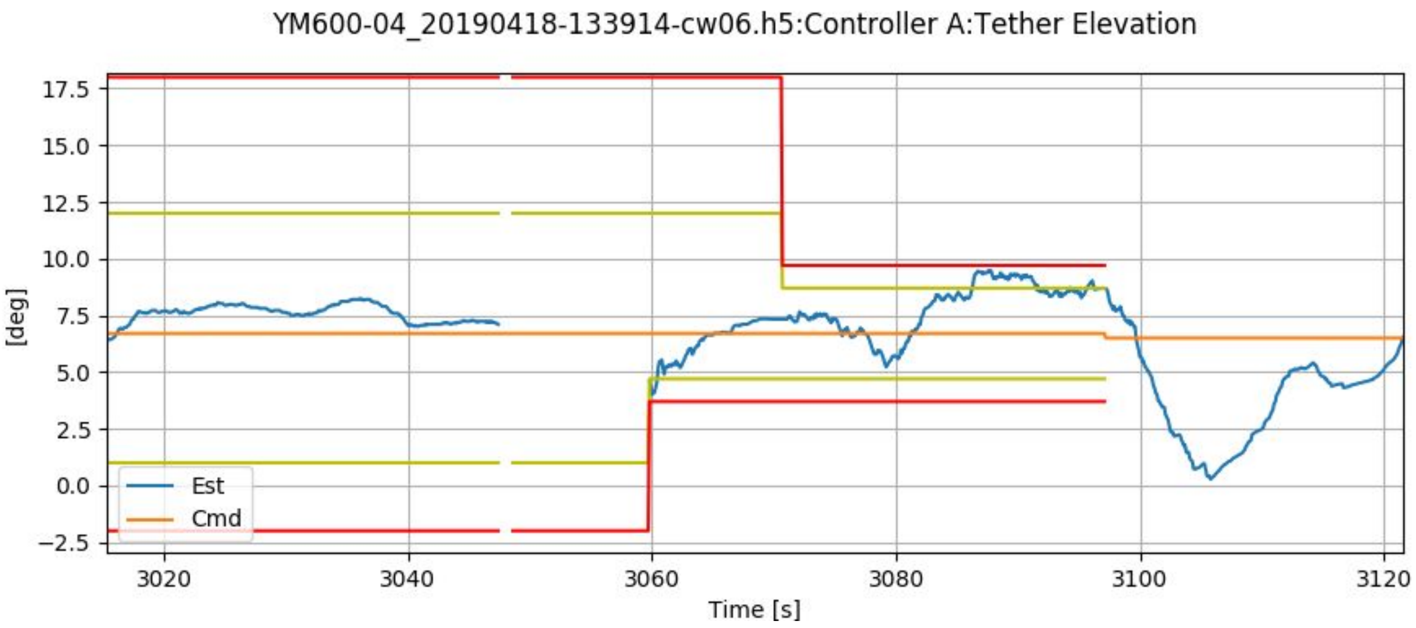
Only playbook shown for CW 06

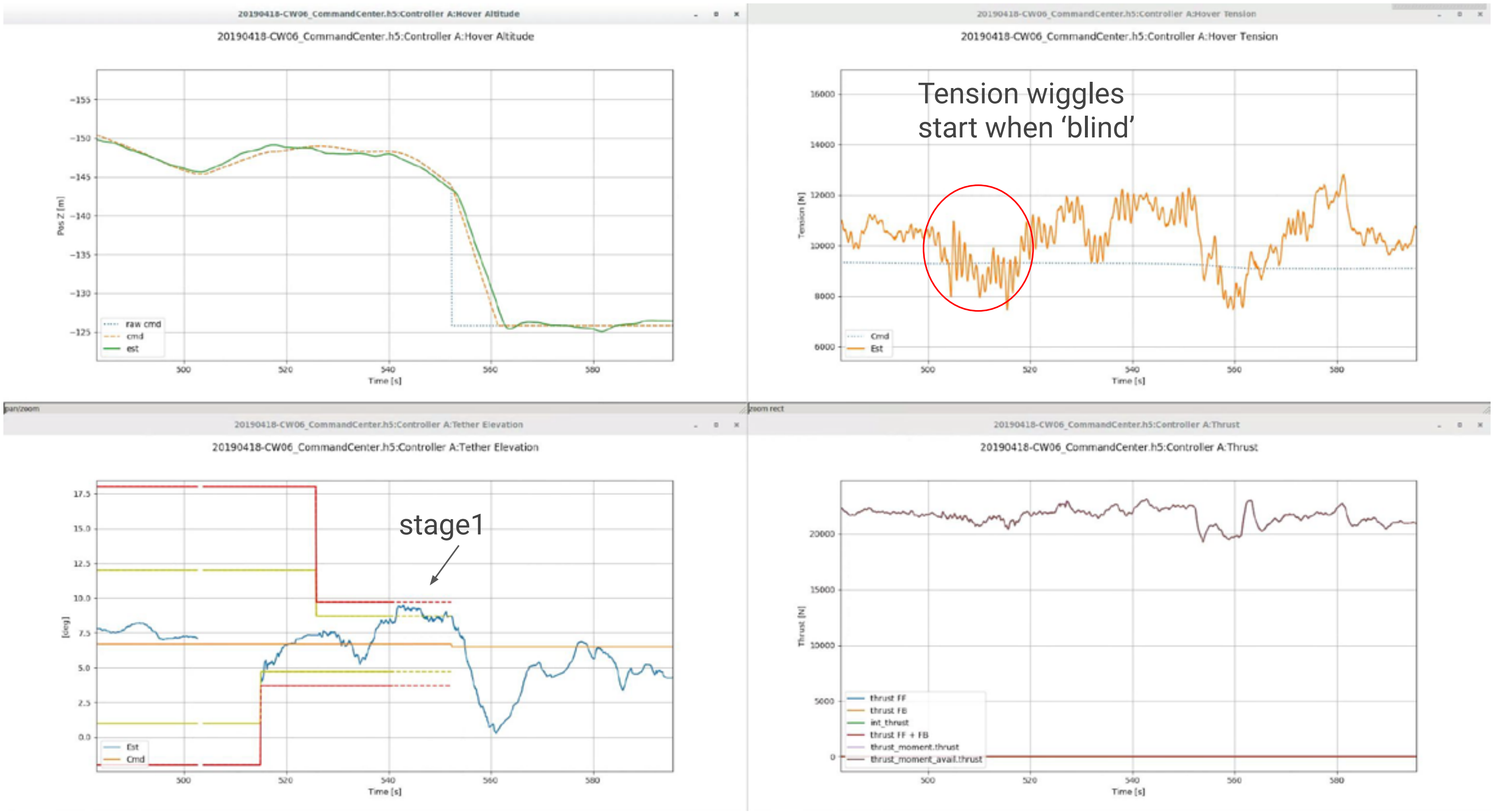


Tether Elevation during CW05 TransformUp



Tether Elevation During CW06 TransformUp

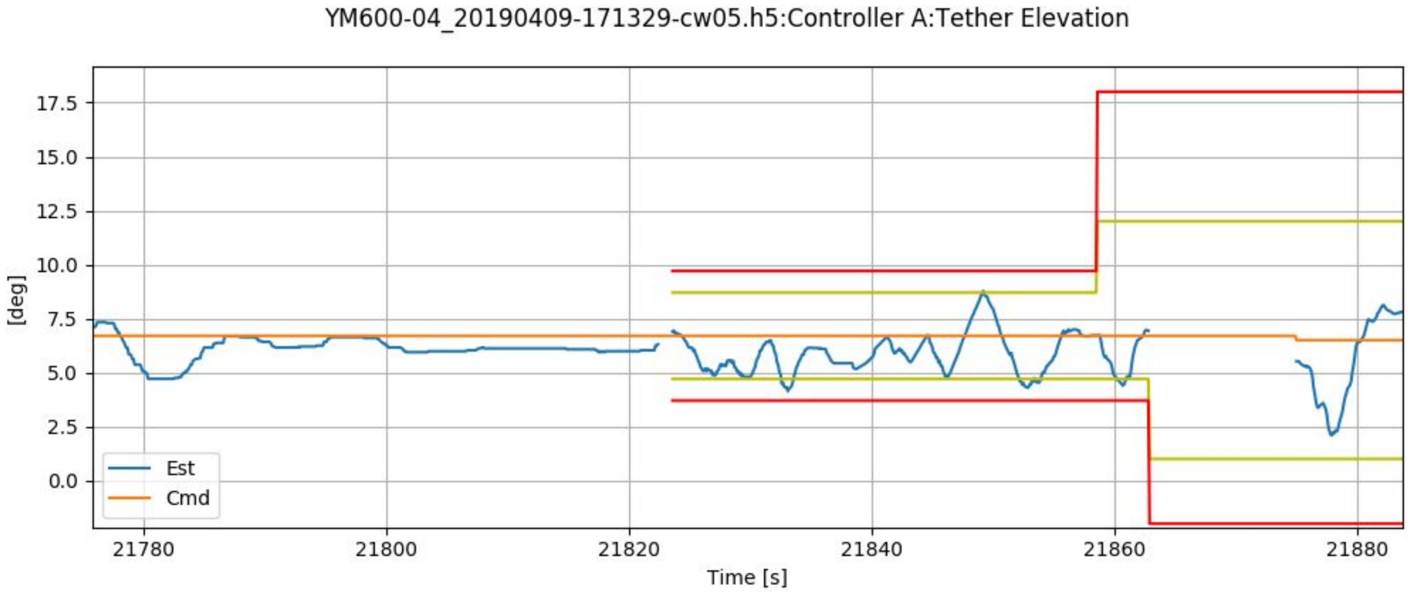




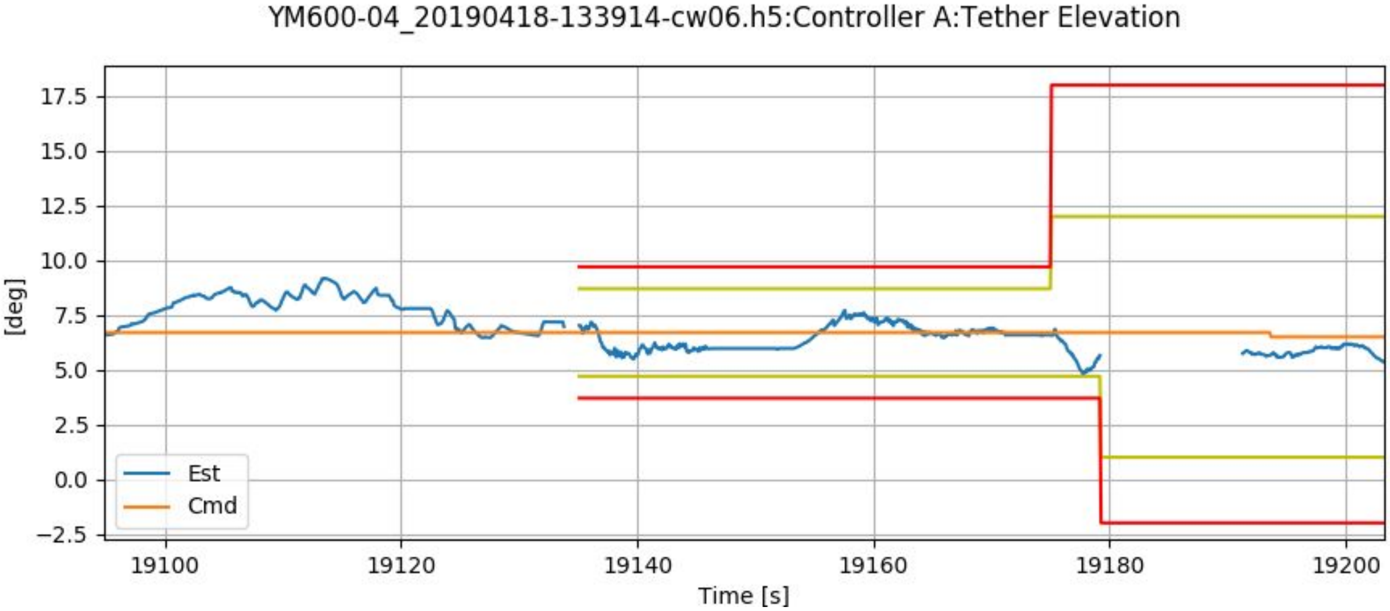
Tension wiggles start when ‘blind’

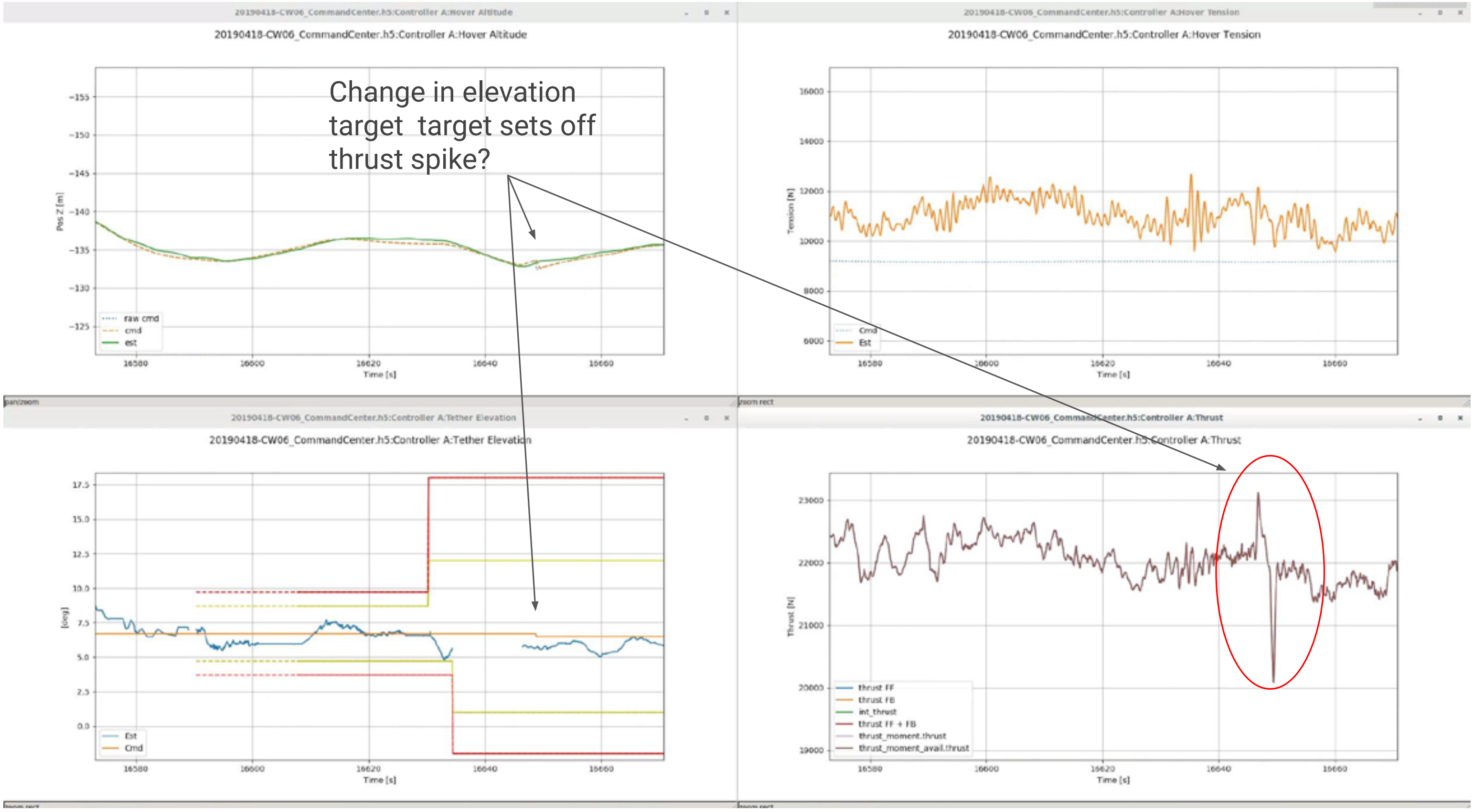
stage1

Tether Elevation During CW05 TransformDown



Tether Elevation During CW06 TransformDown

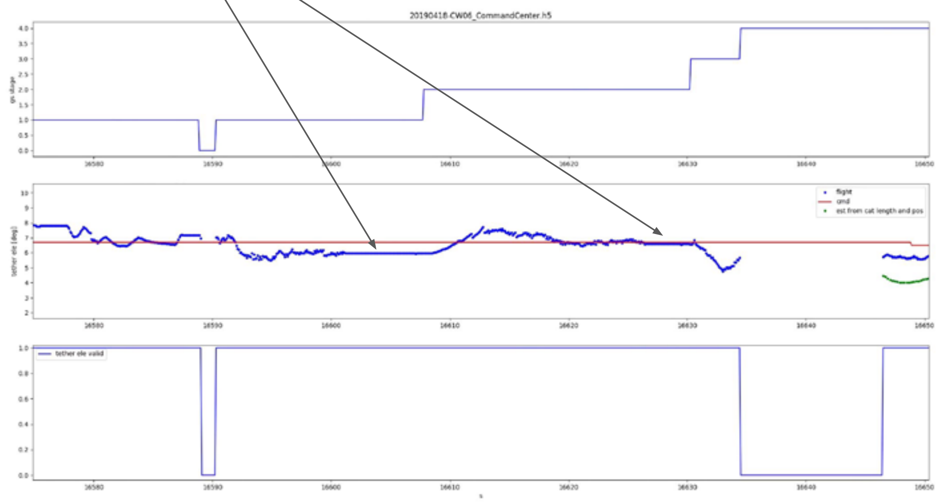




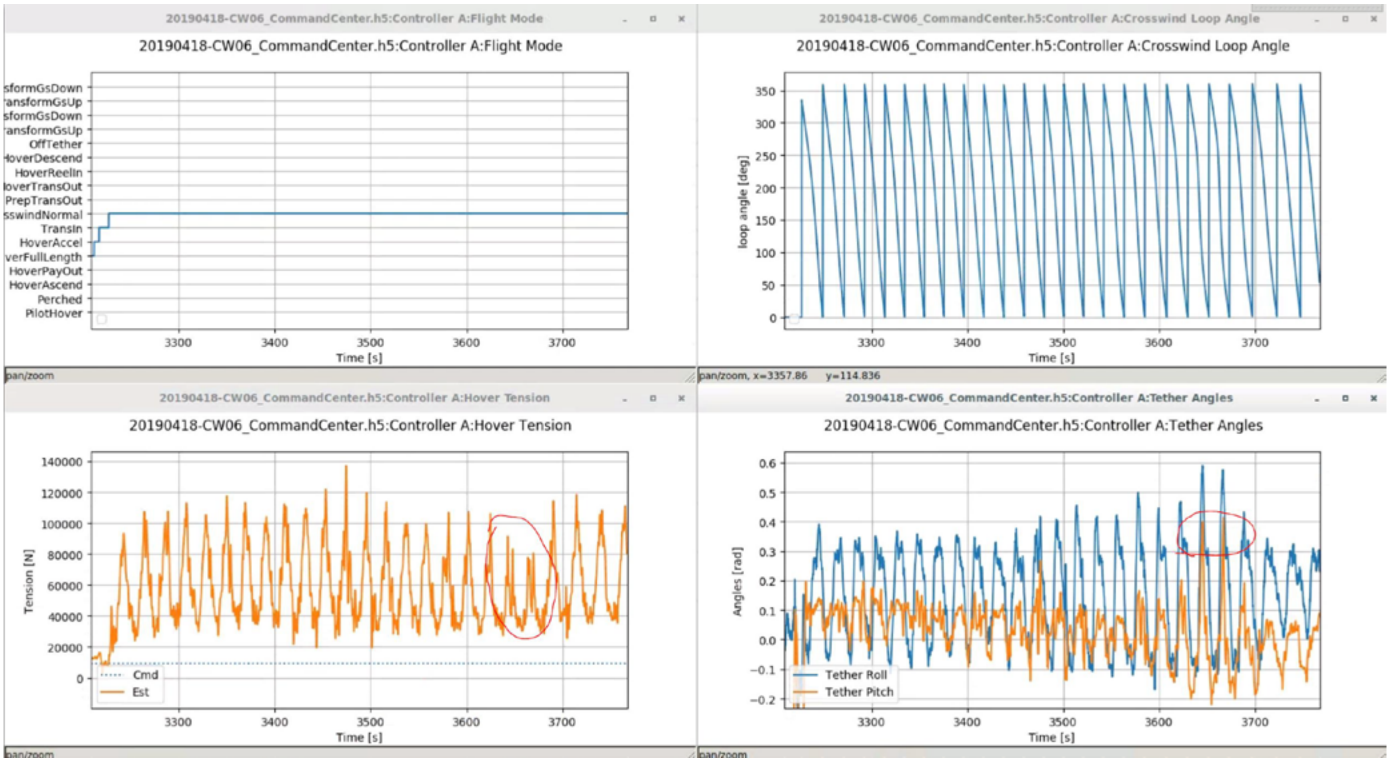
Change in elevation target target sets off thrust spike?

Tether Elevation During CW06 TransformDown

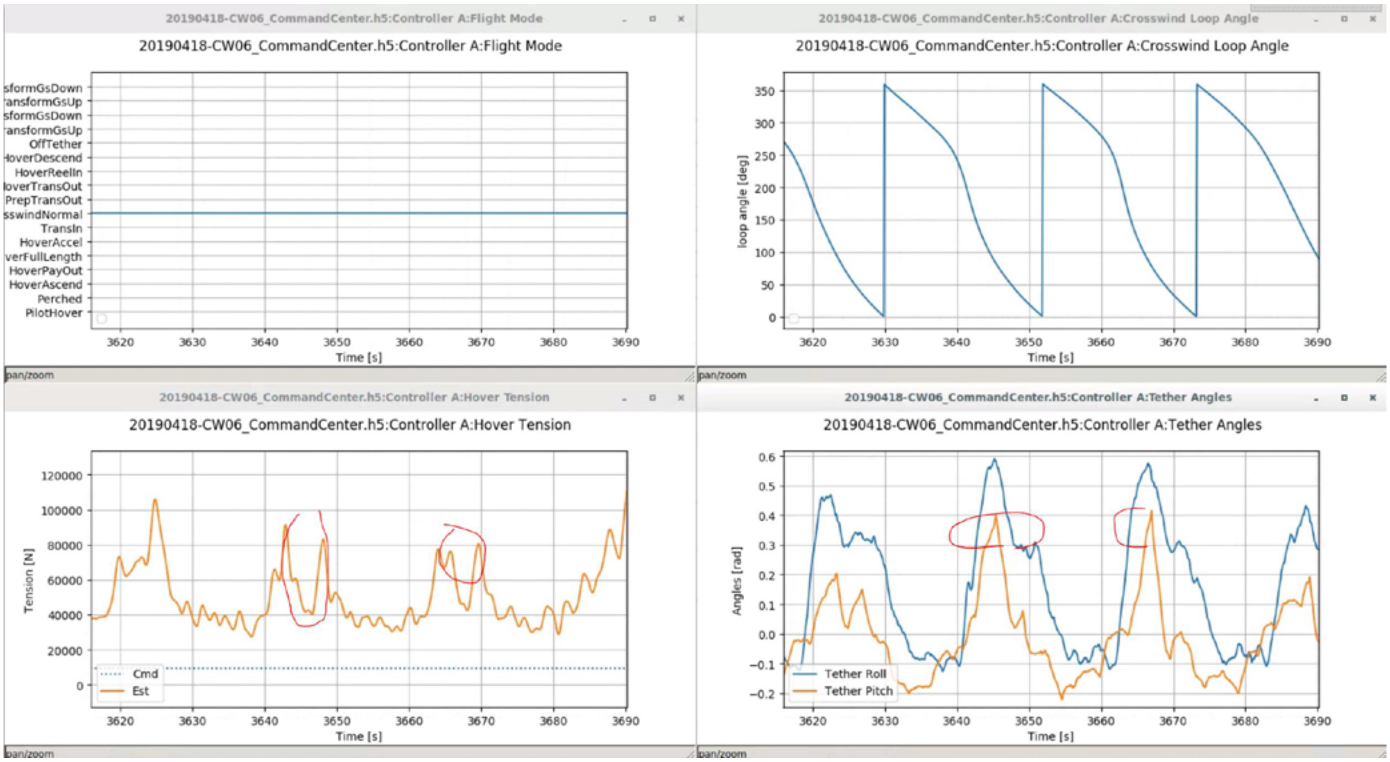
Suspiciously flat... tether_ground_angles.elevation_valid claims to be True



Bridle Impacting Pylon

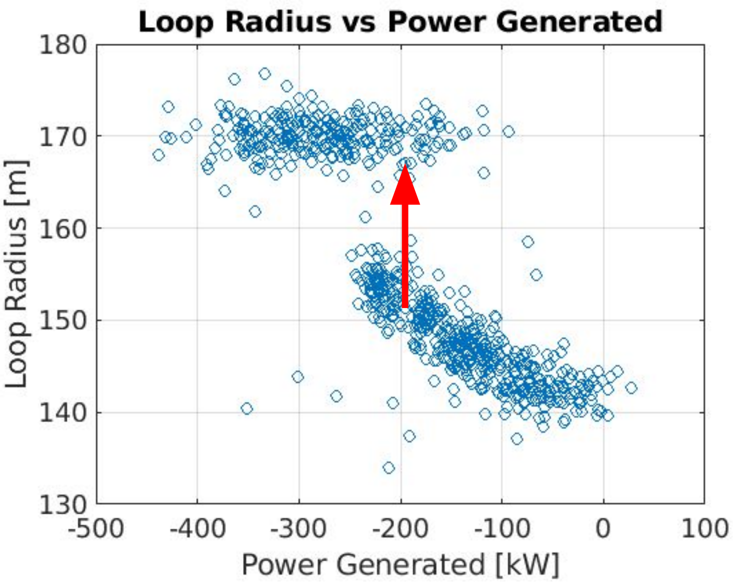


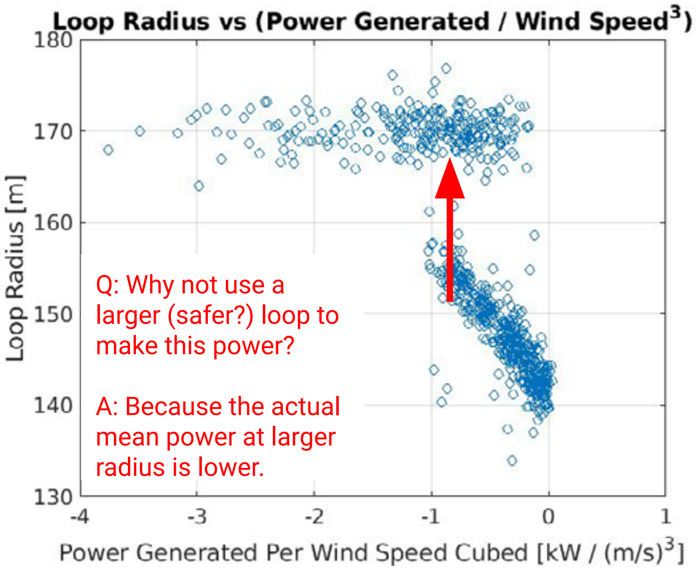
Bridle Impacting Pylon: But Tensions Relatively Low...



CW-06 Appendix

Can Make Same Power with Bigger Loops. Should we?



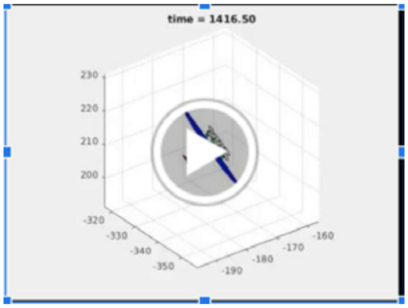


Q: Why not use a larger (safer?) loop to make this power?

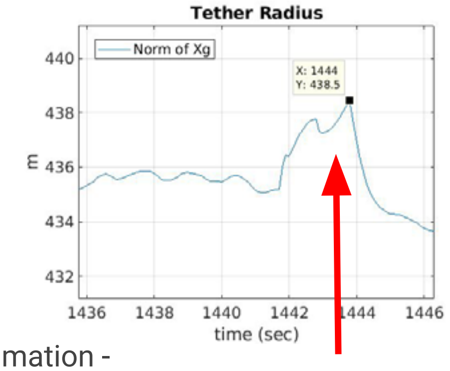
A: Because the actual mean power at larger radius is lower.

What That Strange Increase in Radial Position Is About

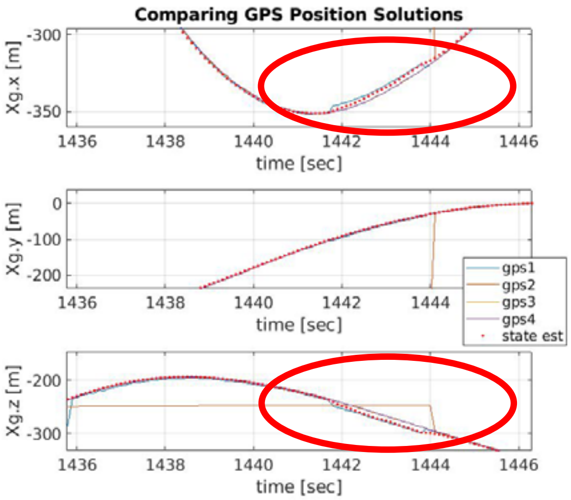
There was a big disagreement among GPS solutions during loop 33



video “20190418 CW-06 - Animation - Kite State Estimate Discontinuities in Crosswind” on YouTube playlist

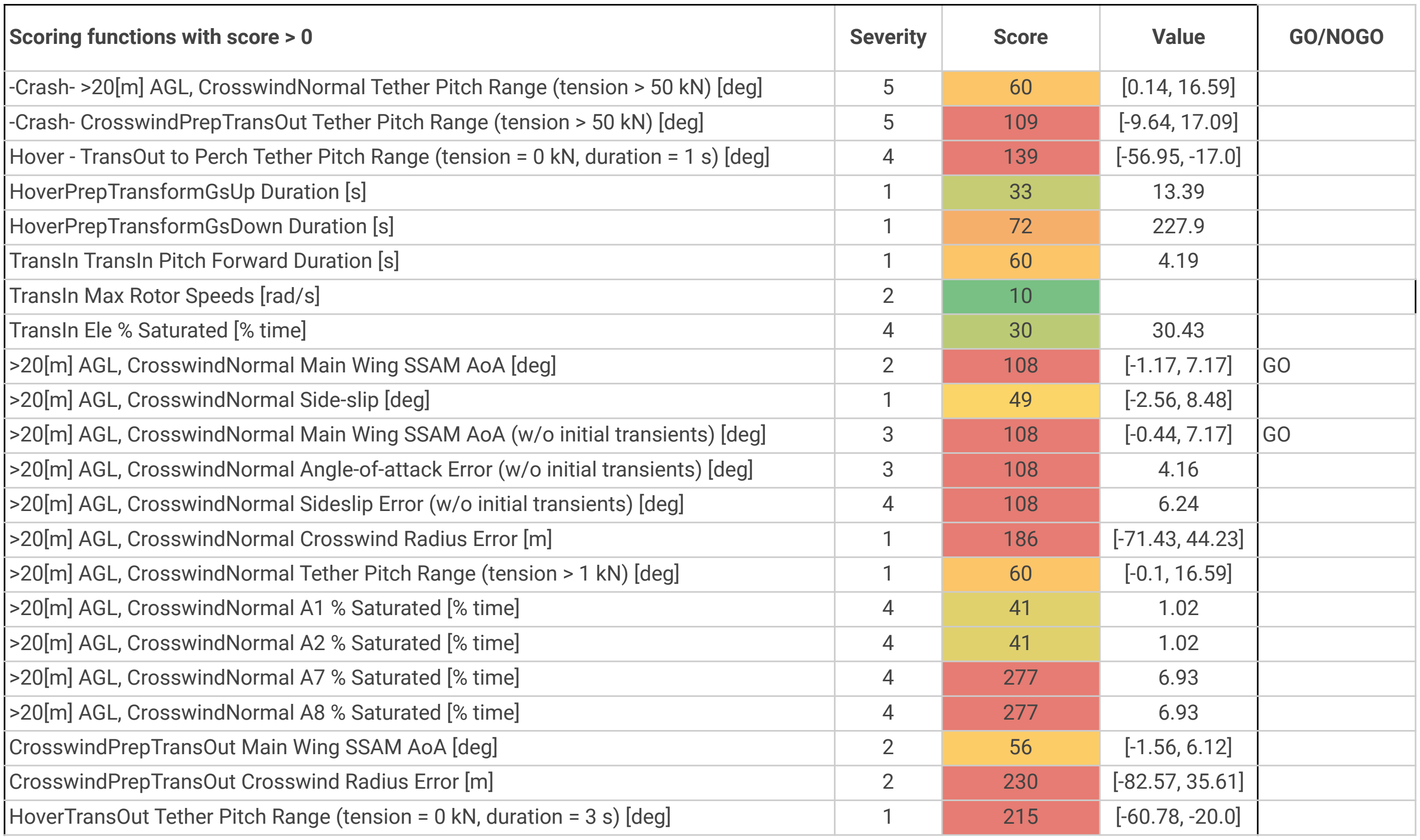


Not real.



Controls CW-07/08 Learnings Review

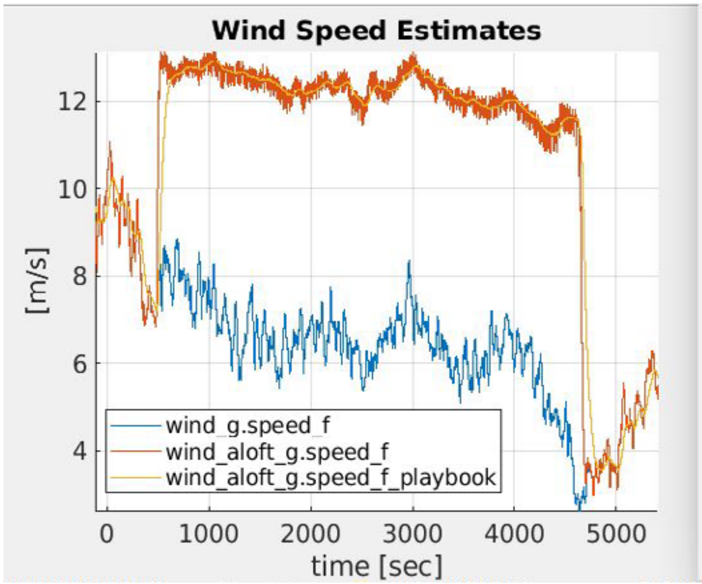
1 May, 2019

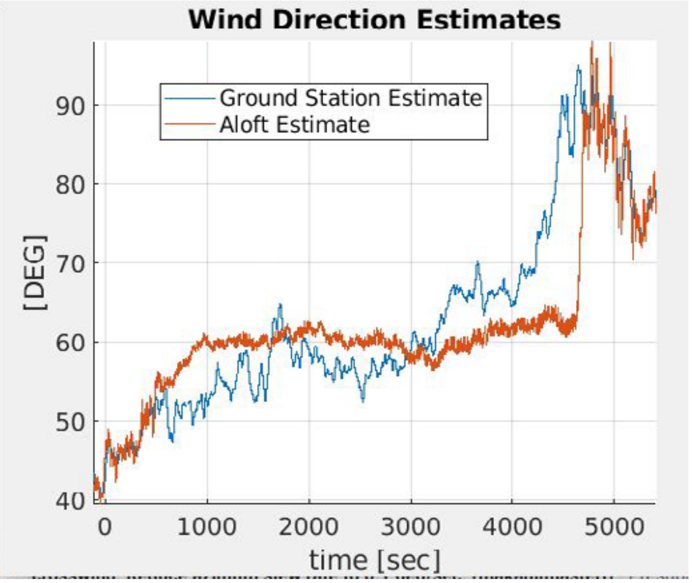


Scoring functions with score > 0	Severity	Score	Value	GO/NOGO
-Crash- >20[m] AGL, CrosswindNormal Tether Pitch Range (tension > 50 kN) [deg]	5	60	[0.14, 16.59]	
-Crash- CrosswindPrepTransOut Tether Pitch Range (tension > 50 kN) [deg]	5	109	[-9.64, 17.09]	
Hover - TransOut to Perch Tether Pitch Range (tension = 0 kN, duration = 1 s) [deg]	4	139	[-56.95, -17.0]	
HoverPrepTransformGsUp Duration [s]	1	33	13.39	
HoverPrepTransformGsDown Duration [s]	1	72	227.9	
TransIn TransIn Pitch Forward Duration [s]	1	60	4.19	
TransIn Max Rotor Speeds [rad/s]	2	10		
TransIn Ele % Saturated [% time]	4	30	30.43	
>20[m] AGL, CrosswindNormal Main Wing SSAM AoA [deg]	2	108	[-1.17, 7.17]	GO
>20[m] AGL, CrosswindNormal Side-slip [deg]	1	49	[-2.56, 8.48]	
>20[m] AGL, CrosswindNormal Main Wing SSAM AoA (w/o initial transients) [deg]	3	108	[-0.44, 7.17]	GO
>20[m] AGL, CrosswindNormal Angle-of-attack Error (w/o initial transients) [deg]	3	108	4.16	
>20[m] AGL, CrosswindNormal Sideslip Error (w/o initial transients) [deg]	4	108	6.24	
>20[m] AGL, CrosswindNormal Crosswind Radius Error [m]	1	186	[-71.43, 44.23]	
>20[m] AGL, CrosswindNormal Tether Pitch Range (tension > 1 kN) [deg]	1	60	[-0.1, 16.59]	
>20[m] AGL, CrosswindNormal A1 % Saturated [% time]	4	41	1.02	
>20[m] AGL, CrosswindNormal A2 % Saturated [% time]	4	41	1.02	
>20[m] AGL, CrosswindNormal A7 % Saturated [% time]	4	277	6.93	
>20[m] AGL, CrosswindNormal A8 % Saturated [% time]	4	277	6.93	
CrosswindPrepTransOut Main Wing SSAM AoA [deg]	2	56	[-1.56, 6.12]	
CrosswindPrepTransOut Crosswind Radius Error [m]	2	230	[-82.57, 35.61]	
HoverTransOut Tether Pitch Range (tension = 0 kN, duration = 3 s) [deg]	1	215	[-60.78, -20.0]	

Wind

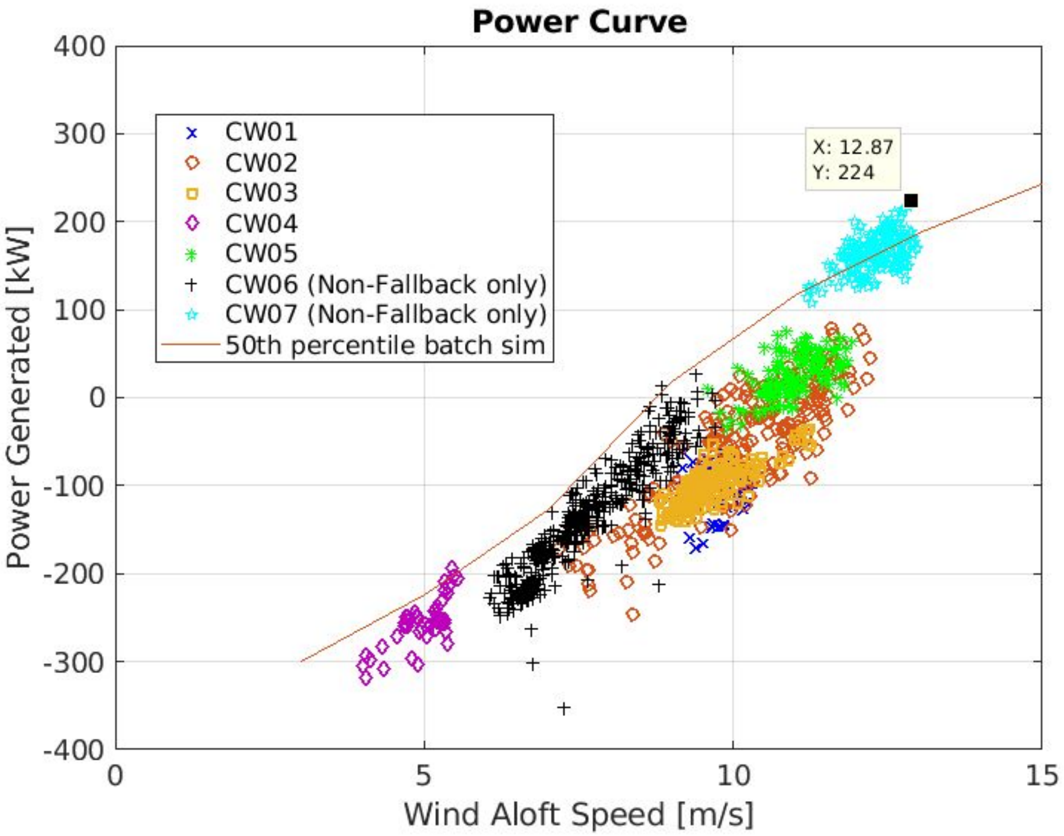
- 6 m/s difference between ground station and aloft
- Direction was mostly constant. A small veer is evident toward the end of the flight.





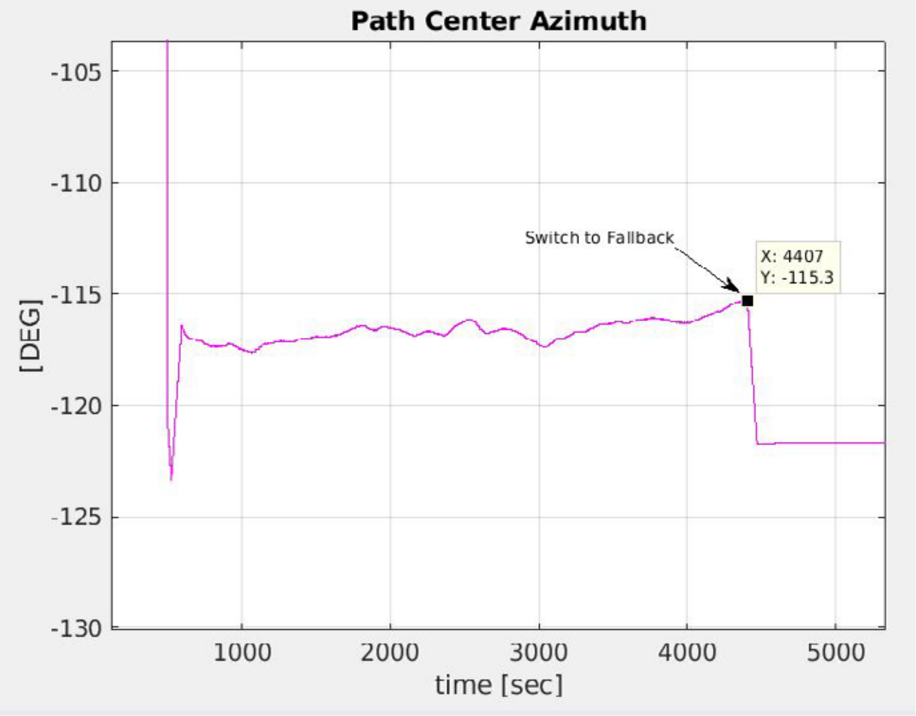
Power

Best power at Parker Ranch yet!



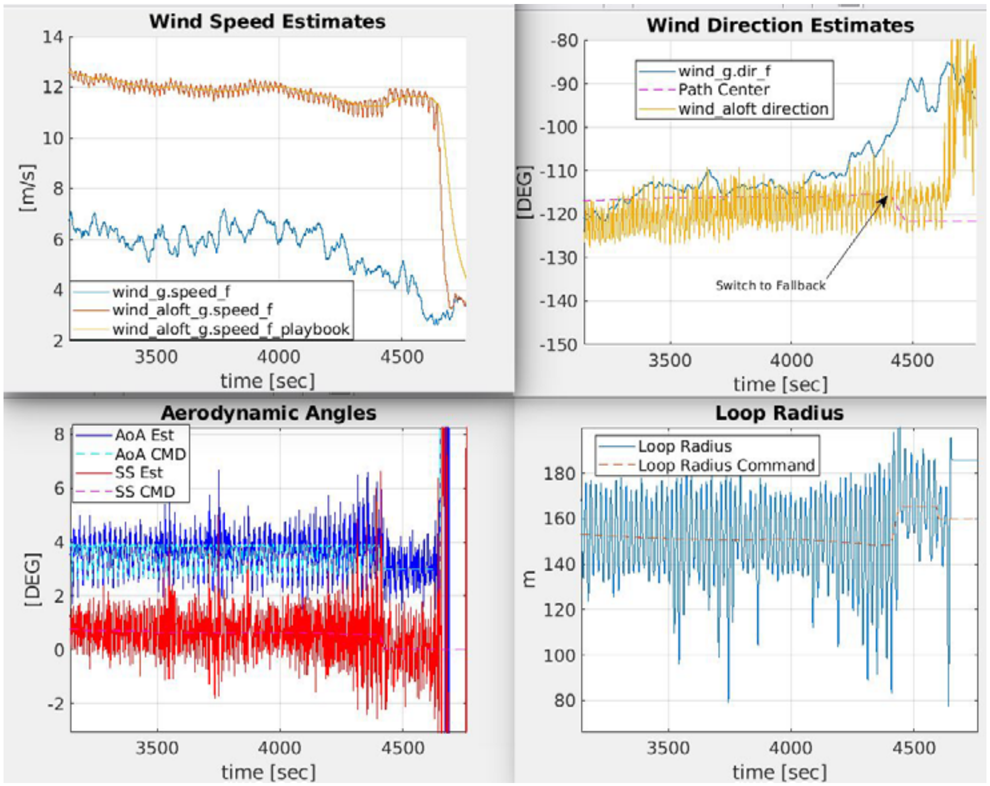
Path Center Azimuth Barely Moved

- Biggest movements were TransIn and the switch to Fallback
- Path center slewing is not the reason for poor flight quality in CW07



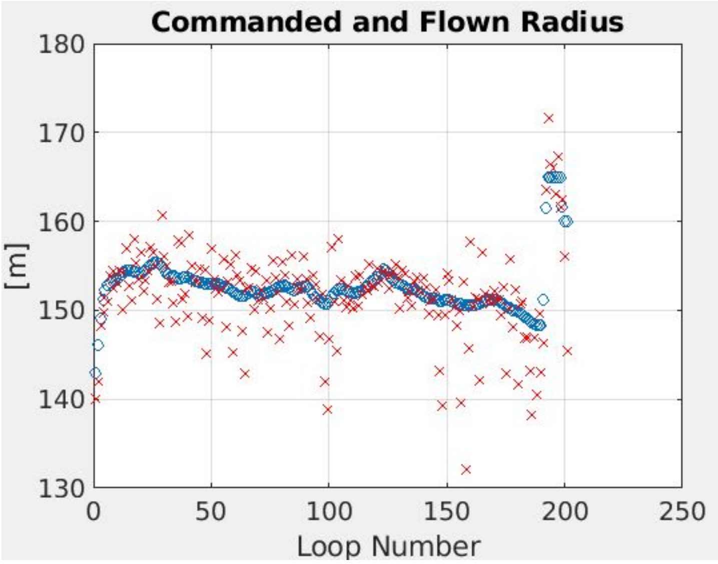
Flight Quality

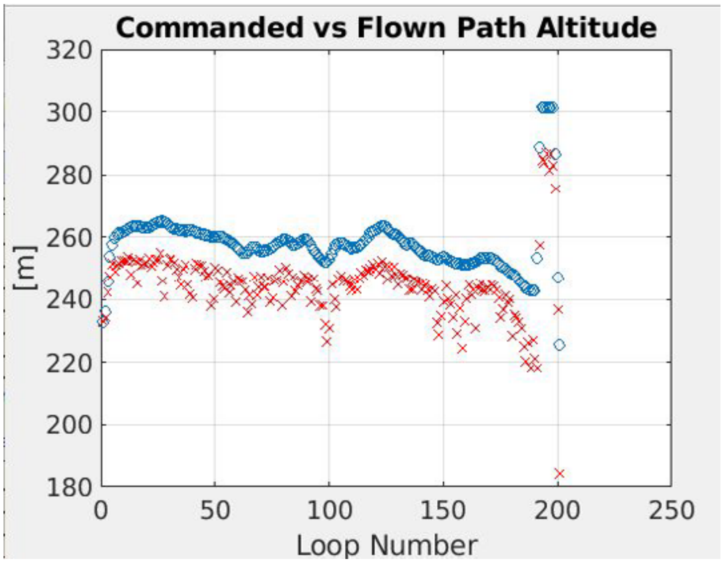
- Better and worse throughout the flight
- Errors in Alpha, Beta, Loop Radius make it clear when the kite is struggling
- This was not as bad as CW06



Path Tracking Performance

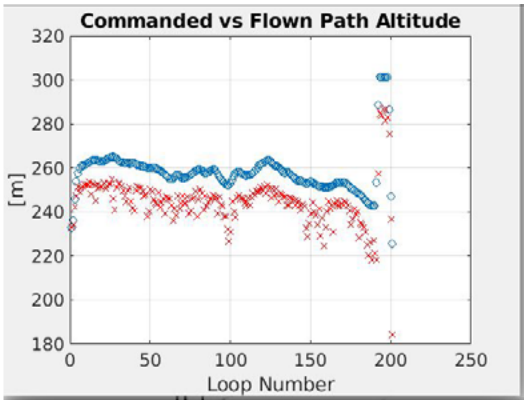
- Loops are generally lower than commanded
- Loops often have smaller radius than commanded

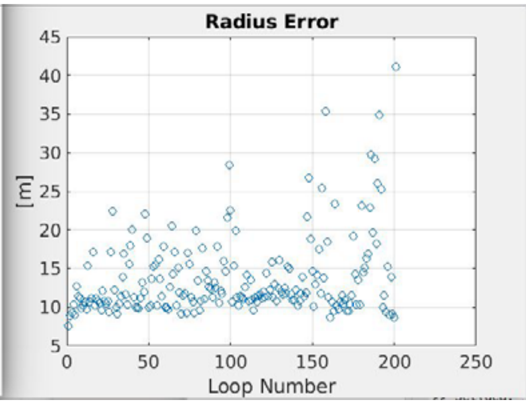


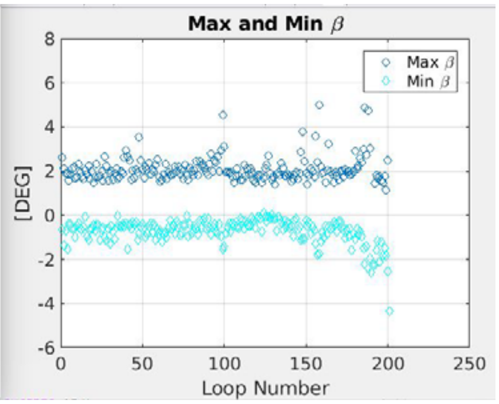


Poor Path Following Leads to Bad Flight Quality

- Bad aero angle tracking correlates with poor path tracking.
- We have poor flight quality because of large path tracking errors

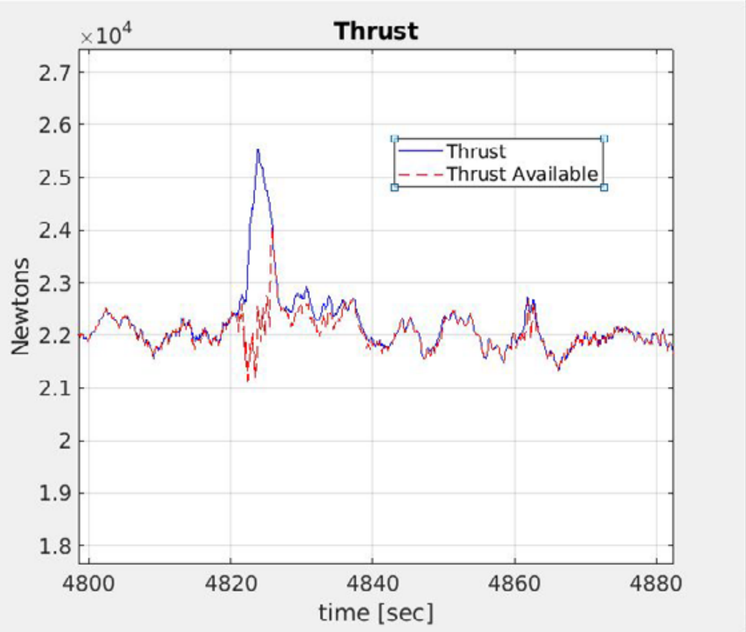


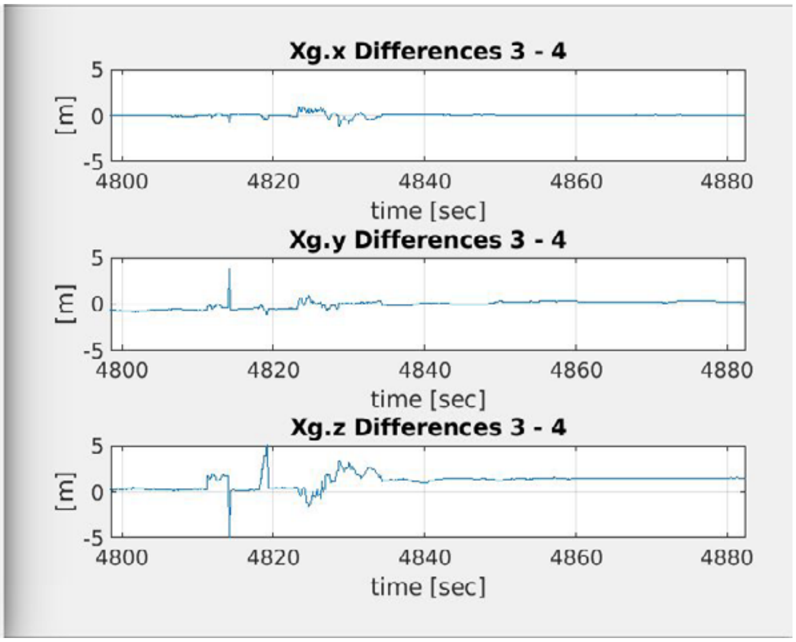




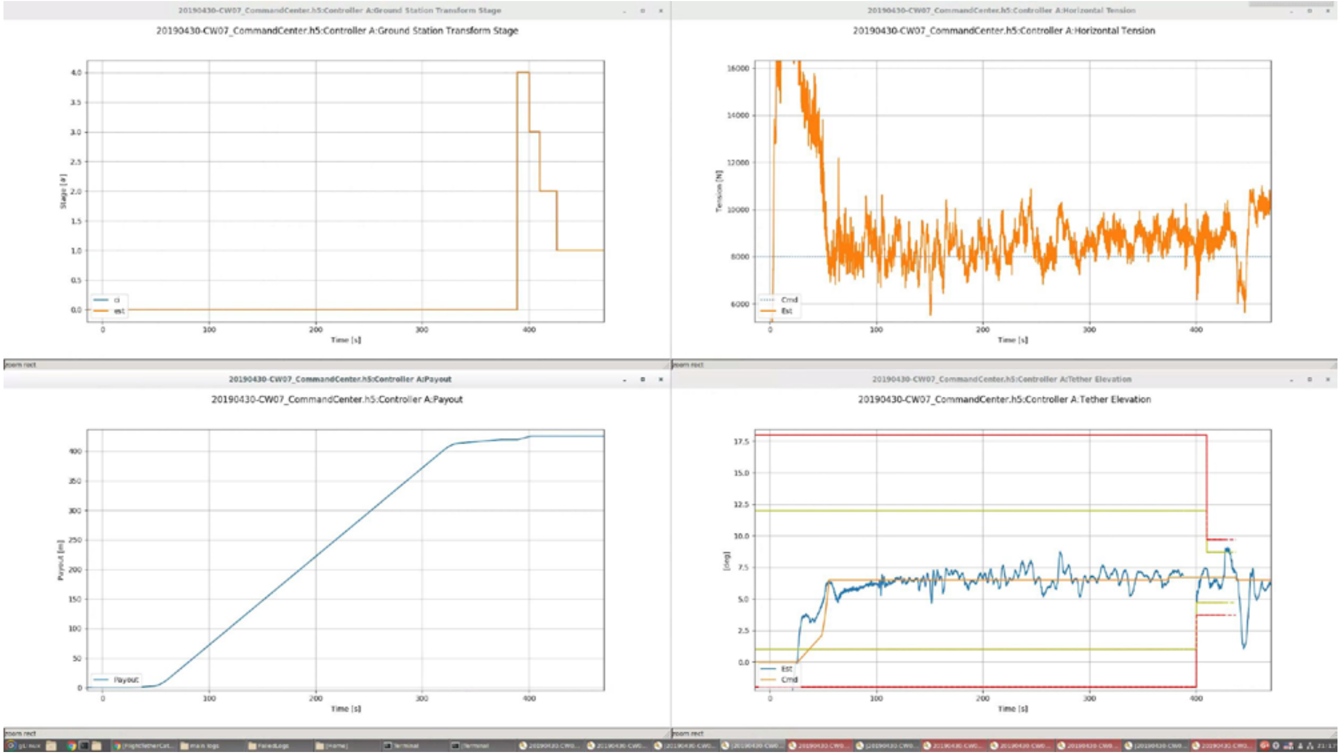
Possible GPS Trouble During PrepTransformDown

Kite isn't doing anything special here, just translating at constant altitude.

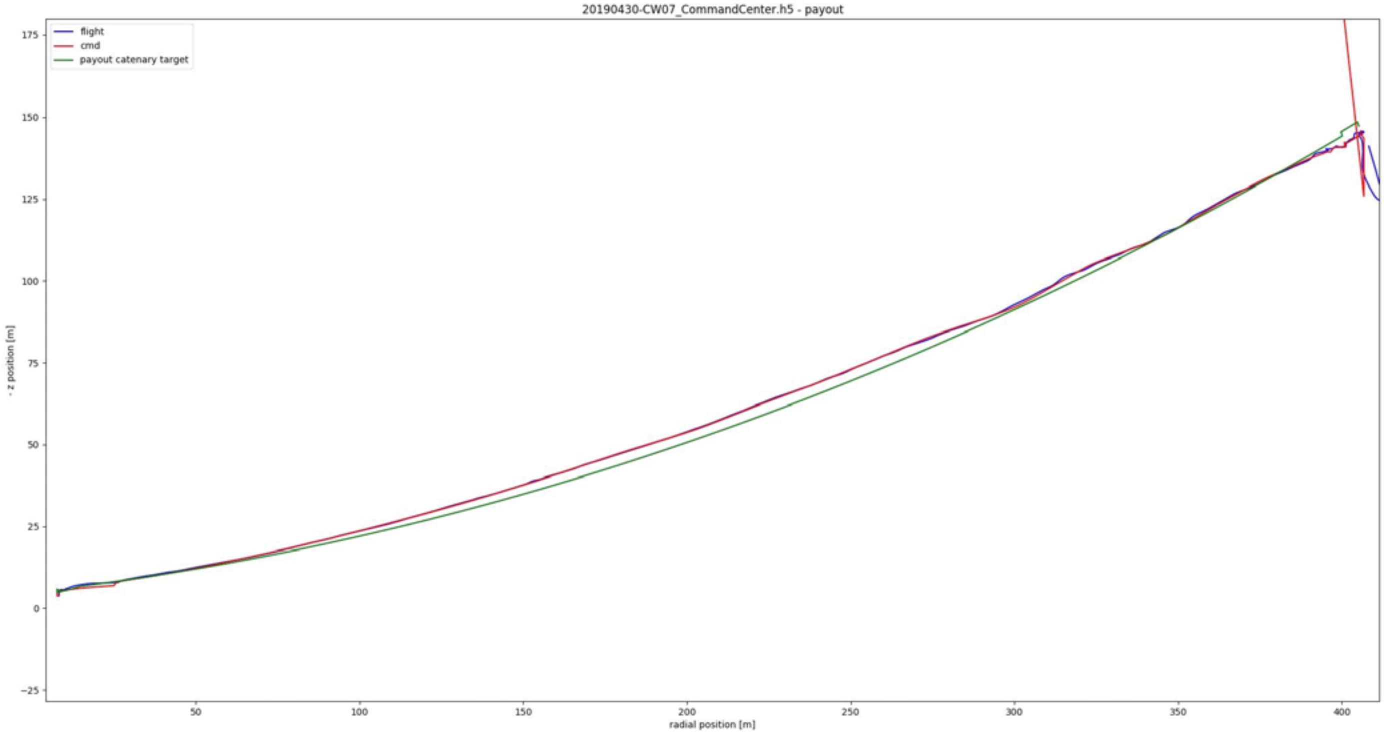




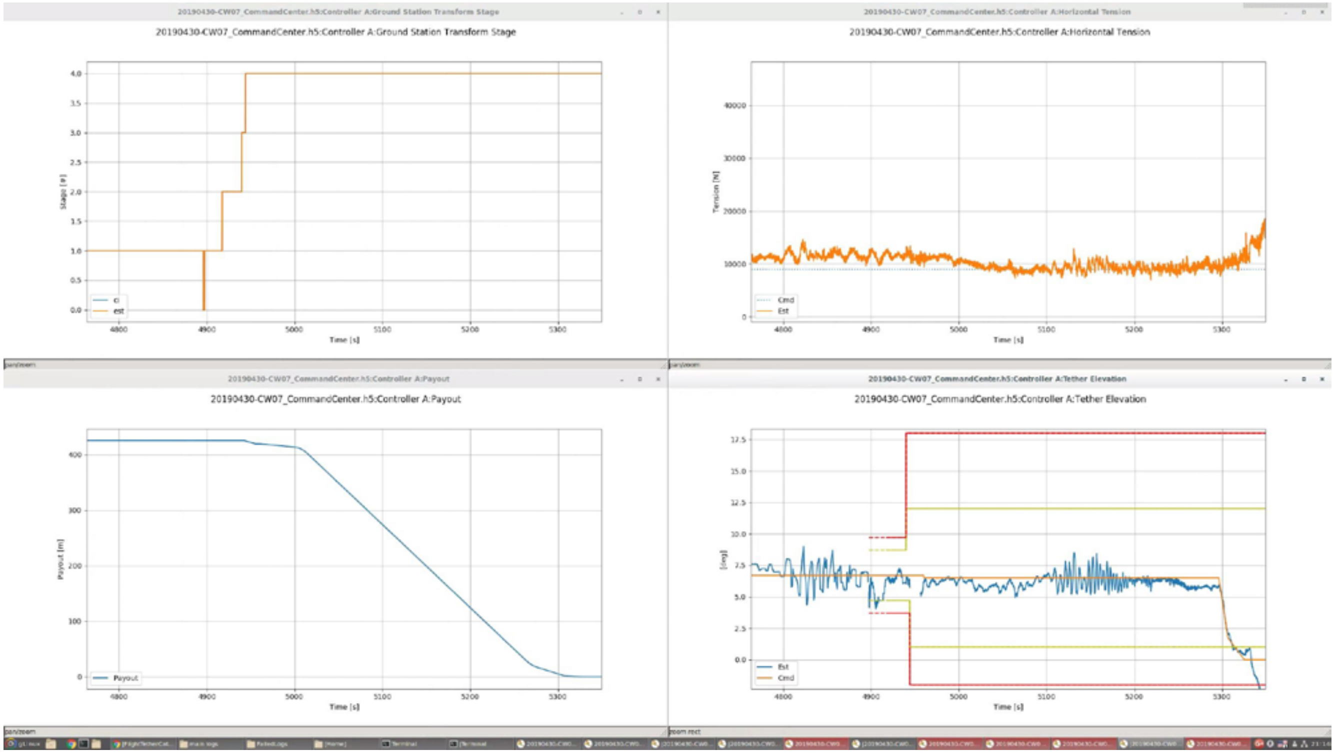
Tether Elevation, Pay Out



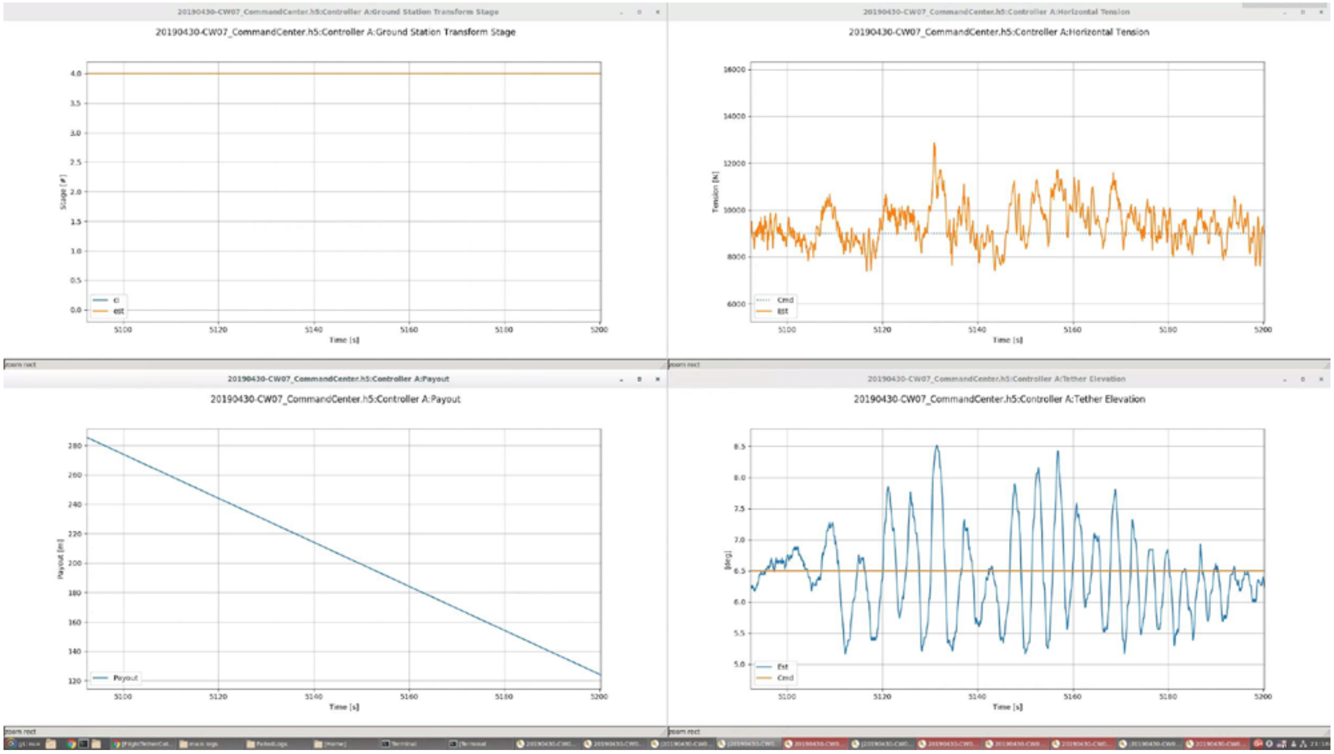
Tether Elevation, Pay Out



Tether Elevation, Reel-In



Tether Elevation, Reel-In



MAKANI

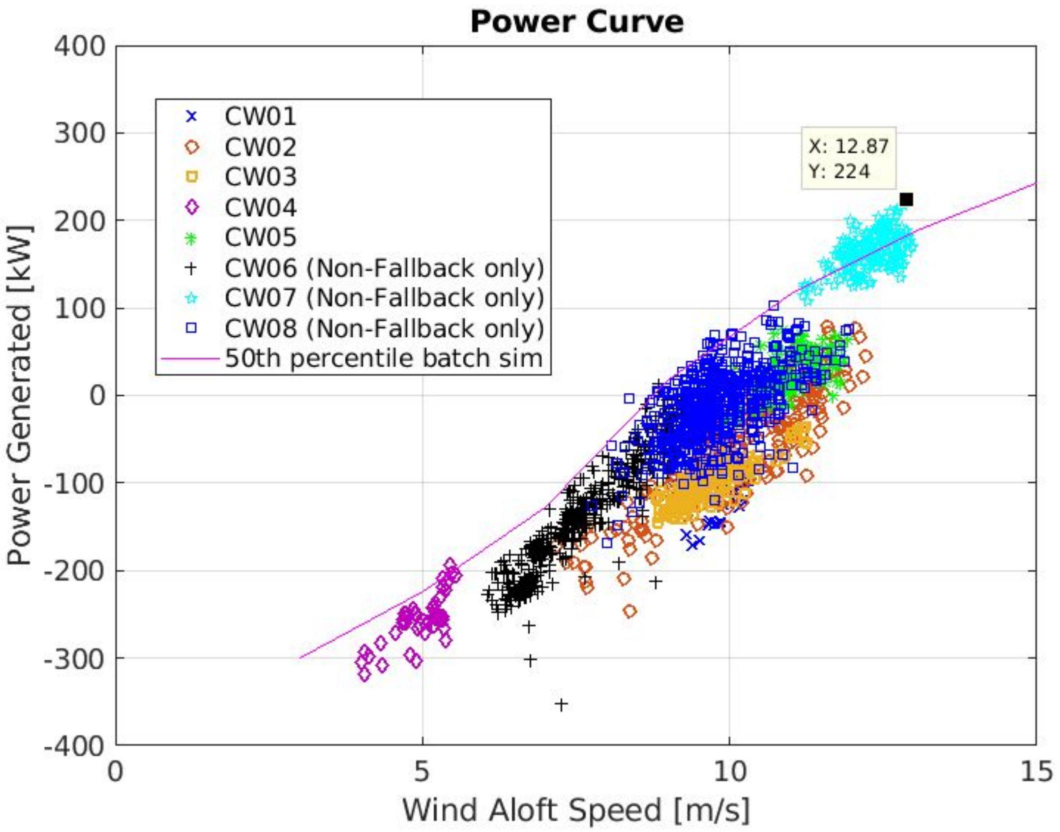
Controls CW-08 Learnings Review

2 May, 2019

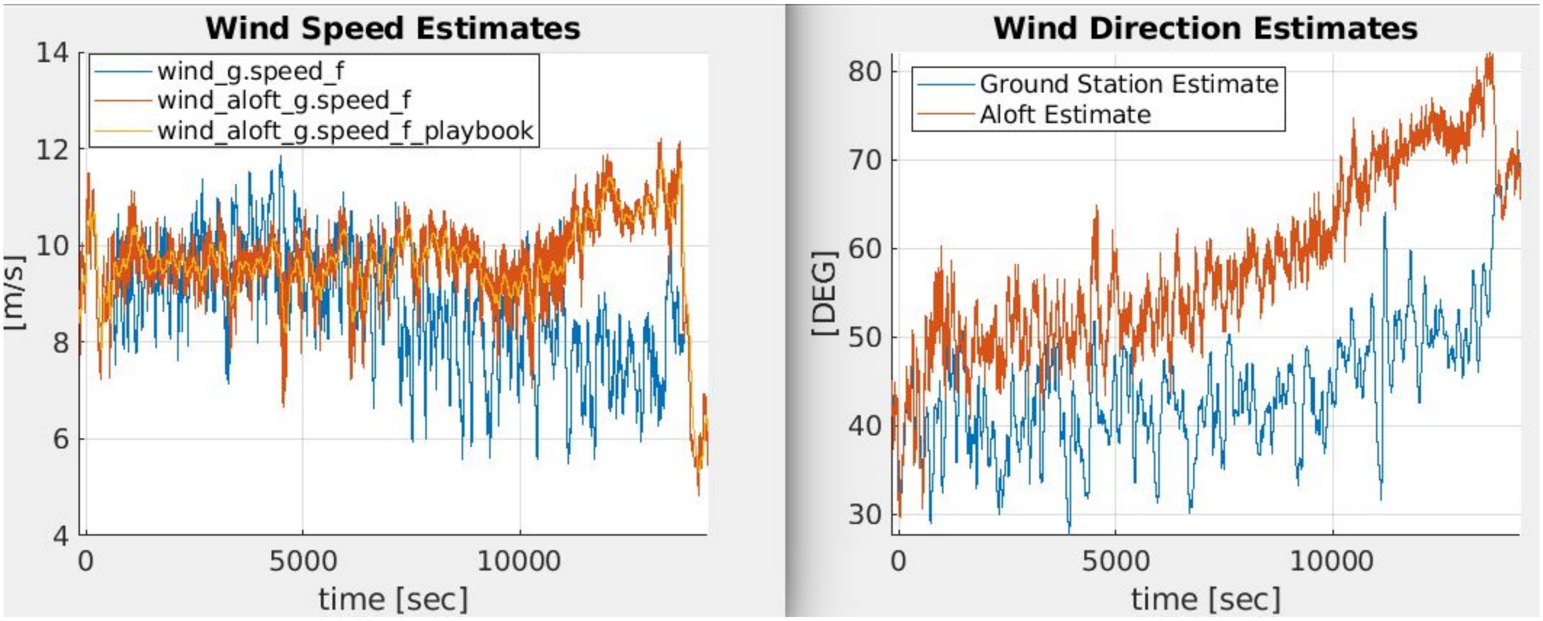
CW08 Data Analysis Status

command center logs (individual)	Available [internal ref]	
command center logs (merged)	available [internal ref]	
wing recorder logs (individual)	available [internal ref]	
wing recorder logs (merged)	does anyone want this?	will be > 25 GB
power curve	On the next slide	
scoring functions	available [internal ref]	

Power Curve

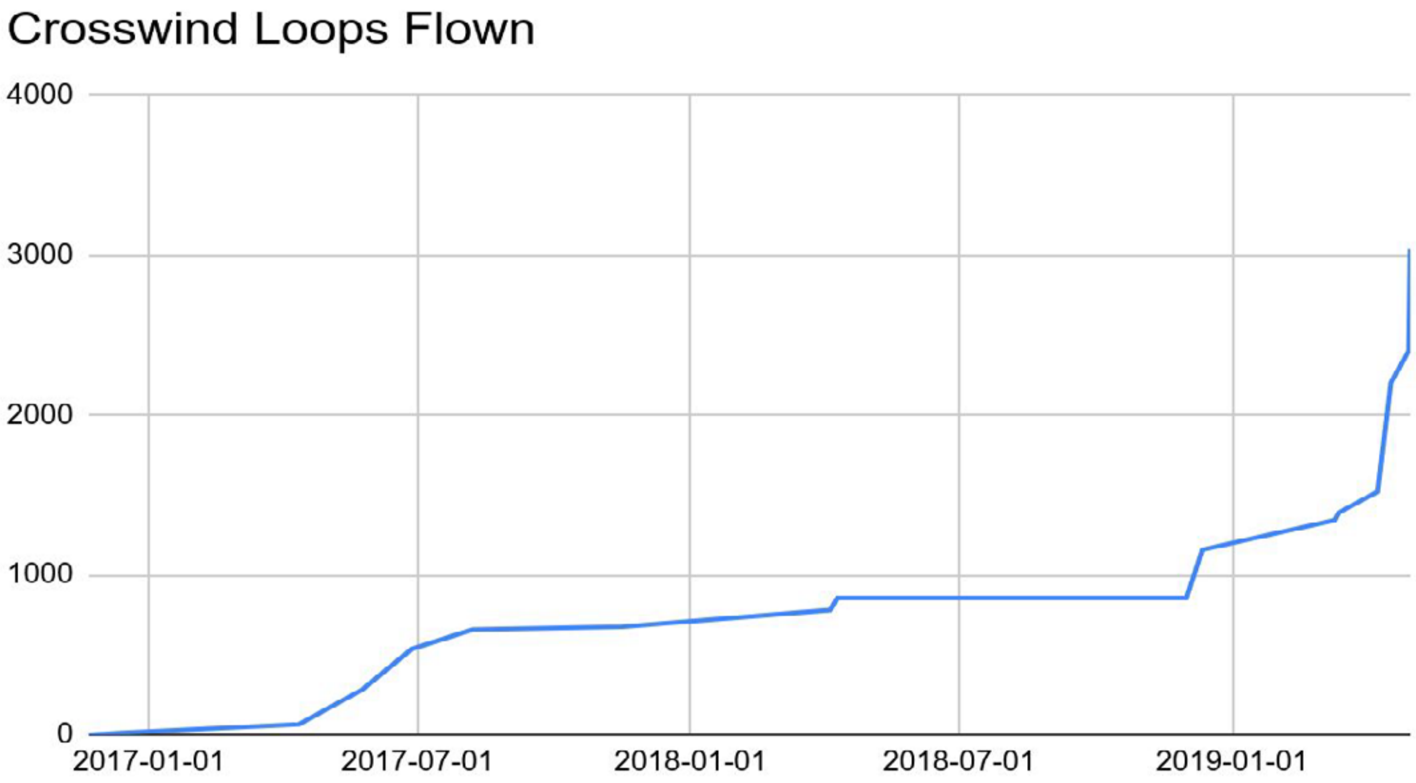


Wind

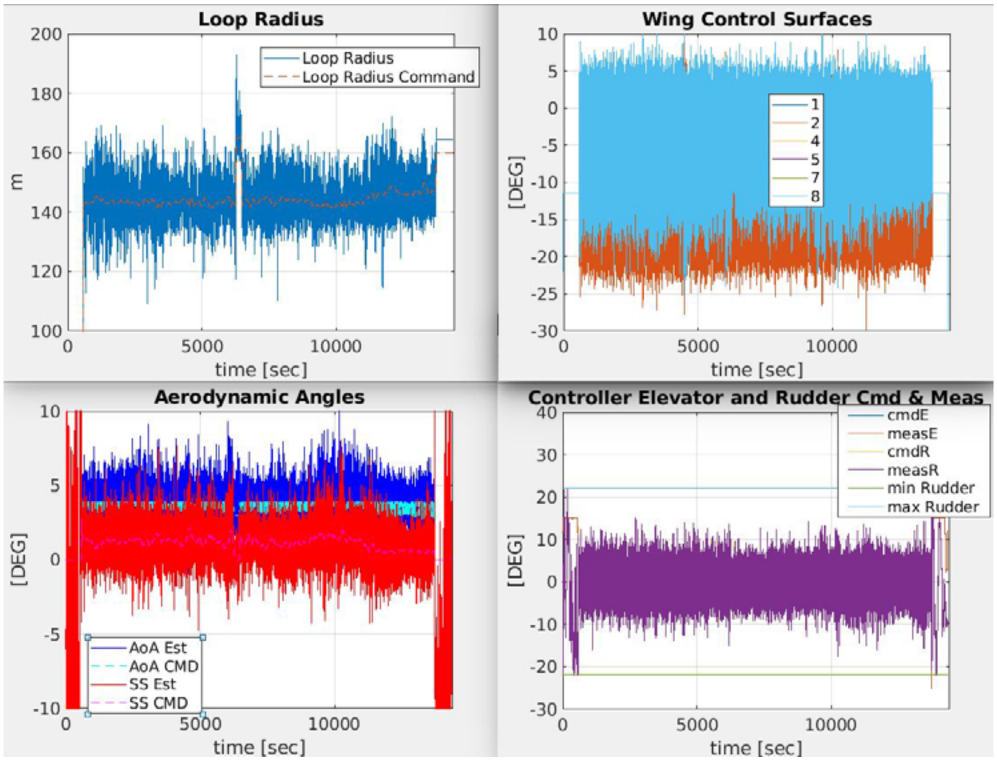


“All Modes” Flight Statistics

Flight	Date	Total Flight Time (min)	Number of Loops	Crosswind Average Wind Aloft [m/s]	Crosswind Average Power [kW]	Launch to Crosswind Duration [min]	Crosswind Duration [min]	HoverTransOut to Perch Duration [min]	Average Crosswind Loop Duration [sec]
CW01	2018-12-04	61	81	9.7	-98	8.6	31	21.6	23.0
CW02	2018-12-12	103	222	10.1	-53	8.9	83	10.8	22.4
CW03	2019-03-11	92	185	9.6	-99	11.7	69	10.9	22.4
CW04	2019-03-14	42	47	5.0	-255	9.0	21	12.1	26.8
CW05	2019-04-09	65	130	11.0	26	9.3	45	10.9	20.5
CW06	2019-04-18	285	682	7.2	-192	11.4	264	9.9	23.2
CW07	2019-04-30	90	201	12.2	158	8.3	69	12.5	20.7
CW08	2019-05-01	239	639	9.8	-14	9.6	219	10.0	20.6
Sum		976	2187				801		

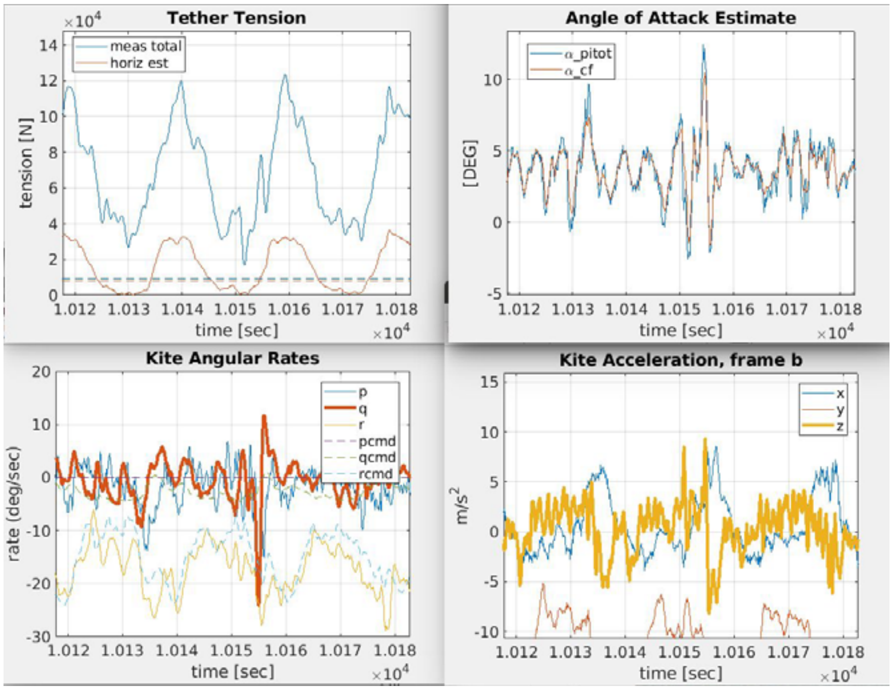


Flight Quality



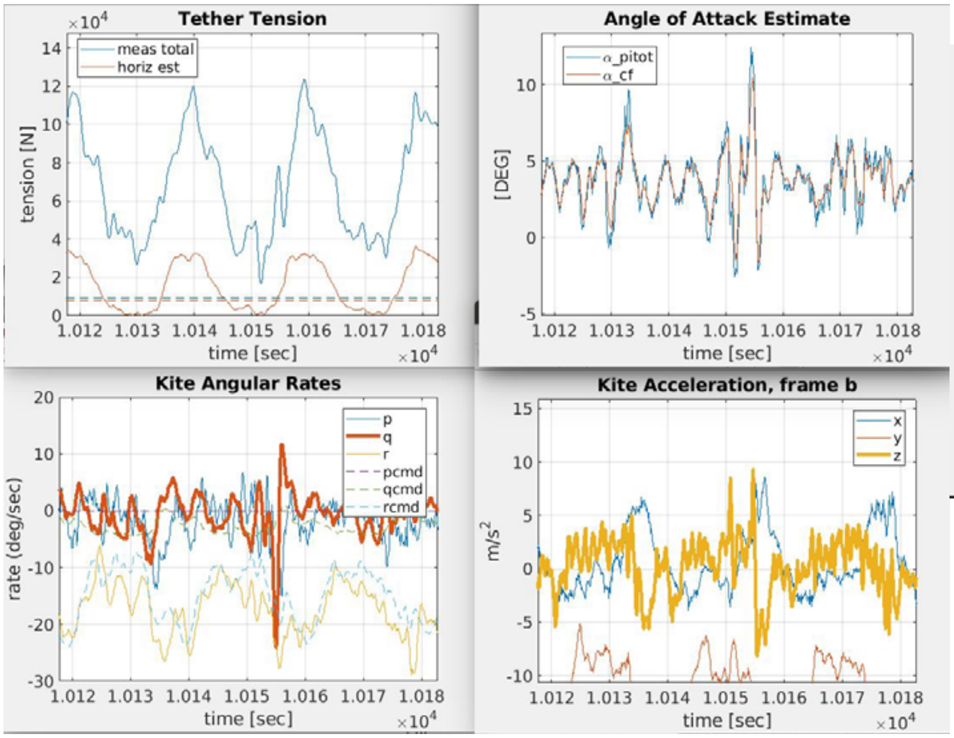
- No extremely scary loops like CW06
- Mostly had aileron margin throughout
    - A few isolated saturation events
- Rudder did not saturate in crosswind
- Aero angles mostly okay
    - A few bad excursions
    - Beta always between -5 and +8 deg
    - Alpha always between -2.8 and +10.5 deg

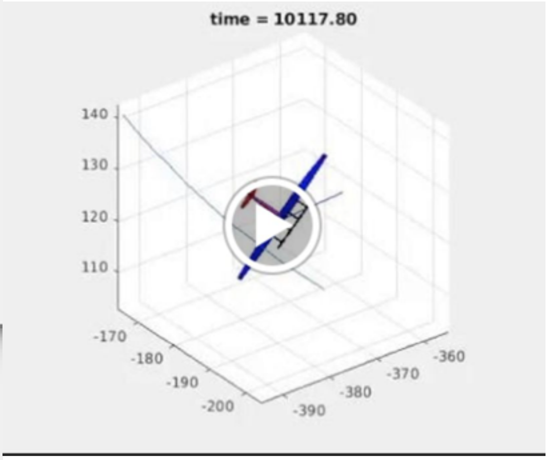
Alpha Excursion Beyond +10 Degrees in Loop 465



- This is our worst alpha excursion of CW08
- The event stands out due to
    - alpha
    - tension
    - kite pitch rate
    - kite heave acceleration
- Time scale shown here is approximately 3 loops
- Event is approximately 2:50:30 in the videos from CW08 day—see specifically “20190501 CW-08 - Onboard View of Makani M600 During Night Flight” on YouTube playlist

Animation of Loops 464-467

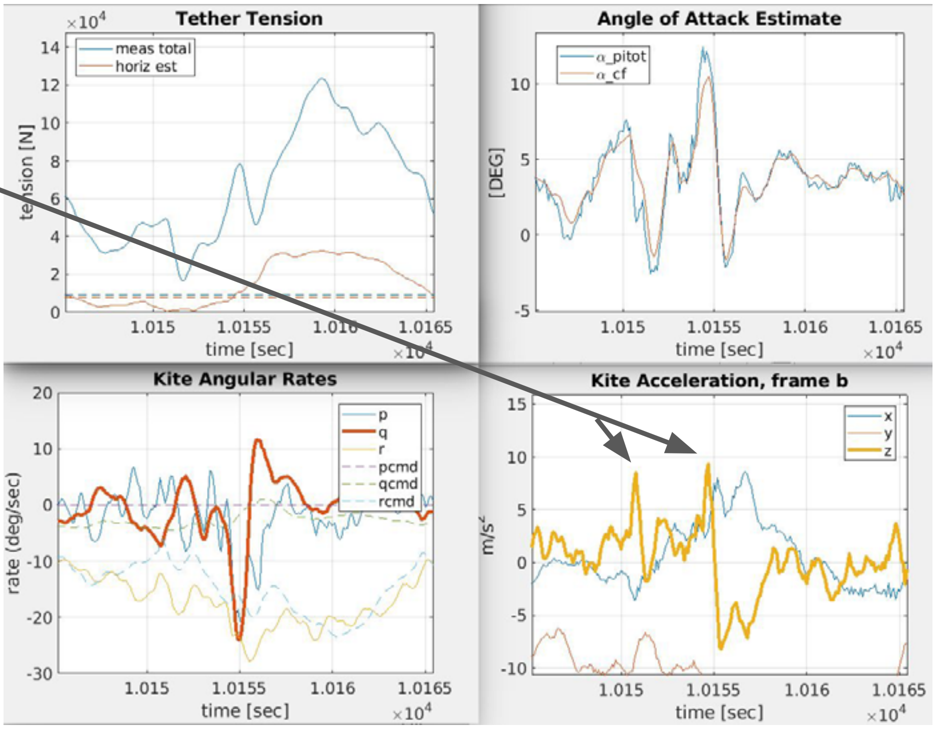




video “20190501 CW-08 - Animation - Alpha Excursion During Crosswind” on YouTube playlist

Loop 465 in Detail

- Sharp excursions toward positive z acceleration may indicate a sudden loss of lift
    - Stall confirmed with video “20190501 CW-08 - Onboard View of Makani M600 During Night Flight” on YouTube playlist
- The large negative pitch rate is due to the stall

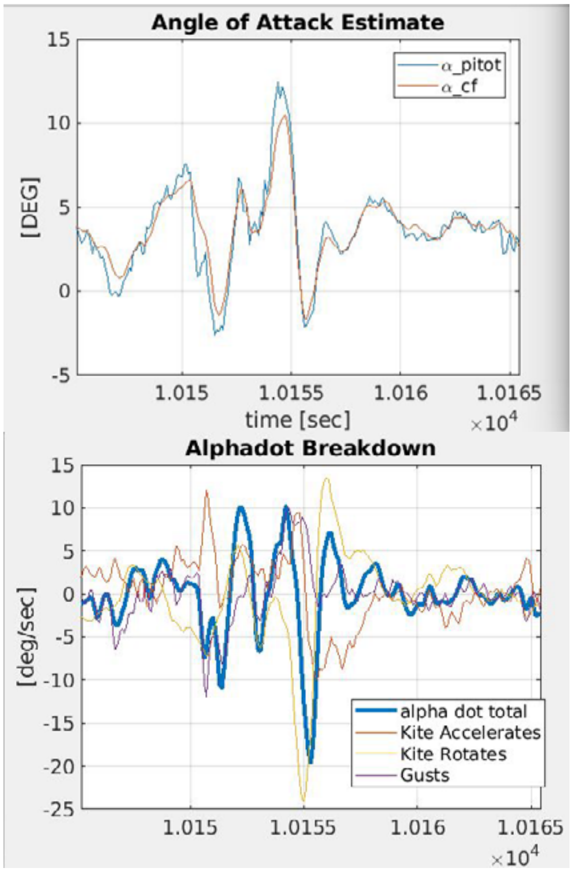


Reasons for Alpha Changes in Loop 465

It is possible to break down the contributions [see internal ref] to the time derivative of alpha (and beta). They come from three sources:

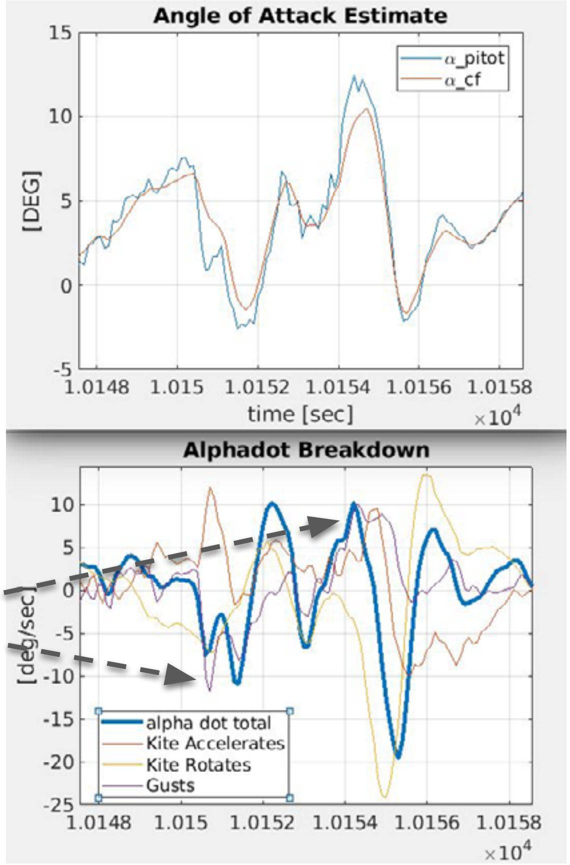
- The kite accelerates (accelerometers)
- The kite rotates (gyros)
- The wind itself changes (everything else)

In Loop 465 (and in general), kite accelerations and gusts are much faster than kite rotations from a d/dt(alpha) perspective. Gust causes the alpha excursions and stalls the wing a bit.



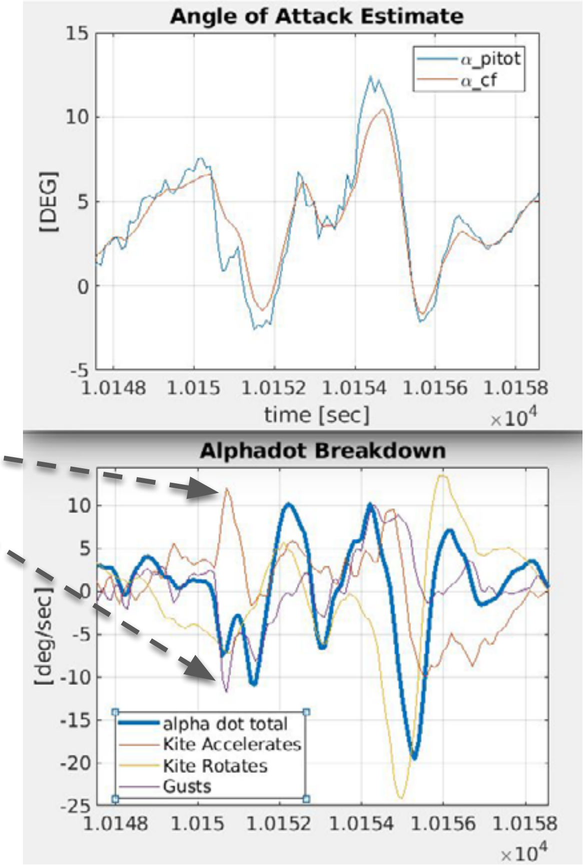
A Closer Look at d/dt(alpha) in Loop 465

- “Gusts” are every part of d/dt(alpha) which cannot be explained by measured kite motion
- The measured kite acceleration is > 0 for the time leading up to the large alpha excursion
  - For well-regulated constant alpha, the acceleration and rotation contributions cancel
- “Gusts” seem responsible for much of the high frequency content in d/dt(alpha)

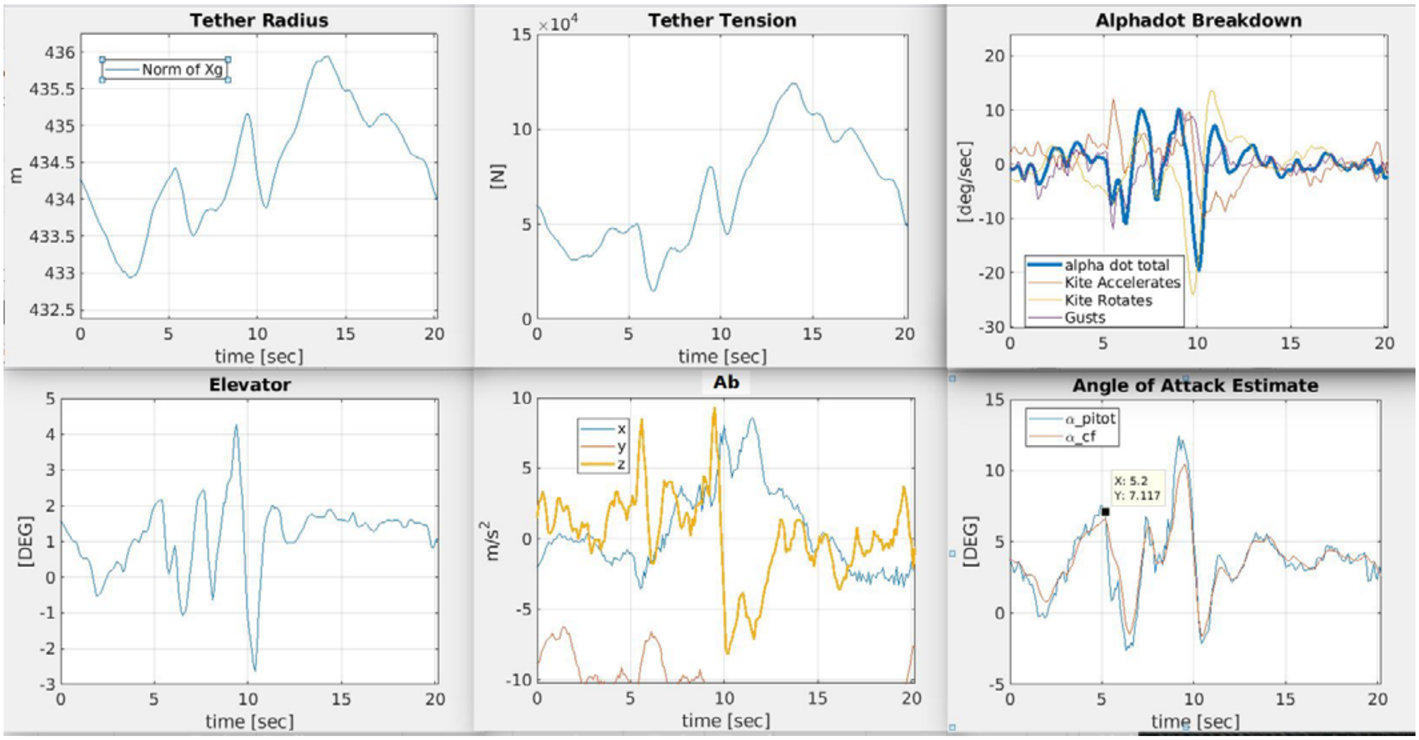


Details about “Gusts”

- “Gusts” are the residual from a rigid body dynamics equation.
    - When contributions from our *estimated* acceleration, angular velocity, & apparent wind do not sum to the estimated d/dt(alpha), the residual is labeled “Gusts”
- Here we see a “Gust” correlate instantaneously with kite acceleration. This could be:
    - Uncertainty in the direction of the wind
    - Uncertainty in the kite attitude
- The kite accelerations as measured *are real* (the inertial measurement system is reliable for this kind of thing).

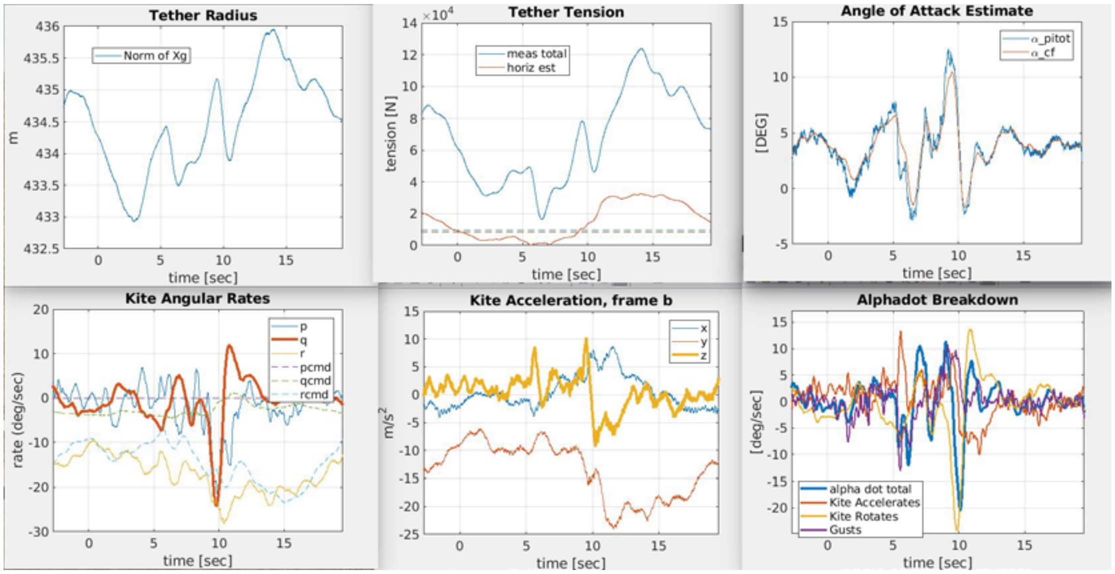


Another Look at Loop 465



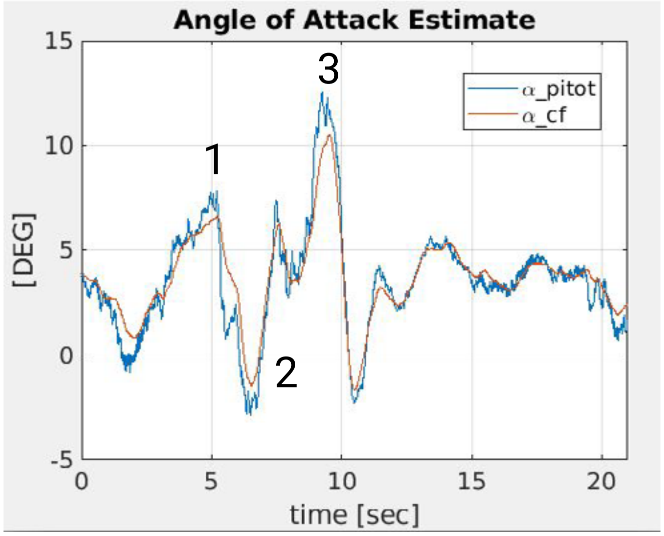
Overview of “The Event” in Loop 465

- Sharp gusts hit the wing at the start of the downstroke
- The gusts changed angle of attack primarily
- Much of the wing stalled when angle of attack went beyond +10 degrees
- Captured on video “20190501 CW-08 - Onboard View of Makani M600 During Night Flight” near 2:50:30 on YouTube playlist



Order of Events in Loop 465

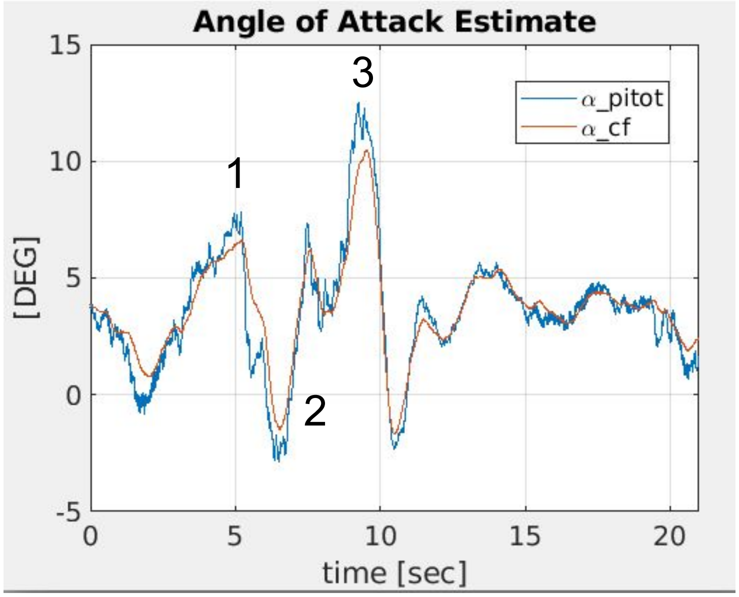
1. A gust swiftly reduces the kite’s angle of attack
    1. The kite loses lift and accelerates “downward”
    2. Tension drops
    3. Kite moves 1 m toward the center of the sphere
    4. Elevator responds to the alpha error
2. Positive kite pitch rate develops in response to the elevator motion
    1. Angle of attack reaches a minimum of -1 deg and then starts recovering



Order of Events in Loop 465

3. The opposite side of the gust arrives, sending angle of attack to over + 10 deg. The wing stalls.

   a. -20 deg/sec pitch rate, -20 deg/sec roll rate
   b. Big heave acceleration (loss of lift)
   c. Tension drops
   d. Kite moves 1 m toward the center of the sphere



Important Facts About The Events of Loop 465

1. *Tension was low* and increasing at the time (start of the downstroke)
2. There were *two sharp heave accelerations* by the kite
   a. First, a gust which reduced alpha (NOT a stall)
   b. Next, the stall when alpha > +10 deg. Large negative pitch rate only on this one.
3. Tether *sphere departure was NOT severe*. Both accelerations led to only 1 m of displacement. RPX09 was 8 m.
4. Kite *pitch rate was negative* (nose down) while alpha exceeded +10 deg
5. Kite *exhibited several stall characteristics* after alpha > +10 deg
   a. Nose down pitch motion (aerodynamic center moves aft)
   b. Roll left (asymmetric stall, aerodynamic center moves starboard)
   c. Fast roll oscillations evident in video (reduced roll damping, mode is stiffened by bridle)
6. There were *no control surface saturations* associated with this event
   a. The elevator moved a lot more than usual but had margin
7. The complementary *filter did attenuate the gusts slightly*
   a. There is room for discussion about filtering the pitot more aggressively

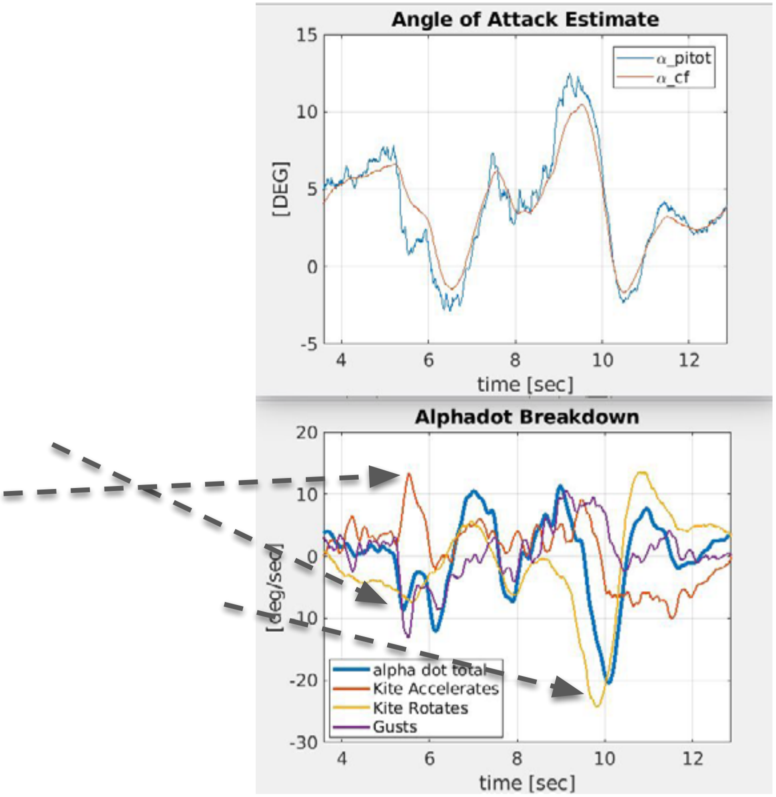
How Do We Know It Was A Gust?

Alpha can change for only 3 reasons:

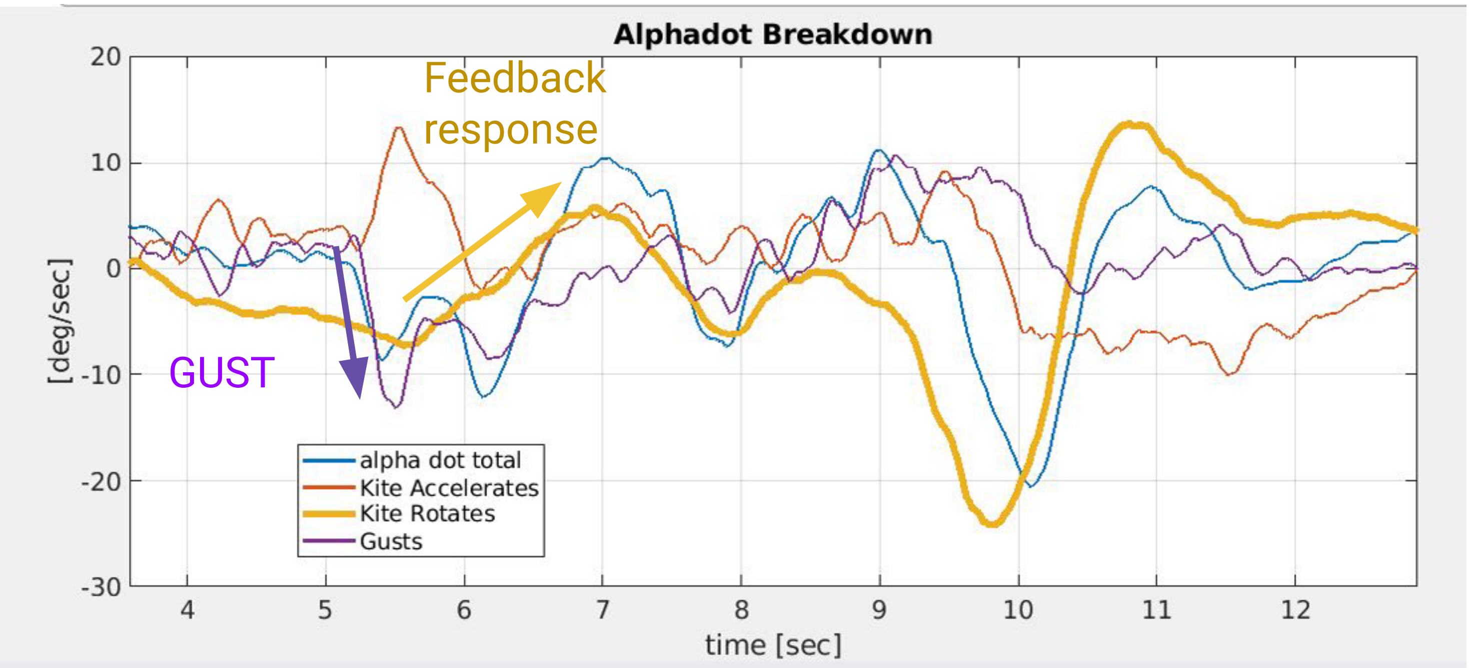
- Kite accelerates
- Kite rotates
- The wind changes (gust)

First event shows a sudden alpha drop and a sudden plunging acceleration.

Second event shows clear kite rotational motion after the stall.

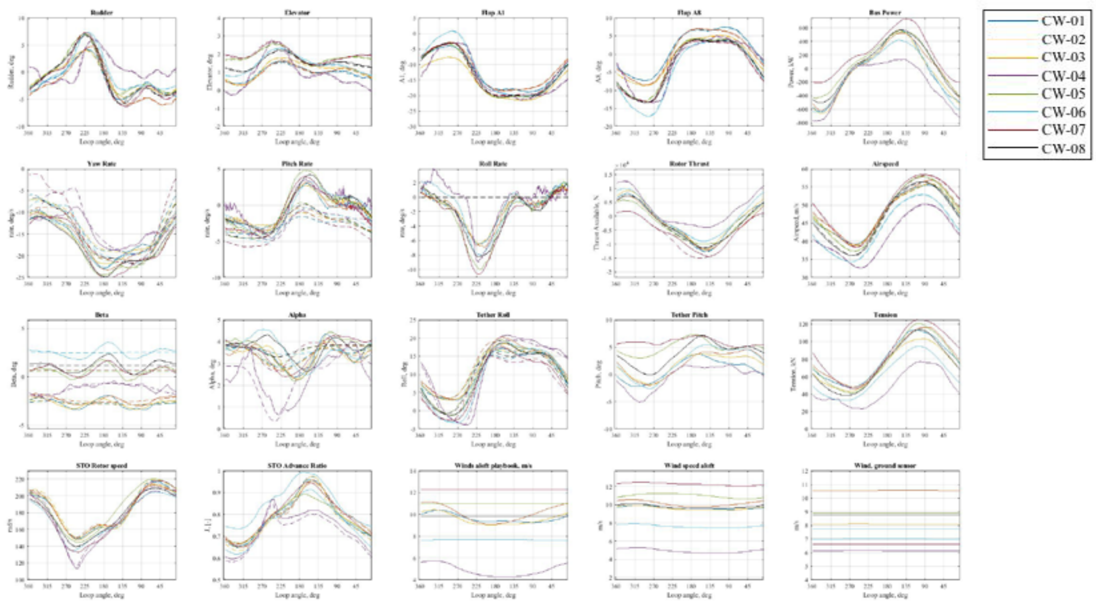


Compared to Gusts, The Kite Pitch Rate Response is Slow



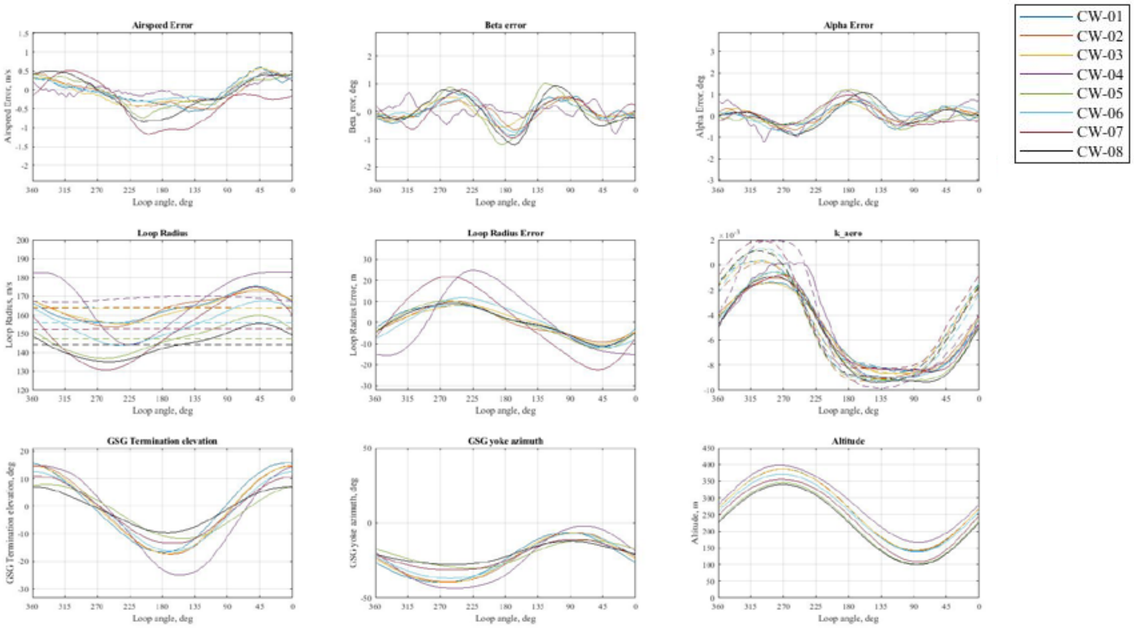
Loop Averages (Playbook Only)

- Generally very similar to CW05
- Loop radius error was similar to CW04 but greater than other flights
- Airspeed errors were very reasonable but larger than previous flights

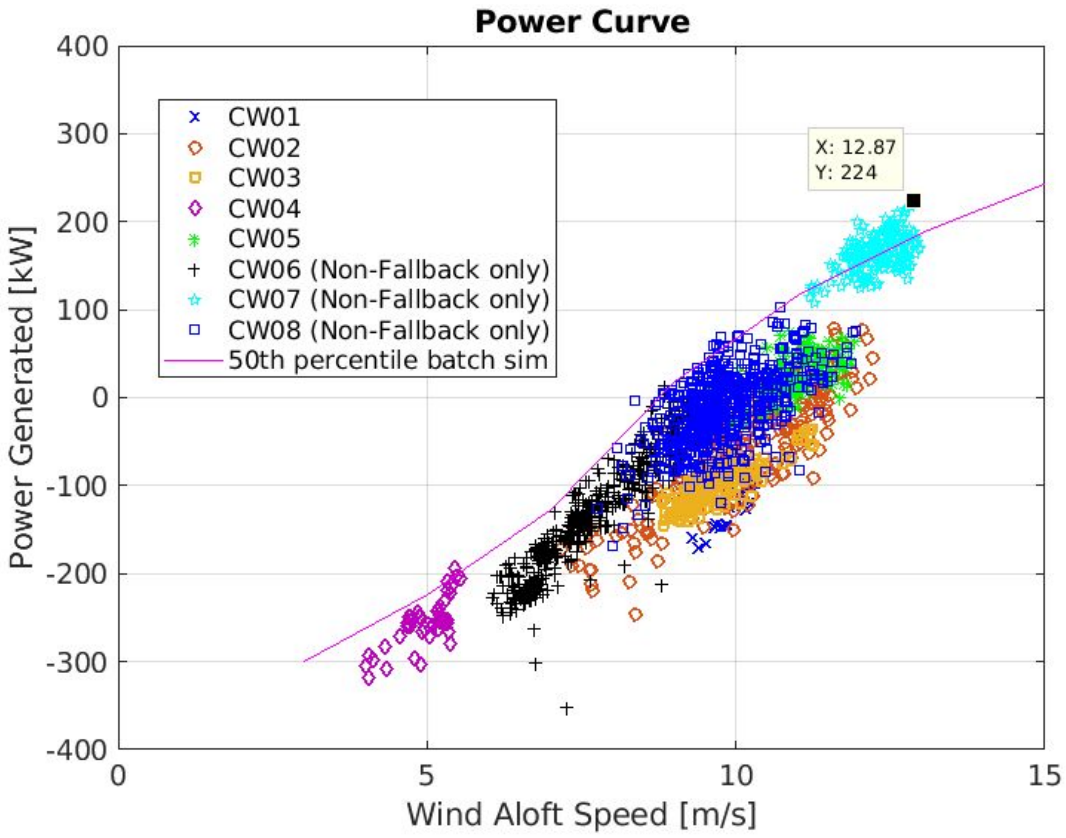


Loop Averaged Crosswind Errors (Playbook Only)

- Loop radius error was similar to CW04 but greater than other flights
- Airspeed errors were very reasonable but larger than previous flights

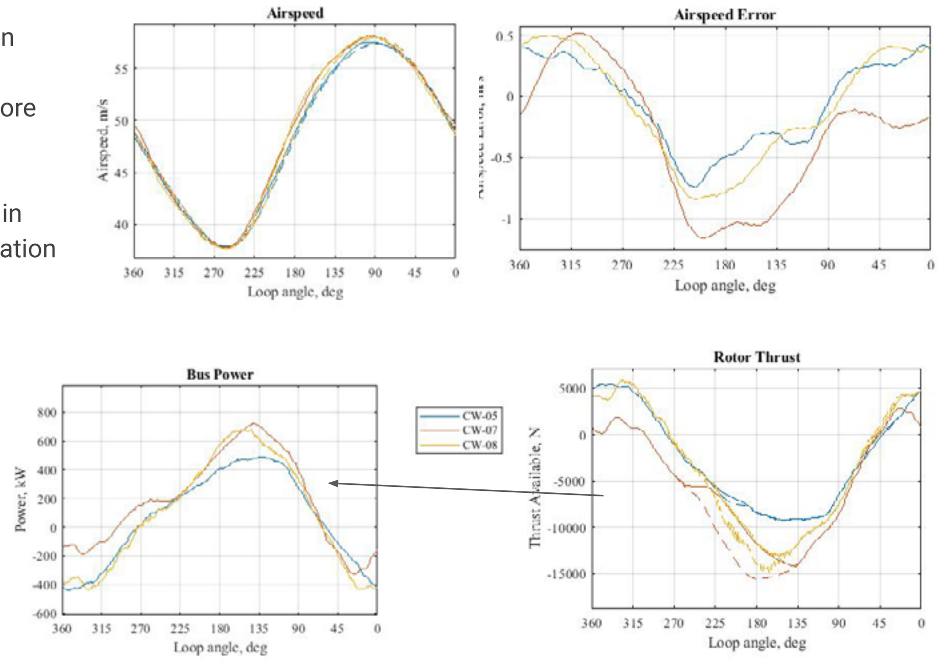


Power Curve



Power Increase at Same Wind Speed

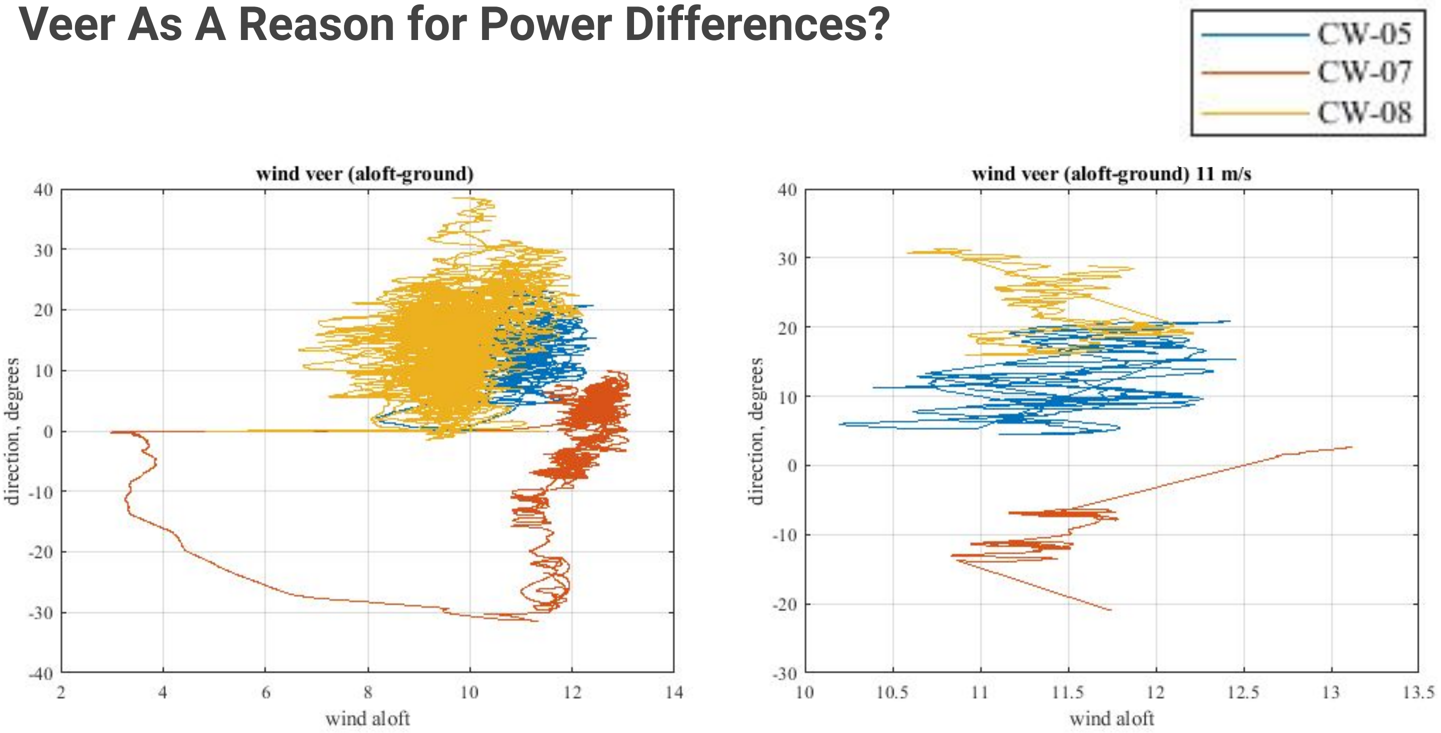
- Compared only 11.3 -11.7 m/s between CW05 and CW07, CW08
- Increased thrust command leads to more power the thrust available is the direct inverse of the power produced
- Playbook conditions were very similar in these loops (Airspeed, Loop size, elevation)
- Airspeed controller drives the thrust commands



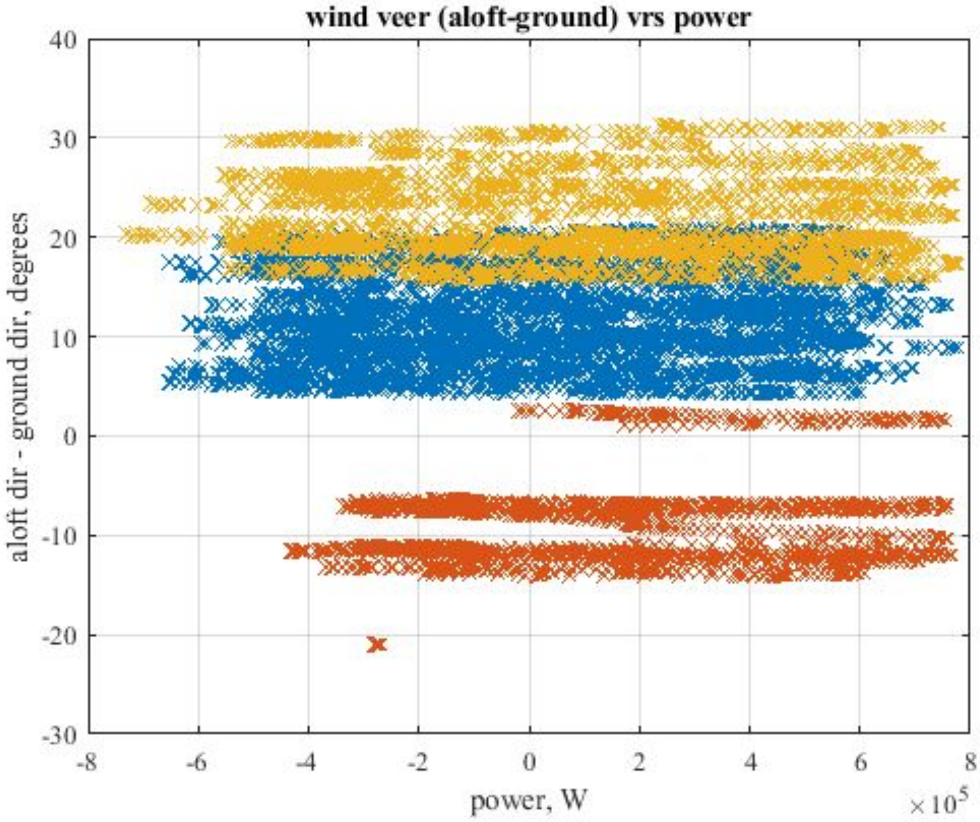
Flight	Average power for 11.3 -11.7 m/s
CW05	24.2 kW
CW07	146.6 kW
CW08	79.3 kW

Presentation with more plots and an on-going investigation here [internal ref]

Veer As A Reason for Power Differences?



Veer vs Power



MAKANI

Flight Testing
CW-05-08 Lessons Review

May, 2019

Executive Summary

- Flight summaries & highlights
- FAA update
- Night ops
- Operational wind limitations
- Cameras
- Flight testing look-ahead through Q2

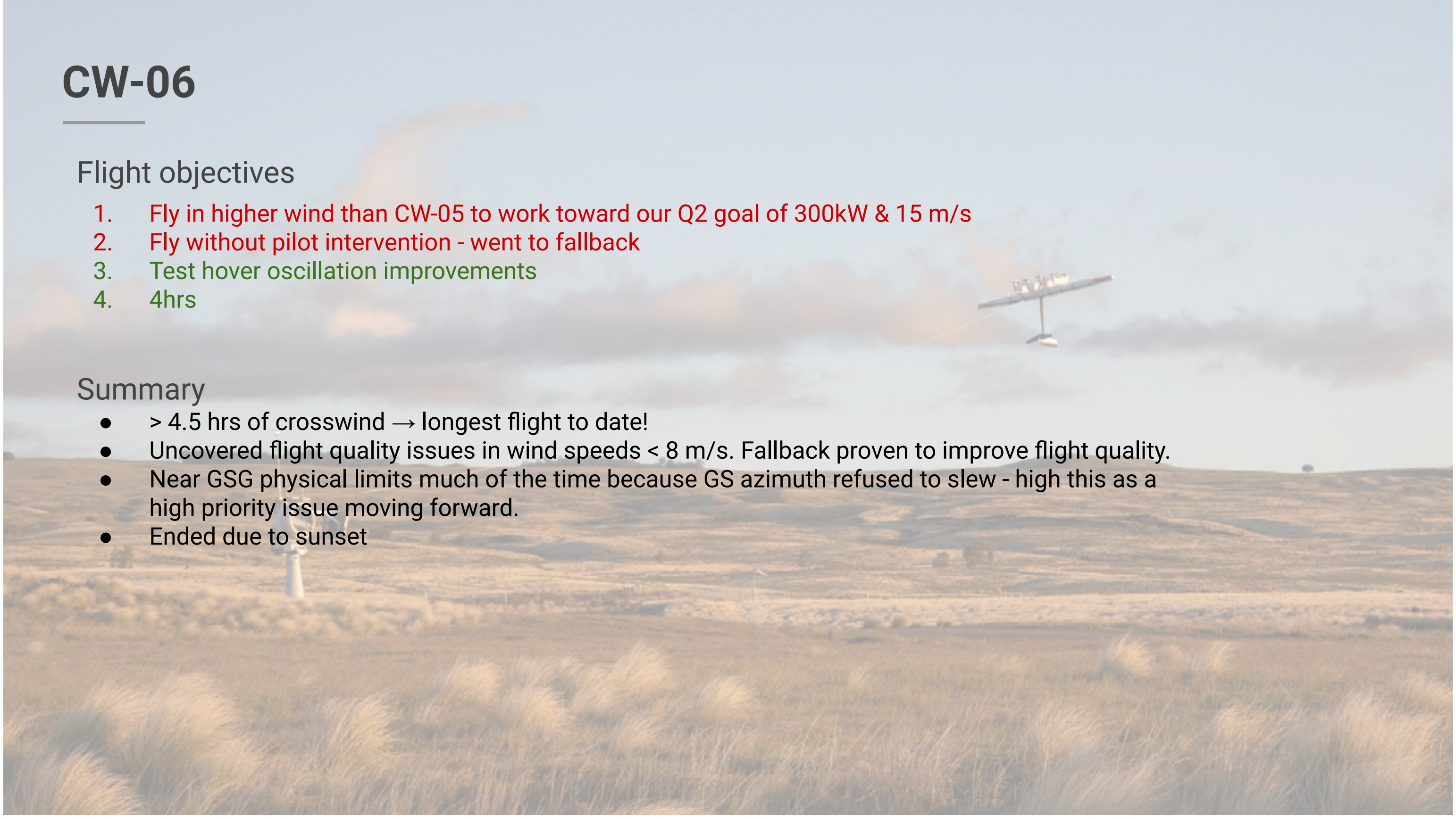
CW-05

Flight objectives

1. Fly lower, tighter loops in order to generate more power
2. Fly without pilot intervention
3. Fly at least four hours of crosswind flight
4. Demonstrate night time conspicuity scheme, including on the fly frequency and brightness adjustments of FAA lights
5. Find unknown issues with GS02 and crosswind that cannot be found in simulation
6. Collect video from numerous ground and onboard cams

Summary

- Demonstrated improved flight quality with lower, tighter loops, in wind > 10 m/s.
- Net positive power in crosswind!
- Flight ended due to sunset.



CW-06

Flight objectives

1. Fly in higher wind than CW-05 to work toward our Q2 goal of 300kW & 15 m/s
2. Fly without pilot intervention - went to fallback
3. Test hover oscillation improvements
4. 4hrs

Summary

- > 4.5 hrs of crosswind → longest flight to date!
- Uncovered flight quality issues in wind speeds < 8 m/s. Fallback proven to improve flight quality.
- Near GSG physical limits much of the time because GS azimuth refused to slew - high this as a high priority issue moving forward.
- Ended due to sunset

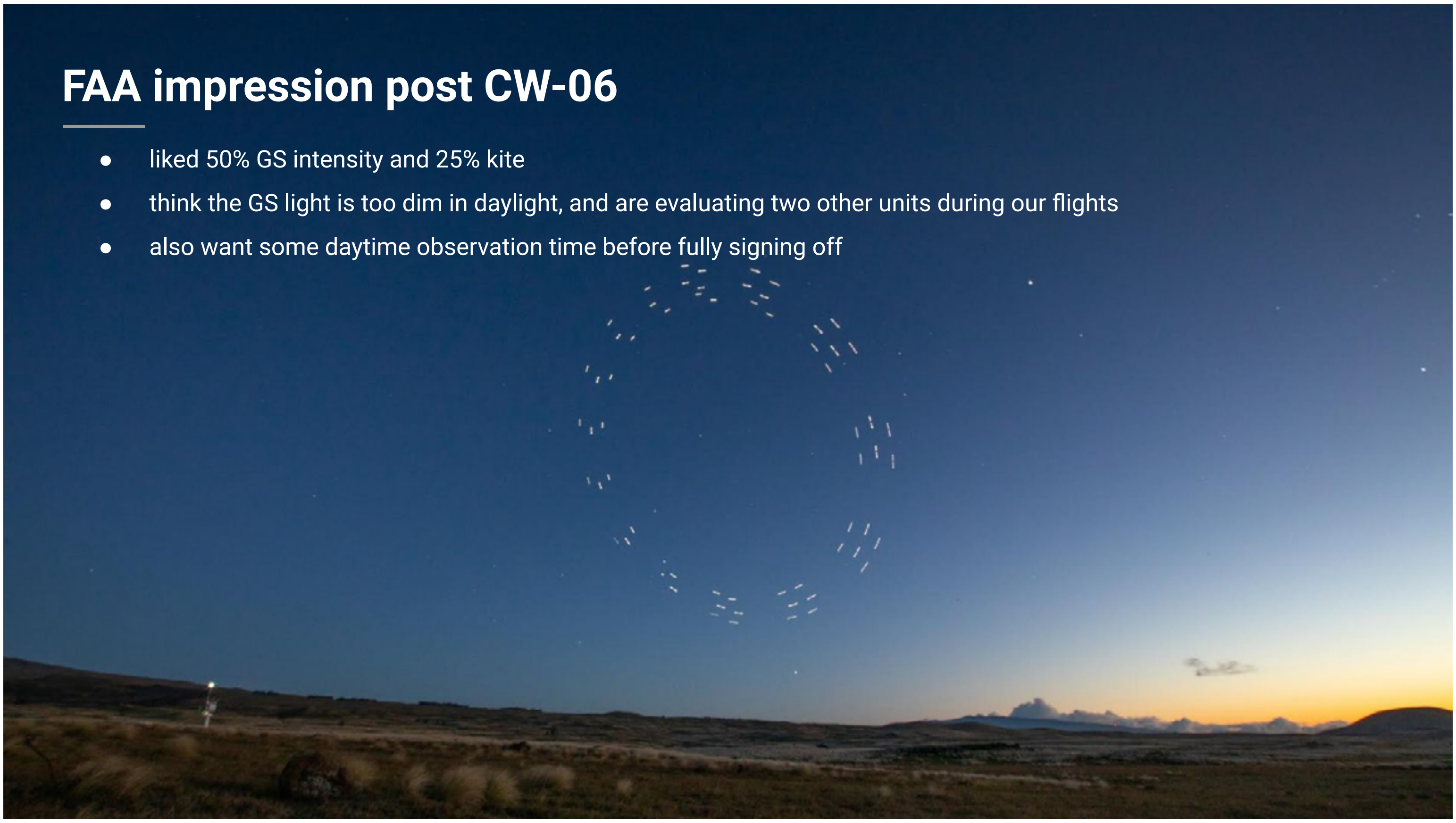
CW-07

Flight objectives

1. Pass final FAA conspicuity testing. Fly two/three flights flights beginning before sunset, until after dark in order to:
    a. Demonstrate lighting and marking scheme at night
    b. Answer remaining questions about daytime conspicuity
    c. Facilitate observation of potential replacement GS lights

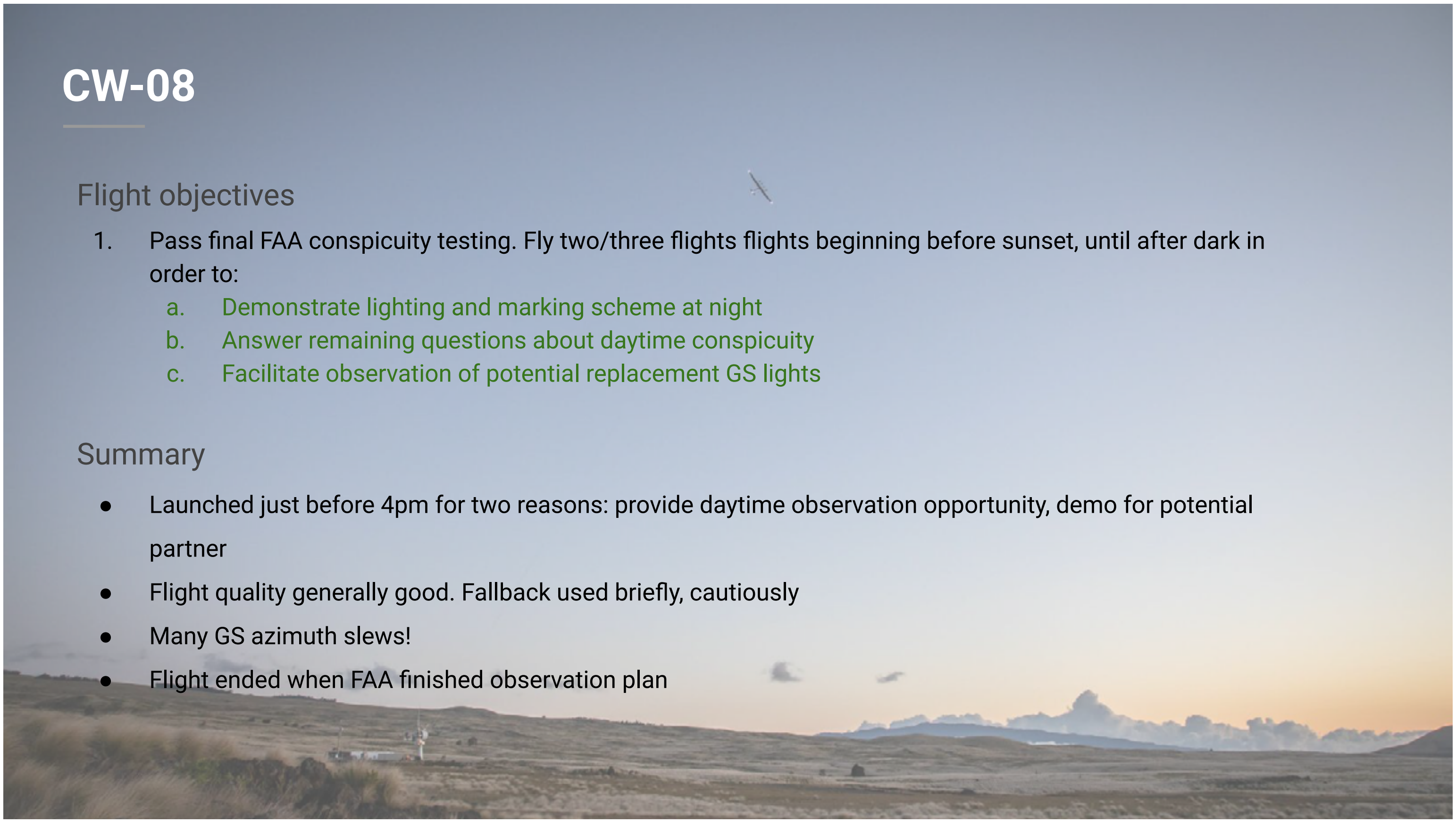
Summary

- First night flight!
- Varied light intensity only, per FAA requests
- Flight quality good through sunset, but degraded after dark. Fallback used and again eliminated undesirable aileron behavior and aero angle excursions.
- Flight ended because:
    - wind direction exceeded the 65° limit (peaked at 90°)
    - wind speed at ground dropped significantly, leading to concerns that we could see a large wind shift that would slew the crosswind path out of alignment with wind aloft



FAA impression post CW-06

- liked 50% GS intensity and 25% kite
- think the GS light is too dim in daylight, and are evaluating two other units during our flights
- also want some daytime observation time before fully signing off



CW-08

Flight objectives

1. Pass final FAA conspicuity testing. Fly two/three flights flights beginning before sunset, until after dark in order to:
   a. Demonstrate lighting and marking scheme at night
   b. Answer remaining questions about daytime conspicuity
   c. Facilitate observation of potential replacement GS lights

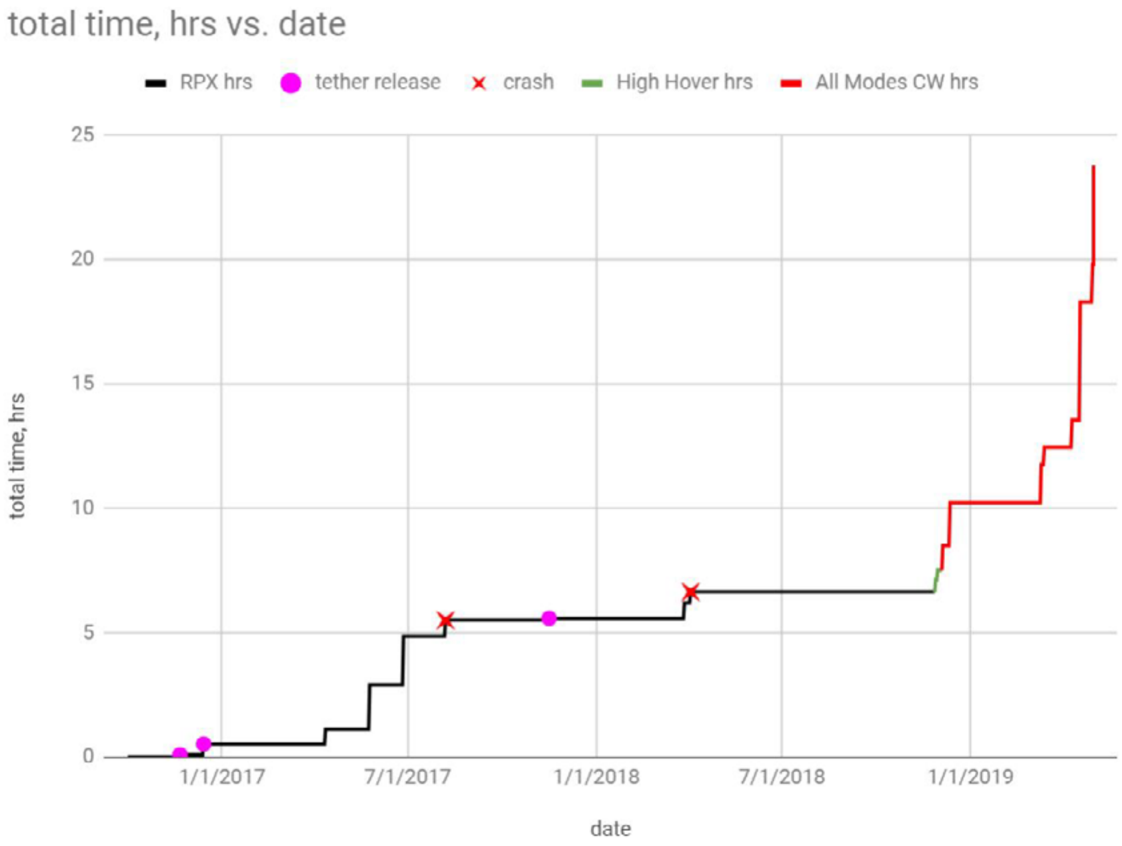
Summary

- Launched just before 4pm for two reasons: provide daytime observation opportunity, demo for potential partner
- Flight quality generally good. Fallback used briefly, cautiously
- Many GS azimuth slews!
- Flight ended when FAA finished observation plan

FAA results & next steps

- Lighting and marking results:
  - FAA satisfied with system conspicuity in day, twilight, dark
  - 25% lighting preferred, though 10% satisfactory in PR with no moon
  - Drake GS light unsatisfactory in day. TWR will need to be swapped in

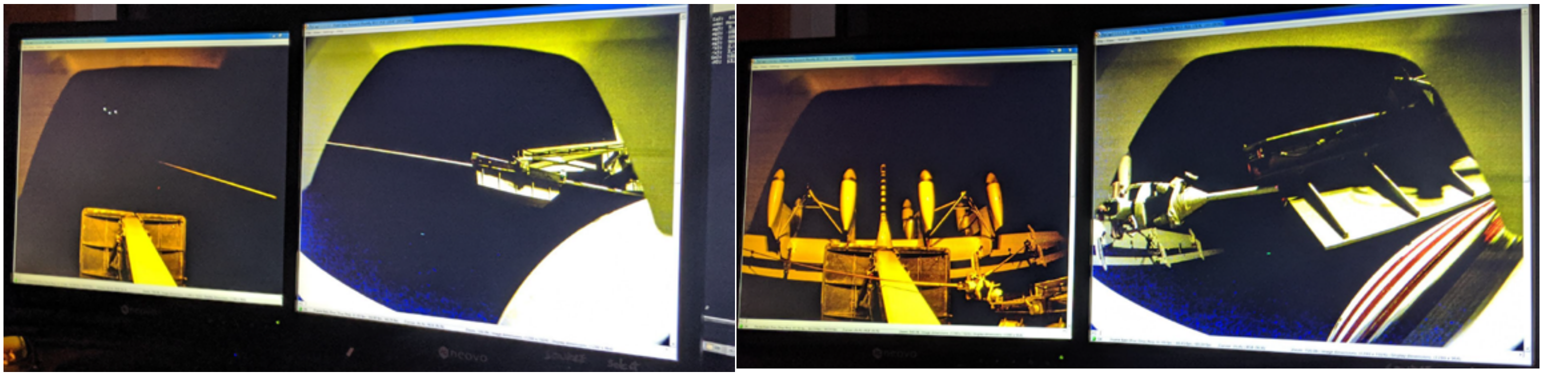
- Temporary Determination of No Hazard expires June 14.
  - R&D team will complete a "Memo" in ~2 weeks from testing complete
  - R&D team will complete a "Tech note" in 4-5 months.
  - To fly at night before June 14:
    - Memo → amend current temporary DNH
  - To fly after June 14:
    - Primary option: memo → permanent DNH that expires without tech note by X date
    - Secondary option: memo → new temporary DNH to bridge until permanent DNH finalized
    - Integrate TWR light (probably)



Night Flight

- Harder to judge flight quality without watching the kite, but we didn't feel like we forgot anything major
- I've heard that CW-07 flight quality that led to fallback was not as bad as CW-06. I hope other presentations confirm this, b/c it'll mean we used the info we had well.

- Long days in PR and ALM. As we expand the envelope this remote support is helpful but should remain P 0.5 as much as possible. Examples of useful conversations with ALM:
    - GSG limit abort scenarios, specifically trans-out behavior
    - Fallback safety in high wind when against azi limits
    - Safety of exceeding wind direction limits
    - General flight quality



M600 vs aerial lift limits

M600 (CW-08): Launch in 12 m/s average
Aerial lift: 12.5 m/s max instantaneous

P0 lift access required for:

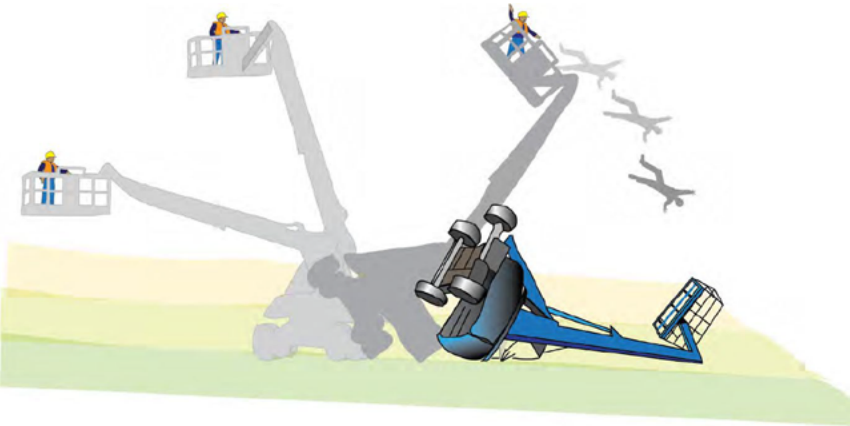
- Pitot checks & cover removal
- Kite tie down removal

How to deal with 15 m/s max wind envelope?
Short term:

- Complete these check early, take some risk of getting pitot wet
- ~~Find lift with higher wind limit~~
- ~~Integrate offshore pitot cover~~

Long term (by fall testing):

- Integrate offshore pitot cover onto PR kites
- Finish/customize offshore tie down prototype for safe operation from the ground



Cameras

- Continuing to cut down # of onboard cams saves time during W4W.
- Remember to communicate actively about which are most useful. Onboard cams will not block flight.
- Andrea and Scott began prototyping drone views for offshore demo. First two attempts (CW-05 & 6) were largely successful!

Under fuse looking at bridle connection to tether (bellycam)	On Fin looking down on airframe	On bridle knot pointed back at kite	On levelwind looking at kite & tether	Inside drum
Eli, Zach?, Mabraham	Trevor, Andrea	Eli, Trevor, Andrea	Simon, Johnny	Simon, Eli, Johnny
4	**16**	**11**	**G1**	**G9**
P1	P0	P2	P0	P0

Q2 Goals

1) Make 300 kW

1) Fly in 15 m/s wind

2) Fly partner demos

Ground Station
CW-05 - 08 Lessons Review

May, 2019

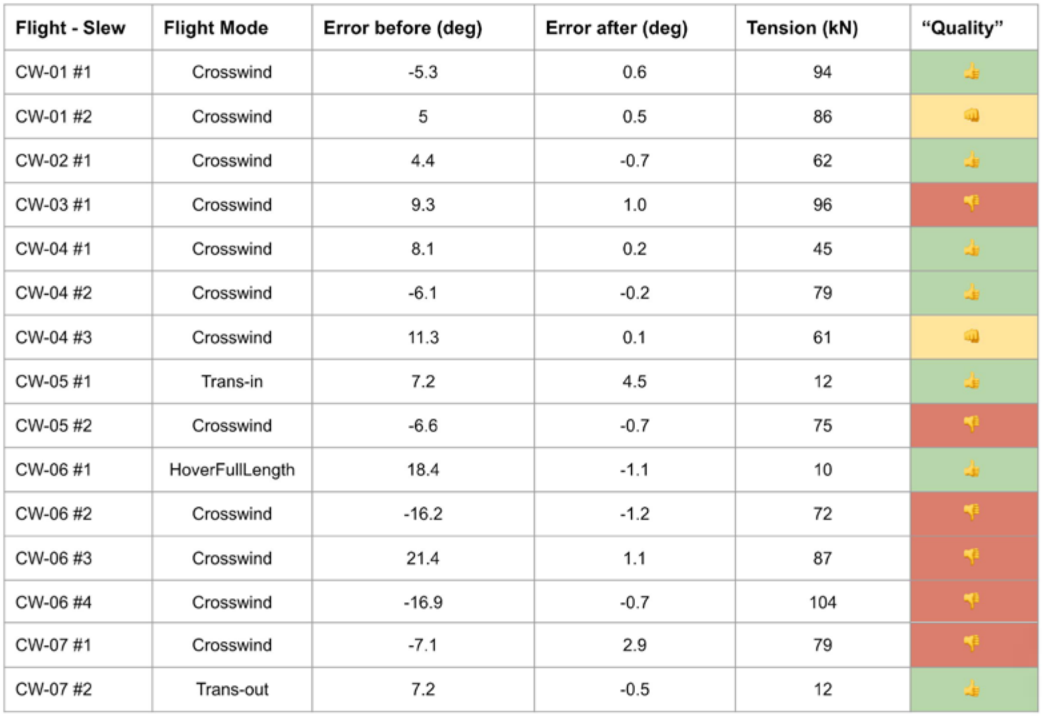
Executive Summary

- High tension slews, unlocked!
- Changes for upcoming flights

HT Slews, Long Story Short

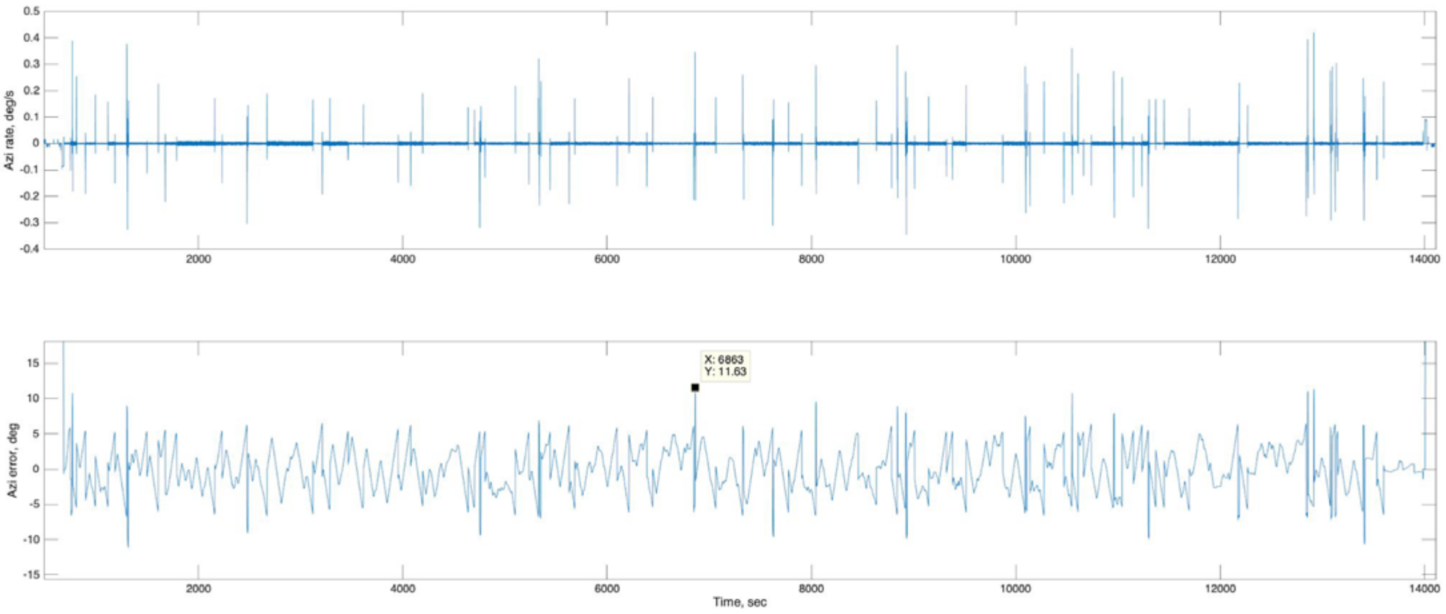
- Only 4 slews total for CW-01 - 03.
- By CW-04, it became obvious that it was not working as intended.
  - The azimuth error exceeded 20 deg on occasion.
  - That caused the gimbal motion to get much closer to its limits, which was one of the main reasons for the “end of flight” call for CW-04.
- A deep dive in the controller showed that the integrator was never reset throughout the flight.
- The integrator reset fix was implemented after CW-06, and voilà! Slews were initiated properly afterwards.
- But CW-06 - 08 saw the slew controller being poorly tuned for high tensions.
  - The gain and the bandwidth of the system appear to be too high.
- The next two slides show relevant information for the 15 slews prior to CW-08, and the 75+ during CW-08.
  - The azimuth error did not exceed 12 deg during CW-08.

HT Slews, CW-01 - 07



Flight - Slew	Flight Mode	Error before (deg)	Error after (deg)	Tension (kN)	“Quality”
CW-01 #1	Crosswind	-5.3	0.6	94	👍
CW-01 #2	Crosswind	5	0.5	86	👊
CW-02 #1	Crosswind	4.4	-0.7	62	👍
CW-03 #1	Crosswind	9.3	1.0	96	👎
CW-04 #1	Crosswind	8.1	0.2	45	👍
CW-04 #2	Crosswind	-6.1	-0.2	79	👍
CW-04 #3	Crosswind	11.3	0.1	61	👊
CW-05 #1	Trans-in	7.2	4.5	12	👍
CW-05 #2	Crosswind	-6.6	-0.7	75	👎
CW-06 #1	HoverFullLength	18.4	-1.1	10	👍
CW-06 #2	Crosswind	-16.2	-1.2	72	👎
CW-06 #3	Crosswind	21.4	1.1	87	👎
CW-06 #4	Crosswind	-16.9	-0.7	104	👎
CW-07 #1	Crosswind	-7.1	2.9	79	👎
CW-07 #2	Trans-out	7.2	-0.5	12	👍

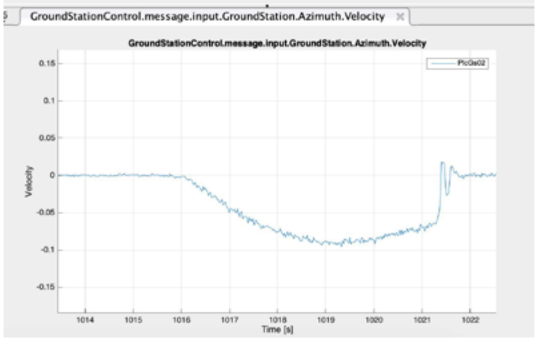
Azimuth Rate and Error During CW-08



What a Typical Good Slew Should Look Like

See video on YouTube playlist “20190418 CW-06 - Makani M600 Base Station Azimuth Slews” around 24:27

IPPV signal

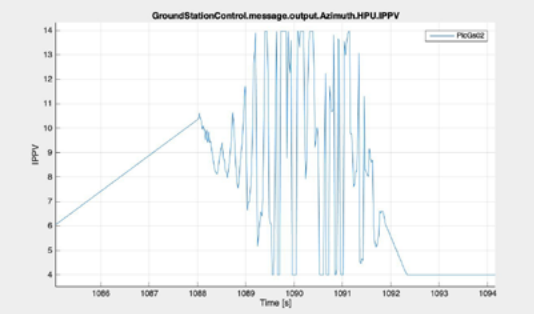


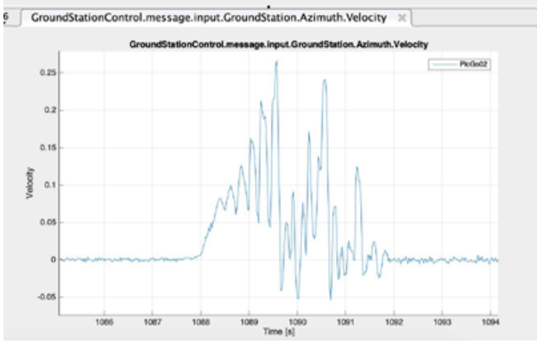
Azimuth rate

What a Bad Slew Looks Like (With Sound!)

See video on YouTube playlist “20190418 CW-06 - Makani M600 Base Station Azimuth Slews” around 15:19

IPPV signal





Azimuth rate

Most Important Changes for Upcoming Flights

- Bump block installed.
  - Winch pos at azimuth slew changed to -165 deg.
  - Winch accel during transform reduced by a factor of 20 to smoothly engage the bump block.
    - ⇒ Transform now takes 80 s instead of 35 s.
- We are tuning the HT slew controller gains.
- We are modifying how the integrator is reset in the controller.
- We are implementing a slew abort if the kite gets pulled in the wrong direction.
- Would love to see Michael’s “racetrack” change for moving the loop circle being implemented.
- We could increase the winch speed during reel to 2 m/s.

MAKANI

Power Systems / Avionics CW-05 thru CW-08 Lessons Review

May, 2019

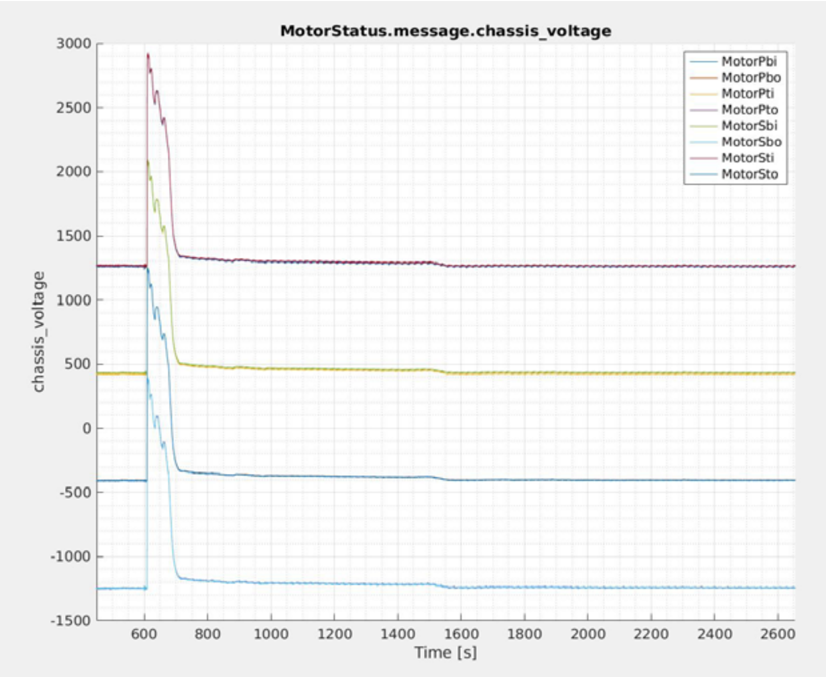
Executive Summary

- Near-term issues:
  - MV isolation
  - MVLV internal comms problem
  - Reliability (component failures)
- Flight summary
  - Loadbank performance
  - Prop differences
  - Step changes in commands

- Long-term reliability hazards
  - High power variation
  - Rapid power variation
  - Rapid servo commands

MV Isolation Bug

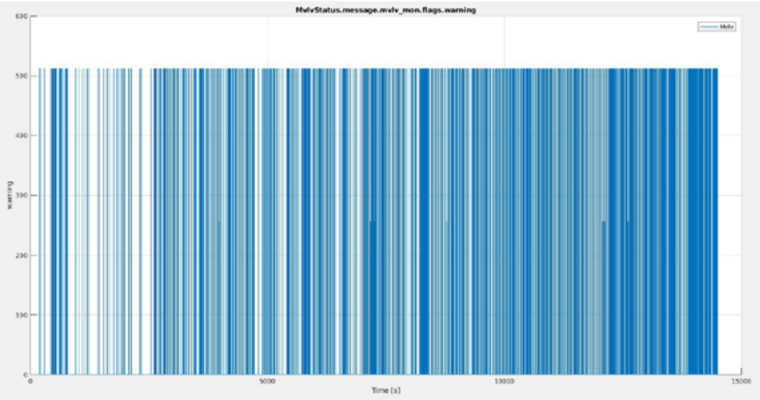
- Reoccurred in CW-07 but not in CW-08
- Less severe
- Still believe due to water ingress
- System performed as-designed
- “Enhanced inspection” this week
    - So far, no “steaming gun”



MVLV Comms Issue

MCP342x reading error warning bothers operator(bug 124316215)

- Increase error counter threshold should reduce probability of this warning.
- Root cause is still under investigation and need spin motor to collect more data.



Si7021 stopped updating in the middle of CW (bug 128433921)

- Reproduced on motor controller
- Si7021 loops between Init state and Flush state after an i2c error.

Component Failures

- Satcontainer network switch failure
    - Traced to sloppy installation
    - Would NOT be flight critical in a grid-connected world
- Genset problems
    - Would not exist at all in a grid-connected world
- Satcon GDB
    - Truly scary; no redundancy present without Ground Power Switch Network
    - To go on-grid, we will need more of a COTS system
- Satcon filter capacitor
    - Ditto

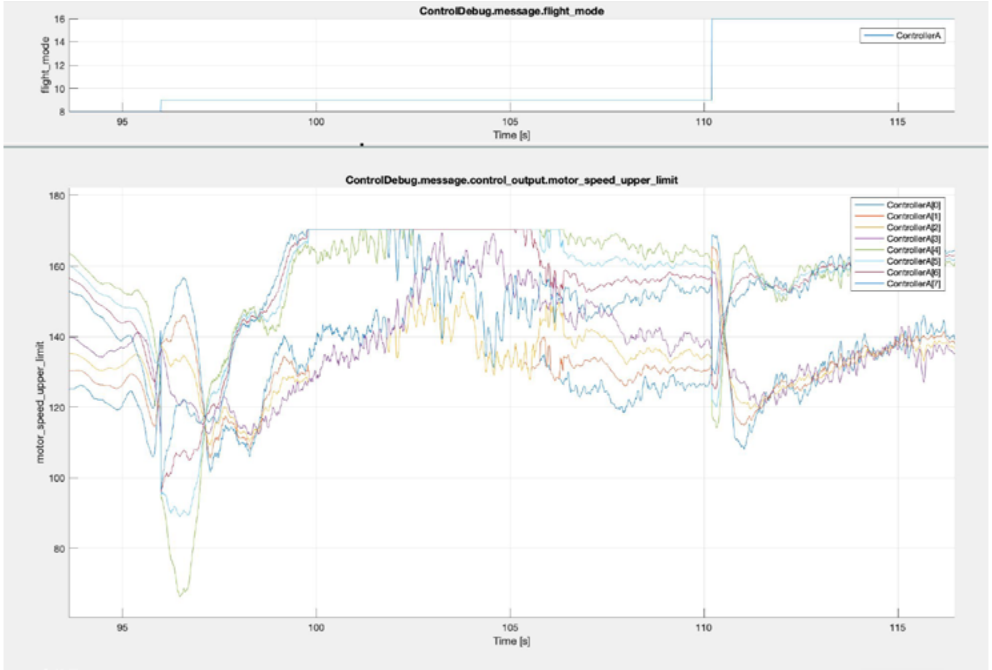
Loadbank Performance / Expected Life

- Loadbank relay life
    - Mechanical: 500,000 operations
    - Electrical: 100,000 operations
- We have 15 individual relays, algorithm implements wear leveling.
- From CW-01 thru CW-08 we've actuated each relay in the loadbank about 2246 times.
- Expected life is ~750 hours of flight.
- Our loadbanks were purchased used; not sure how many cycles the relays have already gone through.

Flight	**Flight time [sec]**	**Loop count**	**Total actuations**	**Individual actuations**
CW-01	3876	82	1372	91.5
CW-02	6825	222	3791	252.7
CW-03	5780	186	2960	197.3
CW-04	2881	48	467	31.1
CW-05	4188	131	2156	143.7
CW-06	17510	683	8890	592.7
CW-07	5535	202	2682	178.8
CW-08	14515	640	11376	758.4
Total	61110	2194	33694	2246.3

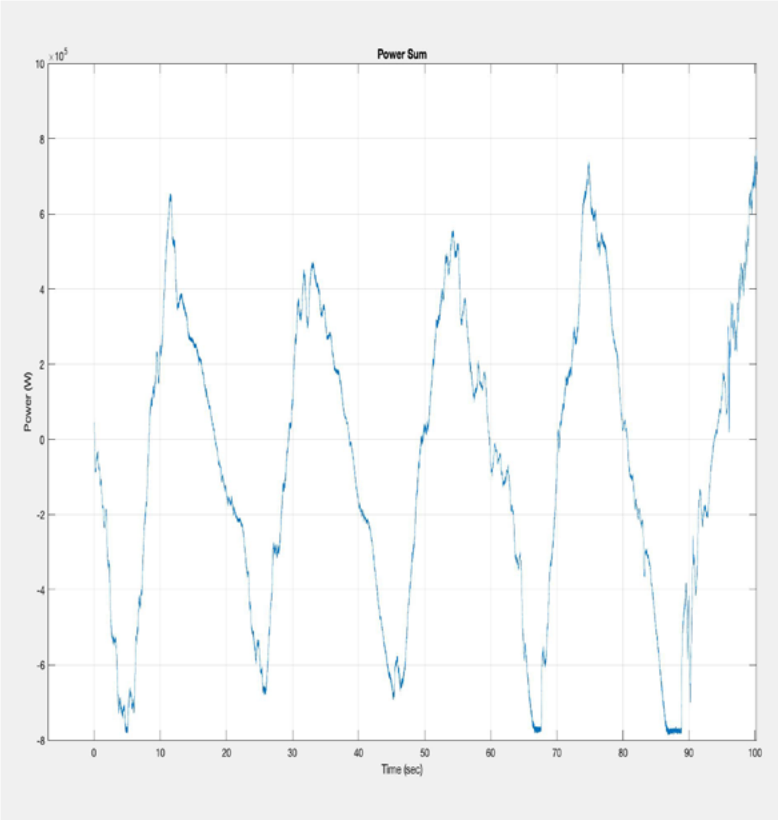
Step Changes in Commands

- Still very large step changes in speed with flight mode changes and due to air speed discontinuity in trans in.
- Step changes lead to voltage swings on tether due to tether and ground power dynamics.
- Large instantaneous power to follow step commands.



Reliability: Power Variation

- Power semiconductor modules (in ground inverters, in motor drives) don't handle repeated power transients well, due mostly to transient mismatches in thermal expansion
- Our group planned for 600 kW +/- 200 kW
- We did NOT plan for 100 kW +/- 600 kW!
- Every flight is a flight on borrowed time until we can smooth the power variation
- Short stack and GPSN may help with this from a "do not crash" standpoint
- BUT: Not from an availability / uptime / maintenance cost standpoint
- ALSO: Cannot attach one of these to the grid

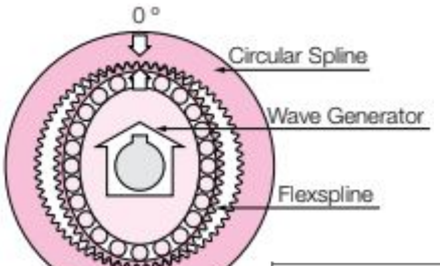


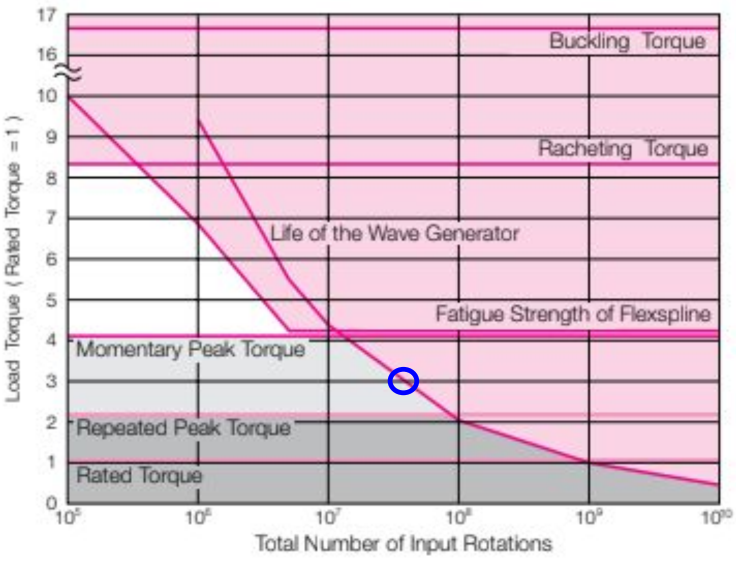
Reliability: High Frequency / Slew Rate Motor Commands

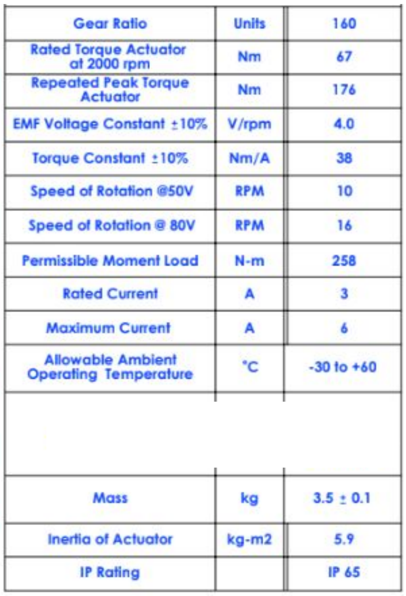
- Ditto the previous slide: Power electronics don’t react well to 100,000’s of rapid load changes
- (Correct me if I’m wrong): There’s no reason to be chasing every gust
- We will continue to fly at significant long-term risk unless and until we can smooth the power commands
- Proposed architecture for power/torque control that may help to smooth the commands
    - Work is stalled since Norway, would welcome some assistance

Rapid Servo Commands

- Torque loads close to 3X rated torque (source)
- 2000 RPM input maps to 1.3 Rad/Sec Actuation (160:1)
- Most actuators constantly moving and reversing
- 5x10^7 Input cycles @2000RPM with constant motion maps to ~400 hour expected life.







Gear Ratio	Units	160
Rated Torque Actuator at 2000 rpm	Nm	67
Repeated Peak Torque Actuator	Nm	176
EMF Voltage Constant ±10%	V/rpm	4.0
Torque Constant ±10%	Nm/A	38
Speed of Rotation @50V	RPM	10
Speed of Rotation @ 80V	RPM	16
Permissible Moment Load	N-m	258
Rated Current	A	3
Maximum Current	A	6
Allowable Ambient Operating Temperature	°C	-30 to +60
Mass	kg	3.5 ± 0.1
Inertia of Actuator	kg-m2	5.9
IP Rating		IP 65

Changes for Upcoming Flights

- Remove nuisance motor warnings from PFD
    - PGOOD warnings will no longer be latching. IF our theory that the warnings are transient is correct, the flight monitor may still flicker occasionally.
- Loadbank / microgrid test suite
- Crowbar upgrade
- Higher voltage / higher power
- Short stack?
- Backup power measurement?

MAKANI

Aeromechanical
CW-05 / CW-08
Lessons Review

May, 2019

Executive Summary

- Going forward - Our **risk-tolerance will need to remain high (and likely increase)**
- We continue to find cracks in bond lines of our primary structure - And that's just where we can inspect...**Who knows what's happening in areas where we are not looking?**
- Continued **crack growth will increase our exposure to events like "jazz hands" due to a reduction in stiffness** (mitigation: monitoring of flight vibration levels, and establish (and enforce) no-go criteria for in-flight vibration levels)
- Undetected, continued **crack growth will increase our exposure to catastrophic structural failure events**
- Sometimes cracks are just cracks!
- Currently hard to **link inspection pics to CAD models and analysis** (mitigation: suggest that we annotate a CAD print-out of areas w/ known cracks, mark zones on CAD print-out that we can then correlate to inspection pictures) to help identify and track areas that are structurally compromised
- We need to be prepared to **update structural analyses based on new findings and inspection results** (cracks, areas where we show negative struct. margins) - This will cause delays or require higher risk tolerance

Insights From These Flights

- Longest flight time on an airframe (and tether, GS, etc) so far
- Cover cracks observed during SN4 inspection
- Our aerodynamic operating envelope seems to be correct:
    - Stall AOA - yes, so probably aero performance and control degradation post-stall
    - Human response time is insufficient to address in-flight problems
        - Could budget to implement an automated fallback scheme
        - Would like more guidance from flight testing on flight monitor fall-back and return-to-base criterion for flight monitors

Changes for Upcoming Flights

- Aerodynamics:
    - Desire a higher angles of attack: slats
        - ⇒ Effect: reduces the cut-in speed
        - ⇒ Effect: increased robustness to gusts at moderate (5 deg) alphas
    - Desire a higher roll authority: bigger flaps
        - ⇒ Effect: keeps Static Margin of 10%, increase roll authority by 30%
        - ⇒ Constraint: Servo torque limits of 65 Nm
    - Desire a higher yaw authority: bigger, aerodynamically balanced rudder
        - ⇒ Effect: Reduce torques, remove high speed table that makes Controls nervous
        - ⇒ Requires: Stays on the tail to maintain structural integrity
    - Re-fit empiricize aerodynamic model to flight test data
        - ⇒ Effect: Matches C-Sim to flight test data

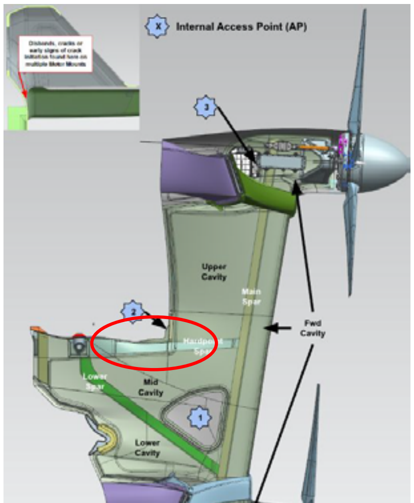
Structural Damage

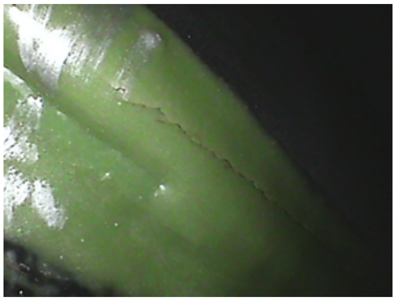
- Pylon 1
    - Hardpoint Spar bond
- Pylon 2
    - Aft hardpoint bond
    - Bond near circular cutout of lower nacelle (under capacitor box)
    - Upper and lower motor mount bonds
- Pylon 3
    - Lower motor mount bond

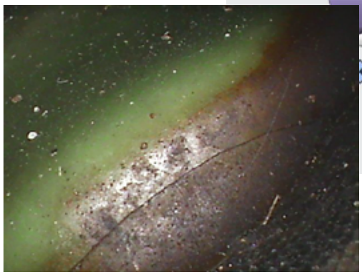
Note: These are ongoing investigations

Pylon 1 - Hardpoint Spar Bond

- Bug 132559403
- RH skin <-> hardpoint spar bond repaired after jazz hands - this crack did not grow
- Possible new cracks on LH skin <-> hardpoint spar bond (still collecting info)







Pylon 2 - Aft Hardpoint Bond, Lower Nacelle

- Bug 132560583
- Also previously repaired from jazz hands incident
- Aft hardpoint upper bond separated
    - Partial separation from jazz hands, wasn't possible to repair: that's OK, joint is clamped by big bolt and is not a primary shear load path.
- Lower nacelle bond: still collecting more info about this

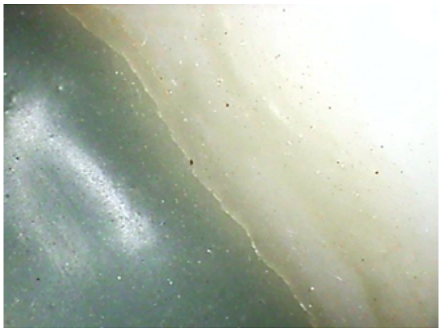
Aft hardpoint

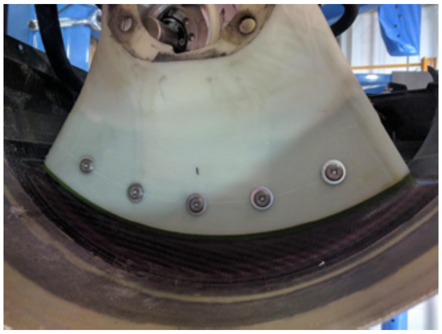
Lower Nacelle

Aft hardpoint

Pylon 2+3 - Motor Mount Bonds

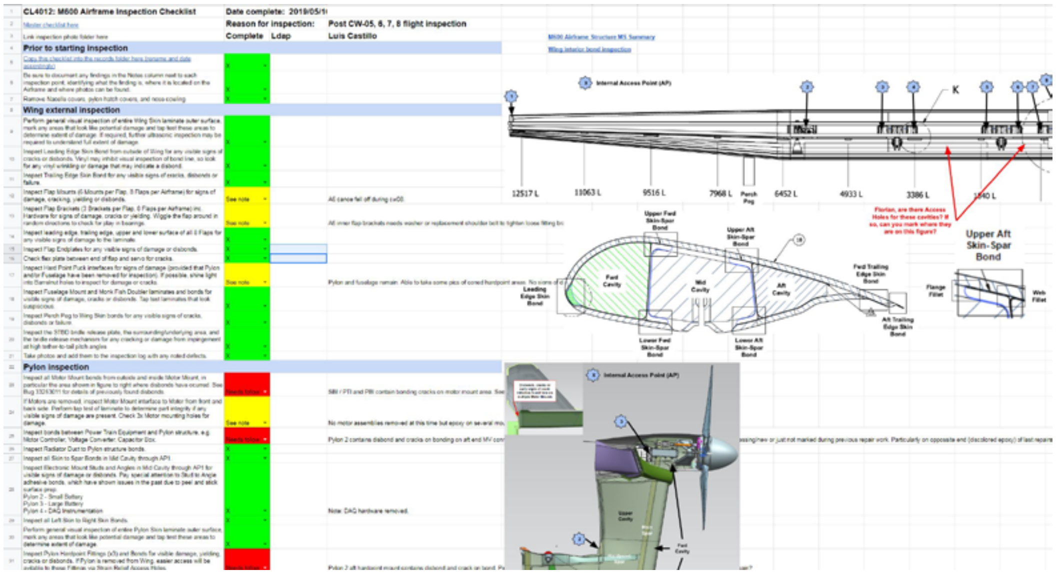
- Bug 132559087
- This first appeared on SN2, fix was 5x fasteners through bond: applied to all pylons, regardless of cracks
- Plan: mark crack extent, inspect each flight unless short+benign.





Structures: Process Improvements

- Streamline inspection report: map location on a diagram and label photos and/or sort into folders
- Define when inspections are mandatory (or when partial inspections may be acceptable)
- Date all crack growth marks



CL4012: M600 Airframe Inspection Checklist
Date complete: 2019/05/1
Reason for inspection: Post CW-05, 6, 7, 8 flight inspection
Complete Ldap Luis Castillo

Prior to starting inspection

Remove Nacelle covers, pylon hatch covers, and nose cowling

Wing external inspection

Inspect Flap Endplates for any visible signs of damage or disbonds.
Check flex plate between end of flap and servo for cracks.
Take photos and add them to the inspection log with any noted defects.

Pylon inspection

Florian, are there Access Holes for these cavities? If so, can you mark where they are on this figure?

Root Cause Analysis and Corrective Actions for FCW-01 Loss of Kite

Kurt Hallamasek
October 2019

High-Level Summary

Root Cause Analysis

RC1: The root cause of the crash is the loss of tether tension:
The kite lost tether tension after transitioning out of crosswind, while it was moving into position to allow the ground station to transform into the reel-in configuration. This resulted in insufficient roll stability. The system lost attitude control, could not recover and crashed.

RC2: The tension controller did not have the ability to correct for the tension loss sufficiently fast. The following factors contributed:

- Buoy motion contributed to tension loss. Even though the buoy slowly retracted towards its pre-flight location after the crosswind tension subsided, the buoy's rocking motion, established by the cyclic tension variations during the crosswind loops, persisted and moved the tether anchor point towards the kite, slackening the tether.
- The kite was pitched far (-13°) forward after transitioning out of crosswind into hover. This requires additional time to correct for by the tension regulator.
- The tension feedback regulator did not increase the tension appreciably.
- The tension feed-forward controller did not increase the tension.

RC3: The state estimator, affected by GPS errors, estimated the altitude too low by 20 to 37 meters which contributed to a high transout altitude, which in turn reduced the roll stability:

- More negative tether pitch reduces the stabilizing bridle roll moment.
- The kite has to carry more of the tether weight as altitude increases.
- More tension is required to generate the roll stabilizing horizontal tension.
- The tension controller must accelerate the kite to a higher radial velocity to keep the tether taut.

RC4: The hover path controller did not control the kite's path along a trajectory that maintains tether tension and contributed to tension loss:

- The kite's radial velocity component is regulated to zero, counteracting the tension regulator.

RC5: The C-sim does not predict roll moments induced by propwash and the thrust generated to maintain yaw attitude during the translation to get into position for reeling the tether in. Simulations to validate control strategies FCW-01 did not warn about hover paths vulnerable to this roll moment.

This “phantom” roll moment overcame the restoring bridle roll moment, which was weakened by the loss of tension and the high tether pitch angle due to the transout altitude. (The exact mechanisms are still under investigation).

RC6: The C-Sim does not predict the kite-buoy interaction leading to tension loss after transitioning from crosswind flight to hover. We rely on simulation to avoid bad control strategies.

Preventive Actions

Preventive actions will be implemented to avoid the loss of another kite in similar circumstances before the next flight. These actions in part change and slow down kite motion to avoid maneuvers that require strong control actions in hover regimes with reduced roll and yaw stability. These changes will be revisited once the corrective actions have been implemented.

PA1: Descend before translate at high transout altitudes.
The bridle’s roll and yaw stiffness is reduced at the tether pitch angles at high altitudes. Avoiding translation avoids the associated rotor-thrust induced roll moments..

PA2: Slow the translation rate during PrepareTransformGsDown from 5 m/s to 2 m/s.
Reduce the sideslip that introduces a roll moment by dragging one wing through the rotor wake.

Corrective Actions

Corrective actions will address underlying the failure mechanisms to avoid these failures in the future.

CA1: Improve the Tension Control.
  - Initialize tension regulator/pitch integrator more carefully after TransOut.
  - Improve tension feed-forward to command correct pitch commanded tension set point.
  - Maximize tension regulation bandwidth within allowable stability margins to counteract tension disturbances caused by unpredictable kite and tether motion.

CA2: Lower the TransOut altitude.
Lower TransOut attitudes provide a bridle geometry with stiffer stabilizing roll moment, more control authority due to improved thrust margin, less total tension to produce roll-stabilizing horizontal tension, less radial motion to absorb by the tension controller.

CA3: Make kite position estimator robust to GPS receiver errors.
Errors in the altitude estimate affect TransOut altitude.

CA4: Explicitly command radial velocity that keeps the kite on the tether sphere in the hover position controller.
This harmonizes the pitch commands with the tension controller.

CA5: Extend simulation capabilities to include “phantom roll moment”.
We rely on the C-Sim to warn us about problematic designs of control strategies. The C-Sim should capture the regions of instability due to the “phantom” rotor-thrust induced roll moment.

CA6: Improve command center monitors to warn about approaching yaw/roll stability limits.
The view from the command center does not let the pilot discern small roll errors. It does not warn the pilot about roll moments that we may expect to become problematic due to yaw thrust and sideslip.

CA7: Improve fidelity of Buoy-Kite interaction simulation to better approximate tether tension behavior during PrepareTransformGsDown.
The C-Sim should call out control strategies that fail to maintain tether tension.

CA8: Kite design change: add active roll control to the kite.
Active roll control allows the system to retain attitude control in hover regimes where the current bridling system is ineffective due to low tether tension or acute tether pitch angles. Active roll control can be prototyped on the M600.

CA9: Ground station design change: avoid the requirement for a ground station transform before reeling in the tether.
Reeling in the tether immediately after TransOut will maintain tether tautness and improve passive stability. If the ground station winches in the tether while keeping it taut, it also allows the kite to maintain a more stable pitched-forward attitude. A “transform-less” ground station should be considered for the next generation ground station design.

Report Structure

List of Figures

Background

Methodology

The loss of kite YM600-05 during flight FCW-01 occured on August 8, 2019 at the Metcentre offshore test site in Norway. The investigation into the root cause was kicked off August 19th with a brainstorming meeting with representatives from the controls, power, tether, and avionics teams. The flight test team had not returned to the US at that time, so the test pilot's input was obtained the following week after his return. This meeting resulted in questions to answer and possible causes to investigate (agenda, notes). Each possible cause was addressed and either eliminated or substantiated by further analysis. In the analysis, we examined whether the observed behaviour was consistent with the design intent and how it compared to previous successful onshore flight tests. A list of corrective and preventive actions was accumulated as the investigation proceeded.

The investigation team

A group of engineers who are intimately familiar with various subsystems of the kite carried out the investigations. Michael Abraham contributed with his expertise on control laws, flight dynamics and his rich set of analysis tools. Geoff Dolan brought his forensic skills and wide reaching system expertise to bear on kite path planning analyzing interactions between the regulation systems. He generated the contour plots based on Eli's catenary model. David Elrom addressed questions about state estimation and GPS measurements. Eli Patten verified that procedures to calibrate and zero loadcells were followed and computed tensions based on catenary models and flight data. Tao Tang investigated wind metrology. Kurt Hallamasek led the investigation and is the principal author of the report.

Review of relevant operational concepts

This section gives a brief overview of the kite operation in the flight modes leading up to the loss of kite. The operation of the systems involved in the analysis is reviewed.

Flight modes leading up to loss of kite

The kite lost attitude control during the maneuver to get in position where the ground station can transform into the reel-in configuration. This flight mode is “PrepTransformGsDown.” The sequence of flight modes leading up to this mode is shown below. The last crosswind flight mode before transitioning to hover is flight mode “PrepTransOut.” There, the kite flies large loops, tether tensions are high. The buoy rocks in sync with the tether tension. The path planner lowers the loop center to target a favorable transout height. The kite then transitions to hover mode in flight mode “TransOut.” The tether tension decays rapidly as the kite comes to a stable hover at a constant altitude. The buoy motion decays, but still persists. In “PrepTransformGsDown,” the kite lowers its altitude while traversing to get into position for the ground station transformation. For FCW-01 this was the last automated flight mode before the pilot assumed control of the flight.

The system operated, mostly nominally, until PrepTransformGsDown; many of the plots in this analysis zero the timescale when the system enters that last flight mode.

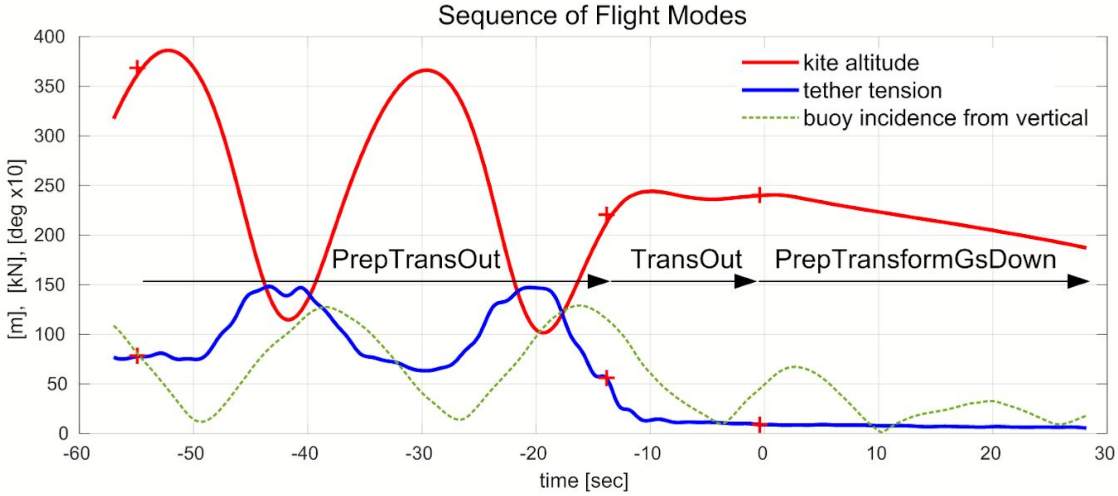


Fig. 1: Sequence of flight modes leading up to the loss of kite.

Tension and attitude regulation

Tether tension and kite motion are coordinated, but they are controlled independently. When hovering, altitude and attitude controllers control kite motion, while the tension controller maintains tether tension. Kite motion and tether tension targets cannot be specified independently and there will be some contention between these control systems. For example, the kite hovering in a fixed position in steady-state will be acted on by the tether tension determined by the tether mass and catenary geometry. Unless that exact tension is specified as reference at that exact position, the tension regulator will experience the kite motion regulation as a disturbance, and vice-versa.

The tension regulator is an integral controller. The integrator will keep integrating the tension error to increase the magnitude of the control effort until the average tension error is zero, or until some limit is reached. Kite position is not regulated in the radial direction (the velocity is). The further the tether is pulled in the radial direction by the tension controller, the higher the tether tension. This allows the kite to find a stable equilibrium point at a commanded altitude without winding up integrator states.

Kite velocity is regulated in the radial direction by the hover position control system. Velocity is regulated with a higher bandwidth than the tether tension. This can interfere with the objective to regulate tension.

The tension regulator bandwidth is limited by the dynamics of the tether. The end of the tether at the kite has to be displaced in order to modulate tension. This limits how fast the tension regulator can adjust the tension. Currently the tension integrator ramps up the pitch at a typical ~0.1°/sec. This makes the level of tension control achieved during PrepTransformGsDown sensitive to the initial conditions, disturbances and the effectiveness of the feed-forward.

Root Cause Analysis

The Loss of Kite YM600-05 during Flight FCW-01

In FCW-01, the autonomous flight controller lost control of the kite's roll attitude, then the kite's yaw attitude, and consequently lost the kite to the Atlantic Ocean. The kite had just transitioned from crosswind flight to hover mode. It was preparing for the tether reel-in operation. In this "PrepTransformGsDown" flight mode, the kite hovers to a position to hold the tether in place so the Ground Station can transform from "the anchoring the tether for crosswind" configuration to the "reeling" configuration. To reach this position, the kite lowers its altitude while simultaneously translating sideways. After 22 seconds, the kite begins to overcome the bridle moment and roll away from the tether. About 28 seconds into PrepTransformGsDown mode, the pilot took over control but could not successfully stabilize the kite. Fig. 2 shows the trajectory of the final moments of the flight. A video of the end of the flight can be seen in the video "FCW-01 end of flight," available on the X Development YouTube channel, in the Makani playlist.

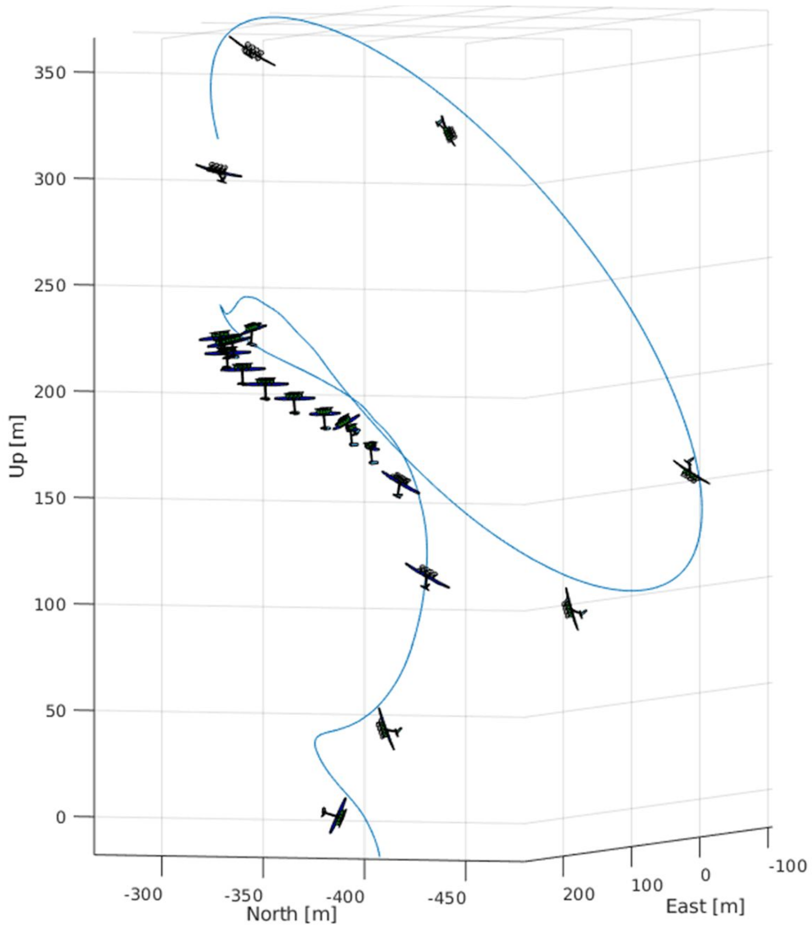


Fig. 2: The kite's trajectory before the loss of the kite.

The kite is intended to operate autonomously. The pilot actions after the failure are not in the scope of this analysis.

Tether tension loss causes loss of roll attitude

We rely on the bridle applying a restoring moment to stabilize kite roll - there is no active roll control on the kite. The kite must maintain an attitude so the bridle force is directed to counteract roll, and tether must tension the bridle so it can apply a force on to the kite. The bridle is most effective in stabilizing roll when the tether is perpendicular to the kite, i.e. the tether pitch angle is 0°. The more the tether pitch angle deviates from 0°, the less the tether tension acts to counteract roll. A tether pitch of down to -45° is considered to be part of the stable hover envelope under nominal tether tension. Furthermore, the more the tether pitch angle deviates from 0°, the more yaw moment the bridle exerts on the kite. This yaw moment is counteracted by the thrust generated by the rotors.

The plots in Fig. 3 show kite roll angle, yaw thrust moment and tether pitch angle for previous on-shore crosswind flights for comparison to the off-shore FCW-01. The first plot shows the kite rolling away from the stabilizing bridle roll moment, at an accelerated rate, 22 seconds into the PrepTransformDown mode. Leading up to this is a steady increase in yaw thrust magnitude. The tether pitch angle deteriorates rapidly after 22 seconds.

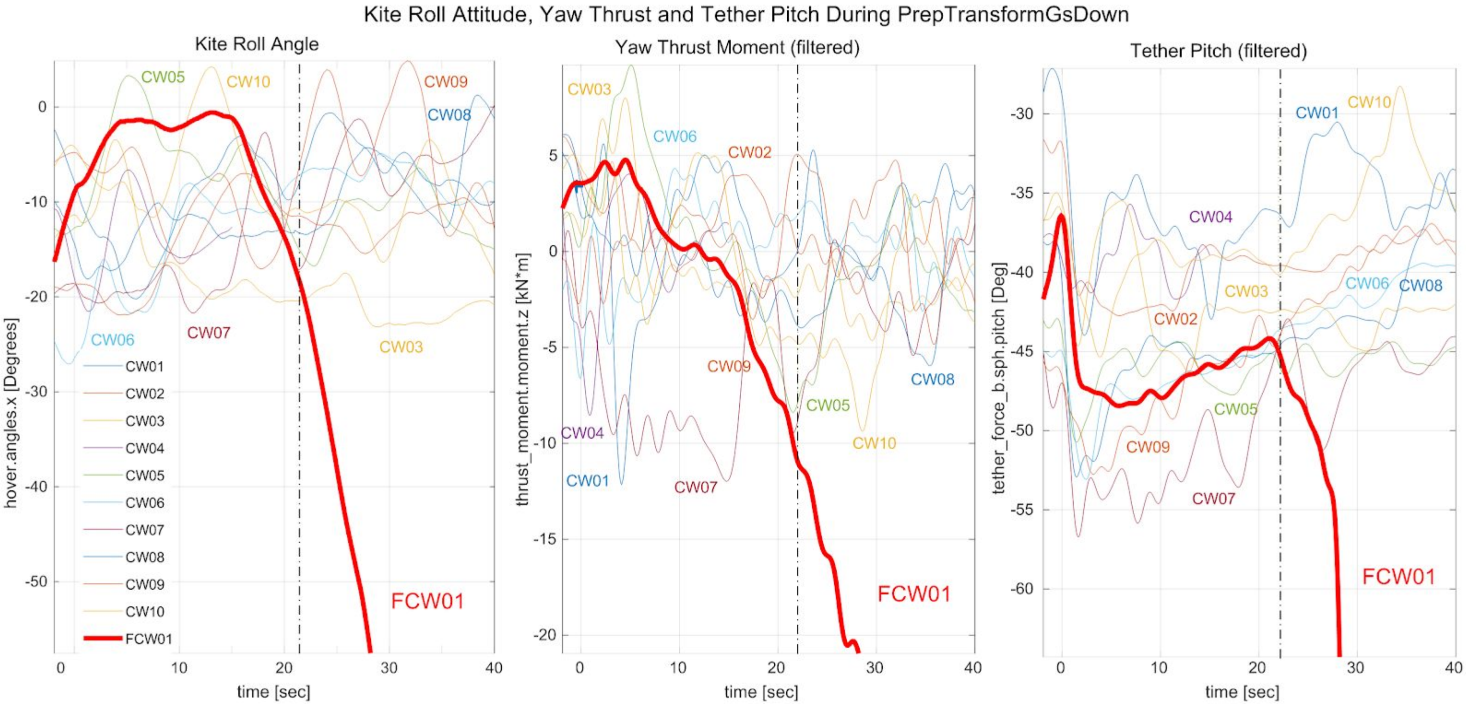


Fig. 3: Kite attitude and tether pitch during PrepTransformGsDown.

FCW-01 lost tether tension steadily after transitioning from crosswind flight into hover. Tether tension became too low for the bridle to stabilize roll. The kite overcame the restoring bridle roll moment and eventually crashed. Fig. 4 below graphs tension vs. time for FCW-01 with kite YM600-05, compared to previous successful crosswind flights at Parker Ranch with kite YM600-04. (For clarity the data is low-pass filtered with a zero-phase non-causal filter with a 0.1Hz cutoff). Some flights start at lower tension than FCW-01. These flights eventually exceed the requisite minimum tension of 8 kN, while

FCW-01 steadily loses tension. The tension measurement based on load cells is somewhat inaccurate, it can be up to 2 kN off. The line on the bottom of the graph shows the measured tension of FCW-01 with the worst-case offset of 2 kN. Fig. 5 shows the horizontal tension component.

The following sections examine the factors contributing to tension loss.

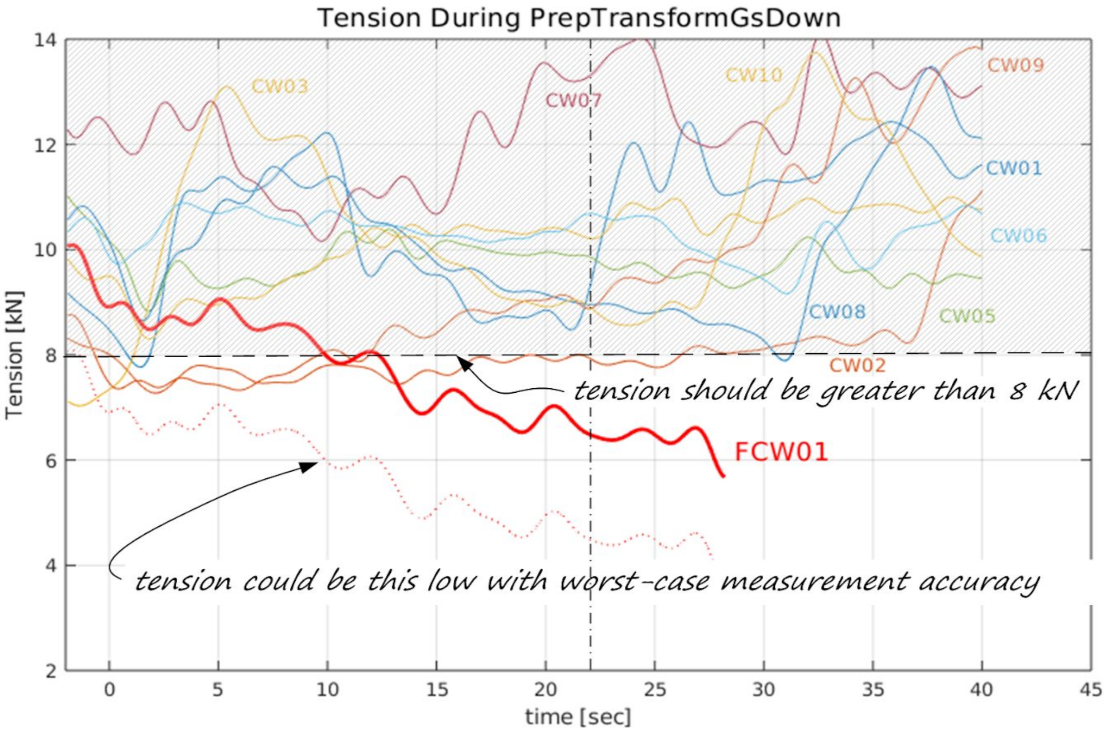


Fig. 4: Total tether tension, low-pass filtered, during PrepTransformGsDown.

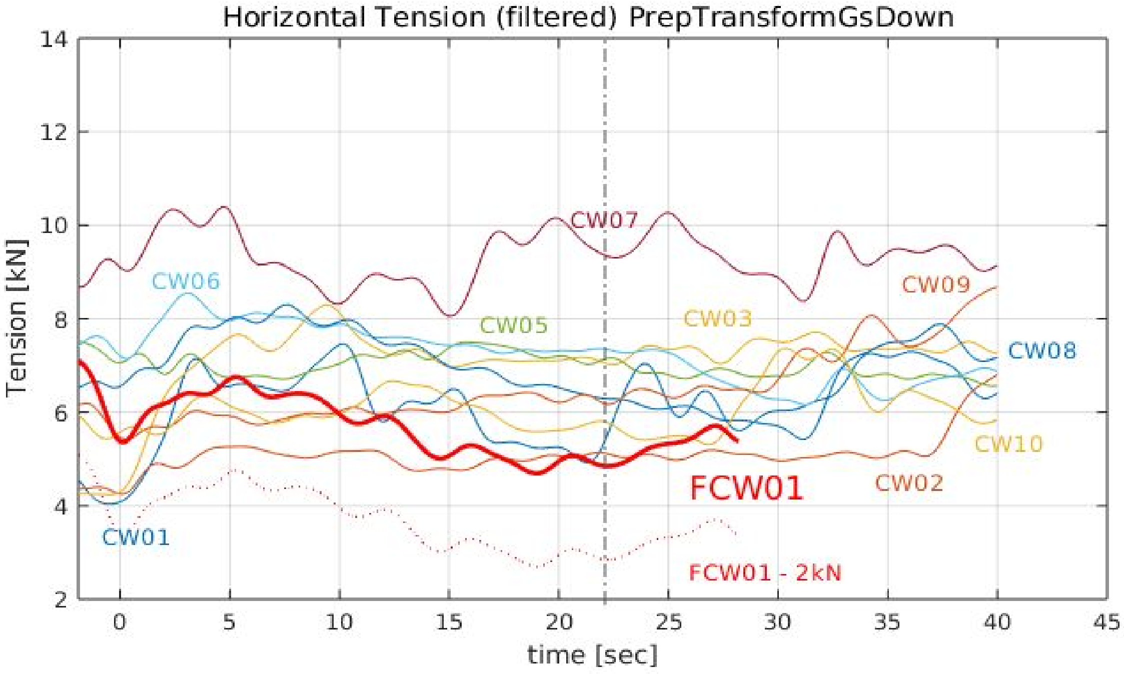


Fig. 5: Horizontal tether tension, low-pass filtered, during PrepTransformGsDown.

Effect of buoy motion on tether tension

The kite nominally descends while keeping the tether taut. With the tether anchored on the ground we can visualize the kite moving along a “tether sphere”. The radius of this sphere is the distance between the tether anchor point on the buoy and centerline of the bridle attachment points on the kite (see illustration Fig. 6). The ratio of tether radius to paid tether length is defined as tautness. As long as the tether radius is maintained, tension is held correspondingly. As the radius decreases, the tether slackens, tension drops. A more detailed analysis of an acceptable range of tautness is given in Catenary analysis of reduced roll stability at high altitude. This analysis also illustrates that the tether should be more taut at high altitudes for comparable tensions.

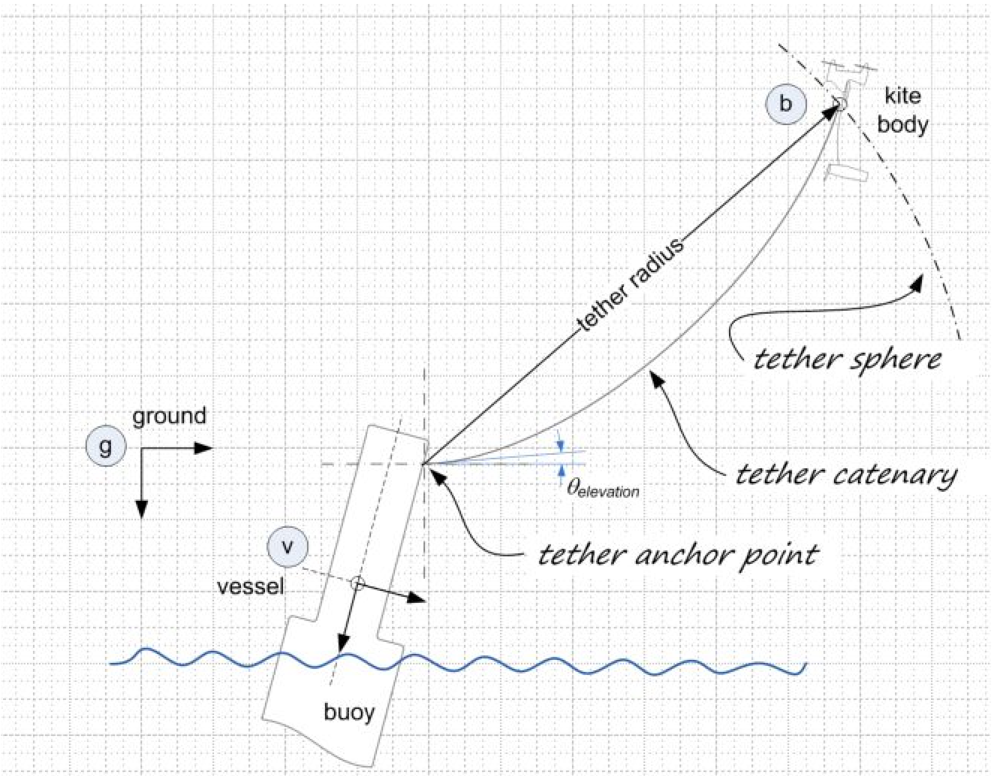


Fig. 6: Illustration of tether radius.

The graph in Fig. 7 below shows the tether radius for crosswind flights at Parker Ranch and the offshore flight FCW-01. Even though FCW-01 starts at a higher altitude than the other flights, the tether starts out stretched less. Then the tether radius decreases further by 7 meters during HoverPrepTansformGsDown. Tension computed based on the catenary model indicates that the tension drop due to the reduction in tether radius is about 2.4 kN (see Appendix D: Tether Catenary Computations).

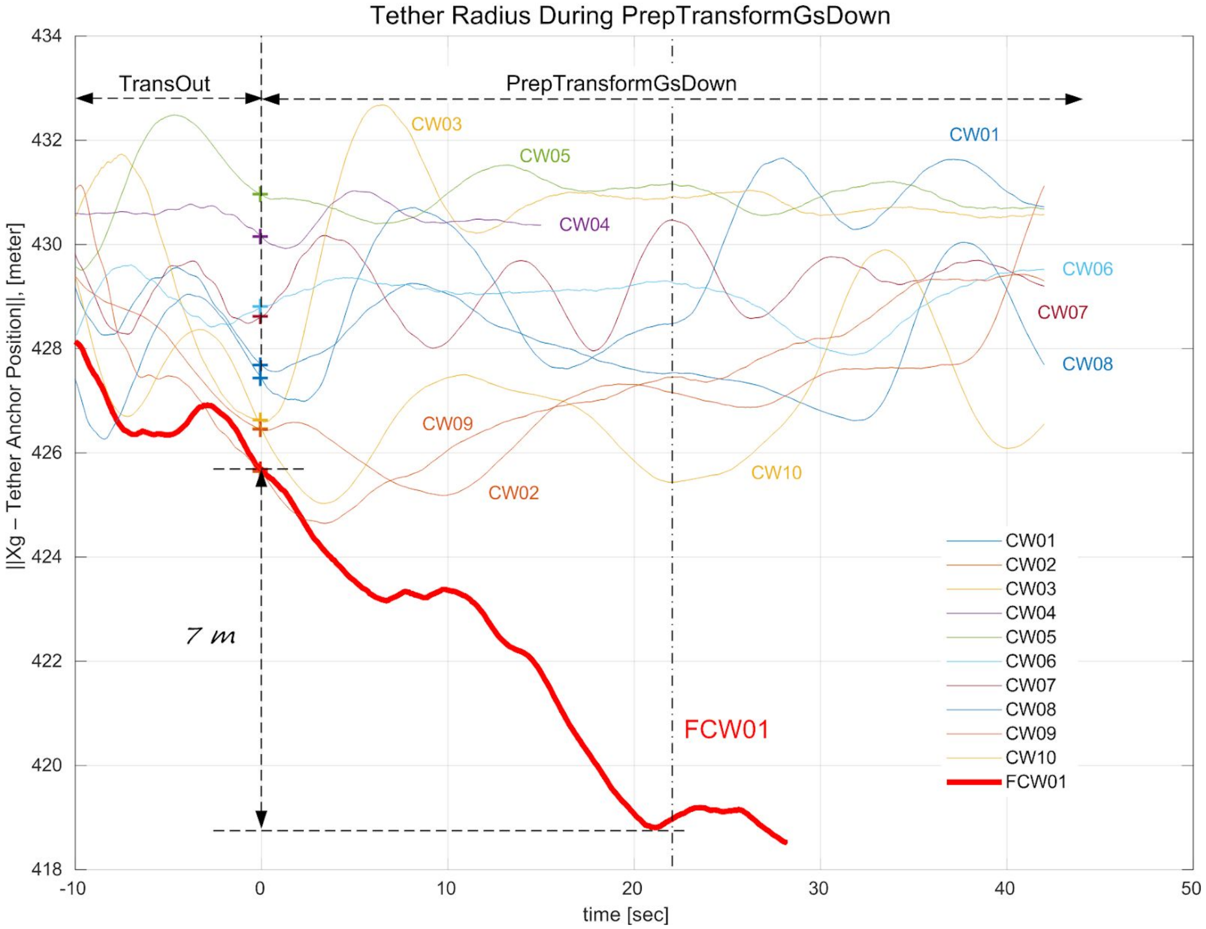


Fig. 7: Tether radius, low-pass filtered, during PrepTransformGsDown.

Fig. 8 below shows plots of the velocity components of kite and buoy along the direction from anchor point to kite, i.e. the components that contribute to the change in tether radius. These components are in the range of 1 meter/second, with a net difference around 0.5 meter/second. This compares to the kite descending at 2 meters/second while translating around 4 meters/second (see plots). The buoy motion, that was in sync with the kite's crosswind loops, is now decaying and rocking with a period of about 17 seconds. At the same time, the mooring lines are slowly retracting the buoy at an average rate of 0.3 meters/sec now that the crosswind tension has subsided. Due to its rocking motion, the buoy does at times slacken the tether. In the plot, zero velocity indicates constant tautness, positive kite velocities correspond to the kite moving away from the buoy, negative anchor velocities correspond to the anchor point moving away from the kite. If the kite velocity is more negative than the anchor point velocity, the kite is closing in on the buoy and tension will drop. If the anchor point velocity is more positive than the kite velocity, the buoy is closing in on the kite and tension will drop. On the average, kite and buoy are moving towards one another.

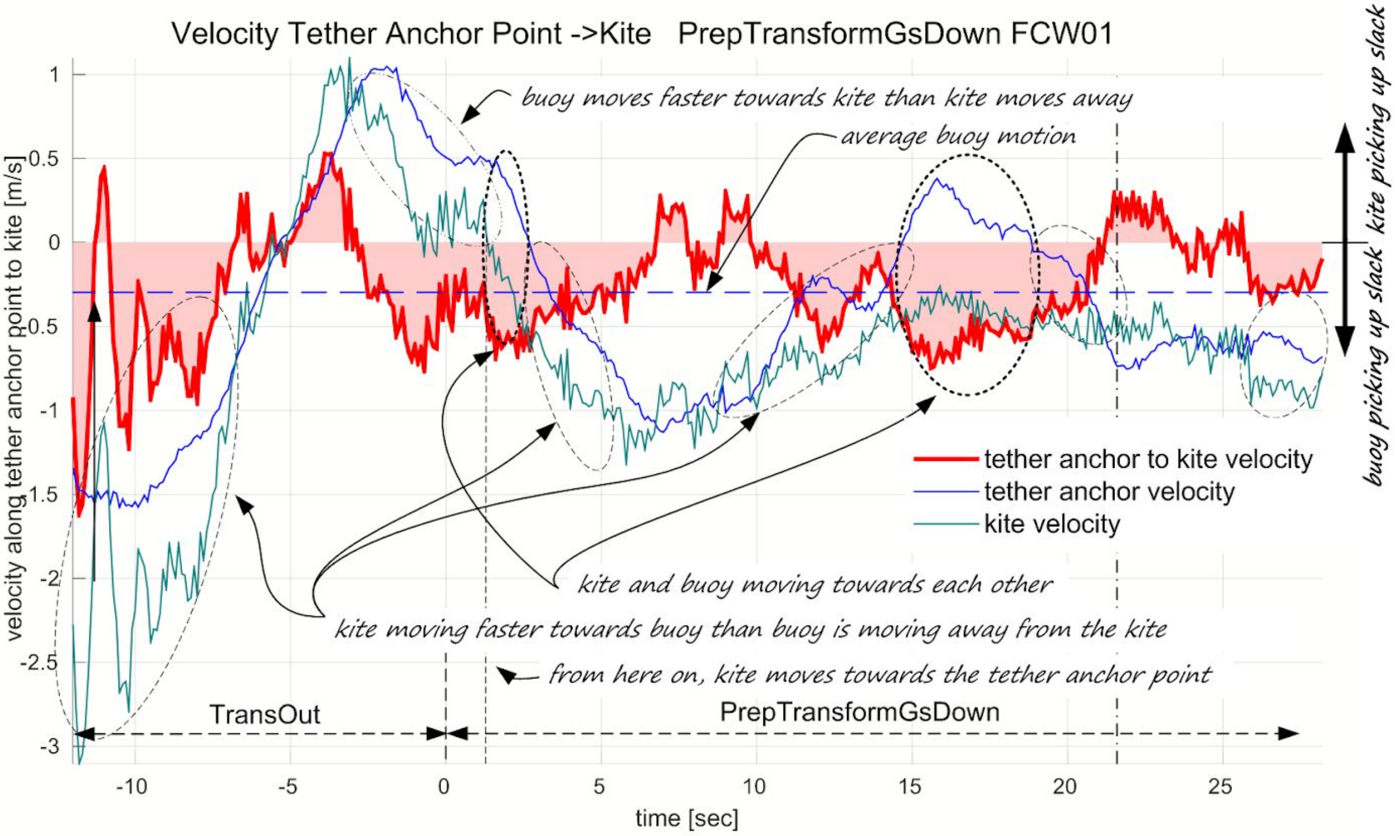
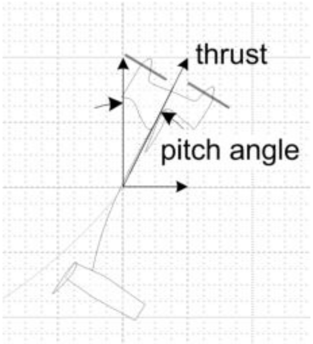


Fig. 8: Velocity components along the direction of the tether anchor to the kite. The shaded area indicates the distance is shortening, thus lowering tension.

Kite pitched forward after TransOut



The tension regulator commands a pitch angle to the attitude controller. Pitching the kite back (a positive pitch angle) vectors the thrust to increase tether tension. The maximum horizontal tension Pitching the kite forward lowers tension. After the transition from crosswind to hover mode is complete in FCW-01, the kite is pitched forward 13°. This puts the tension controller in the following PrepTransformGsDown mode in an unfavorable initial condition if the tension is low and the kite must move in the radial direction to maintain tautness.

The plots below show the pitch angle for FCW-01 and previous on-shore flights at Parker Ranch. The step change at time 0 is the result of a change in pitch integrator limit from -20° to -7° at the transition into the PrepTransformGsDown flight mode. Other than CW-02, all flights started at a more positive pitch angle. CW-02 had, hoverver, the benefit of a lower TransOut height. The more favorable bridle geometry resulted in a more stable operating regime for the PrepTransformGsDown operation in CW-02, roll and yaw stability were maintained throughout (see Tether pitch contours from catenary equations).

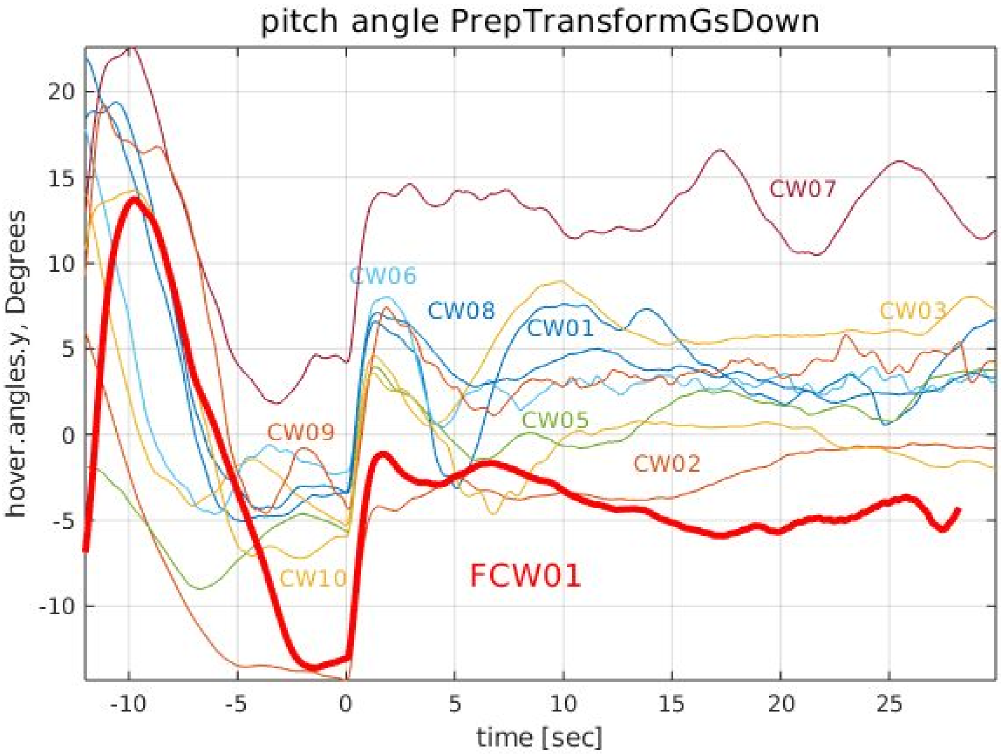


Fig. 9: Pitch angle during TransOut and PrepTransformGsDown.

Kite remains pitched forward despite low tension during PrepTransform Down

Even though tension is steadily decreasing, the pitch command produced by the tension controller remains negative during PrepTransformDown.

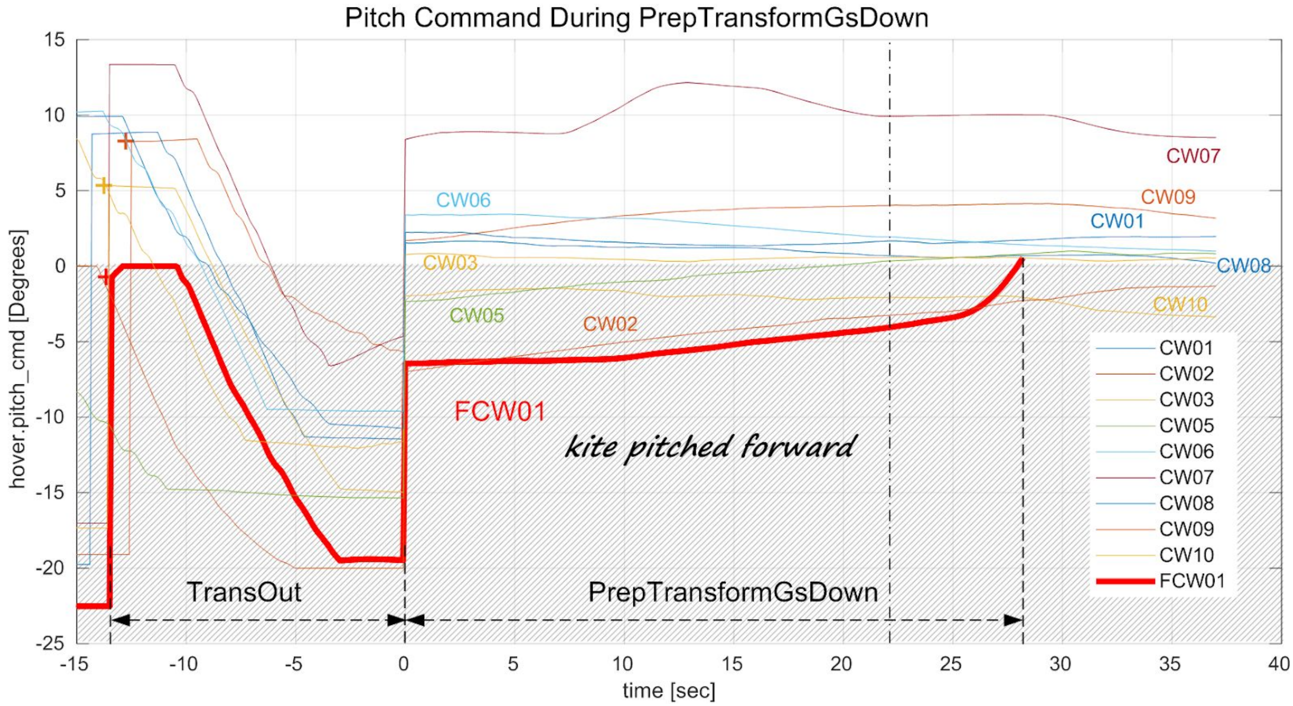


Fig. 10: The pitch commanded by the tension controller.

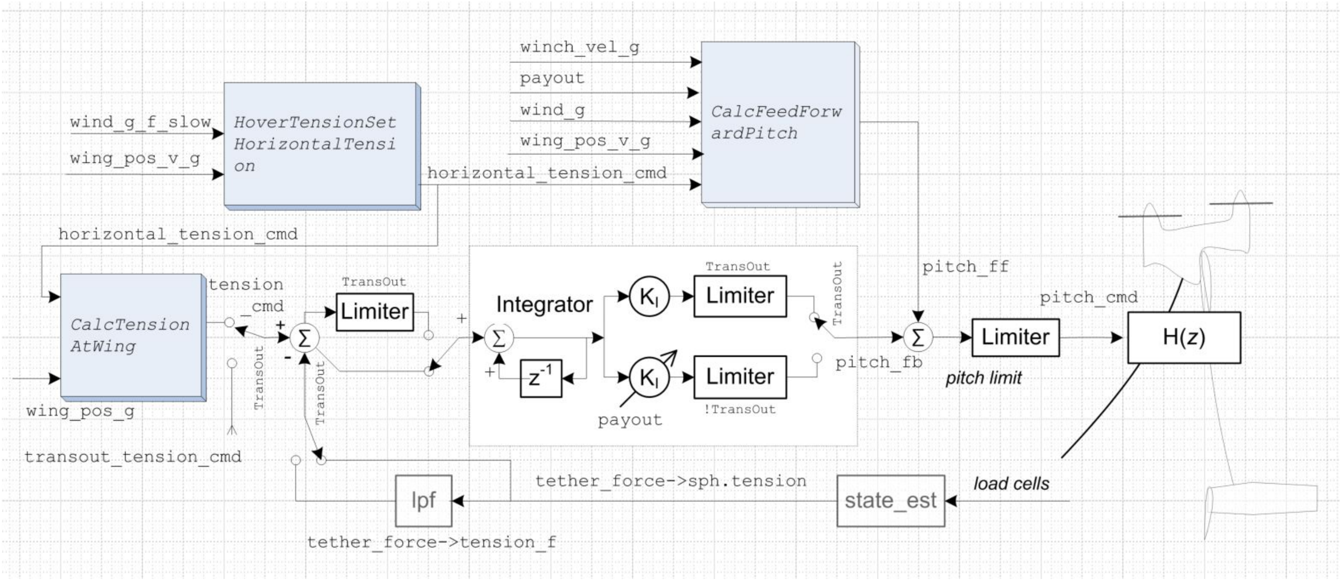


Fig. 11: Block diagram of tension controller.

The block diagram above illustrates the tension controller. The controller produces a pitch command which has feed-forward and feedback components. The pitch feed-forward is computed based on a desired horizontal tension, wind speed, winch velocity and the vertical kite position. The pitch feedback is the output of an I-controller with the feedback gain scheduled as a function of tether payout. The reference tension is computed from the desired horizontal tension and the wing position. The horizontal tension commanded takes into account the wind speed, with the intent not to have the kite fight the tension imparted by aero forces.

The TransOut flight mode is treated as a special case in the controller. The kite attitude is less constrained during this dynamic maneuver. The tension regulator operates at a different tension setpoint, uses a different gain to regulate error, rate limits the error, and uses a low-pass filtered signal as measurement. It also applies more generous limits to the pitch integrator. The choice of tension set points, regulator gains and limit changes gives the pitch command the characteristic pitch sequence for TransOut that has proven to be beneficial in simulations.

The operation of the tension controller leading up to the crash of FCW-01 is shown in the figure below. Three seconds after entering the TransOut mode, the controller aggressively pitches the kite forward at a rate limit, since the rapidly decaying tether tension is higher than the setpoint and the integrator gain is high. The flight mode moves from TransOut to PrepTransformGsDown when the Kite has finished the TransOut flare and hovering at nominally zero velocity. At that flight mode transition, the tension reference is increased, regulation gains are lowered and the forward pitch limit on the integrator is adjusted from -20° to -7°. The tension regulator now slowly acts to pitch back the kite to increase tension, about 2.5° in 22 seconds. At maximum thrust of 28 kN, this change in pitch is good for about 1.2 kN in horizontal tension. However, the pitch, also commanded by the hover position controller with radial velocity damping, actually decreases the pitch angle. Tension continues to drop.

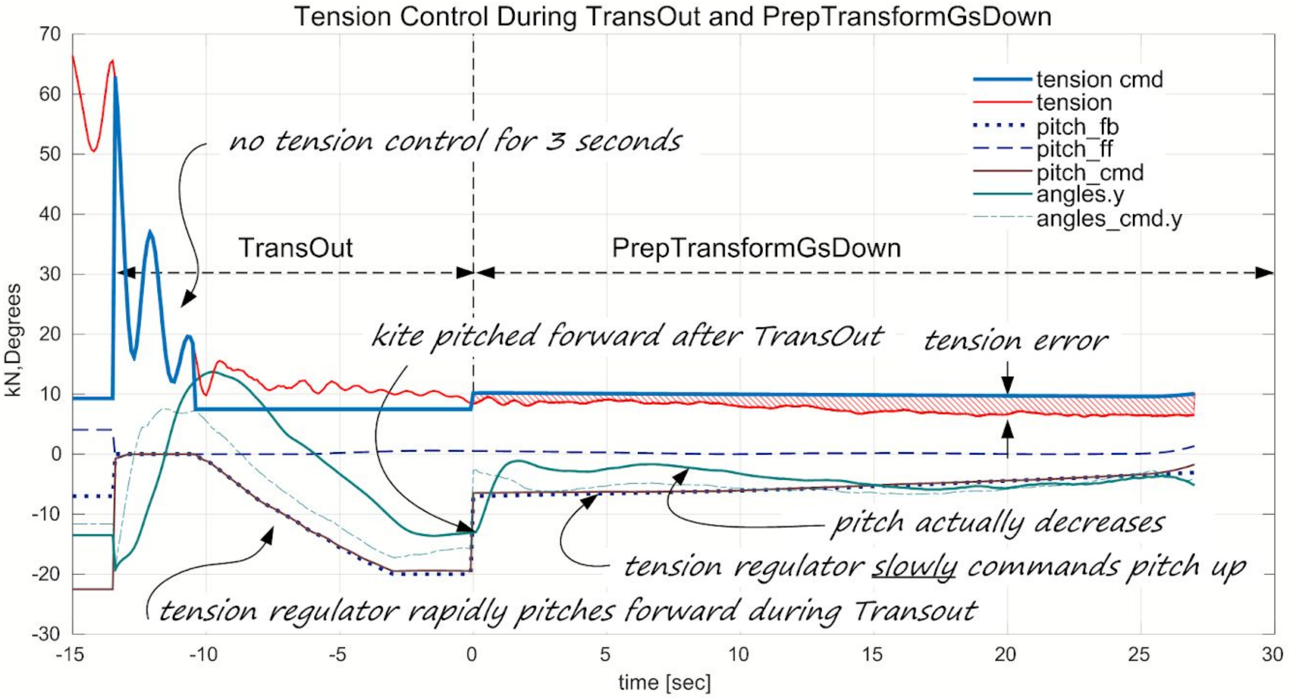


Fig. 12: Tension control during TransOut and PrepTrasformGsDown.

Pitch feed-forward not assisting with tension control in FCW-01

The pitch feed-forward is combined with pitch integrator feedback to form the pitch command shown in Fig. 10. The feed-forward pitch command attempts to command the correct pitch angle to achieve the desired horizontal tether tension, taking into account the aerodynamic force on the wing and the tether, the mass of the kite and tether. Many past flights achieved commanded (or higher) tensions in the PrepTransformGsDown mode based on the feed-forward commands. The feed-forward compensated for the pitch feedback commanding a strong forward pitch after TransOut. The pitch integrator, usually starting at the pitch forward limit of -7°, typically ramps up slowly. The fastest rate seen on past flights is CW-02, which started at a similar initial pitch as FCW-01, is about 3 degrees in 16 seconds. Compare that to CW-10 (appendix G). The (excessive) feed-forward in CW-10 puts the pitch at the requisite pitch angle to maintain tension immediately.

Flights CW-01, CW-05, CW-06, CW-08 and CW-10 were at the commanded tether tension at the 15 second mark in these figures.

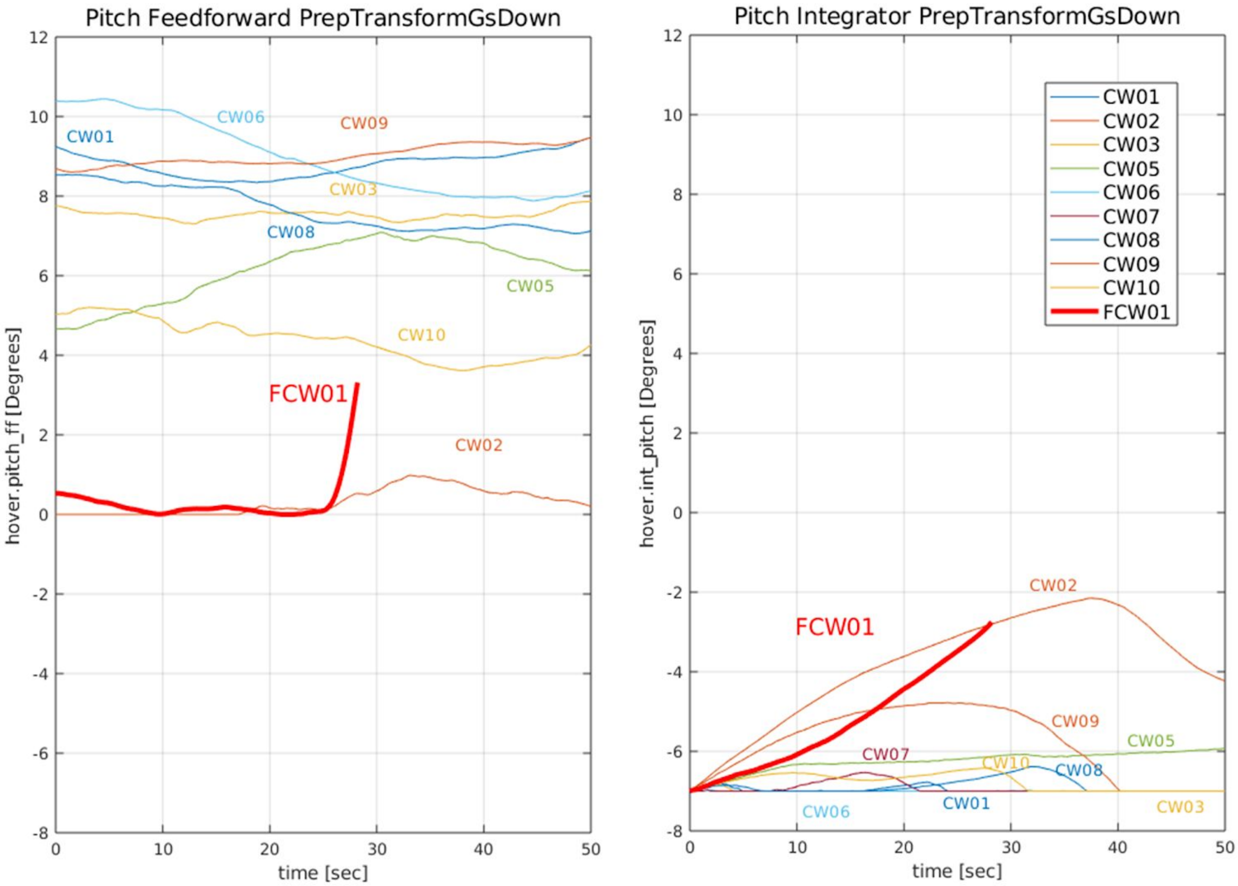


Fig. 13: Pitch feed-forward and pitch feedback components of the pitch command.

CA1 Corrective Action to improve tension control

Corrective action CA1 calls for improving the tension controller. The specific actions and their status are described in this section.

Initialize tension regulator/pitch integrator more carefully after TransOut.

This change addresses Kite pitched forward after TransOut. It is addressed in 65260: Initialize hover tension integrator at start of PrepTransformDown. The change has been merged into the controller code. The change is described in ECR415.

Improve tension feed-forward to command correct pitch commanded tension set point.

This change addresses Pitch feed-forward not assisting with tension control in FCW-01. It is addressed in 65402: hover: Lump propwash_lift into feed-forward pitch angle. The change is also described in ECR415.

Maximize tension regulation bandwidth within allowable stability margins to counteract tension disturbances caused by unpredictable kite and tether motion.

This corrective action should address the regulation problem described in Kite remains pitched forward despite low tension during PrepTransform Down. One difficulty associated with increasing regulation bandwidth is that the C-Sim does not capture the tether dynamics that predict the stability of the tension controller. In test flight HH-1 a sustained oscillation of the tether elevation loop was observed that is not predicted by the C-Sim. A better model of the system needs to be created to design and test feedback controllers against. A plan to experimentally identify the dynamics (Hover System ID Test Plan) is under development. Once a model has been derived from flight test data, it should be possible to design a feedback regulator and test it against the identified model.

High TransOut altitude contributes to loss of roll stability

Catenary analysis of reduced roll stability at high altitude

Flight FCW-01 transitioned from crosswind to hover at a comparatively high altitude of 245 meters (applying a 20 meter correction motivated in the next section). Flight CW-05 had a similar TransOut height but maintained tension and remained in control. A more detailed analysis is in Appendix E: FCW-01 comparison with CW-05.

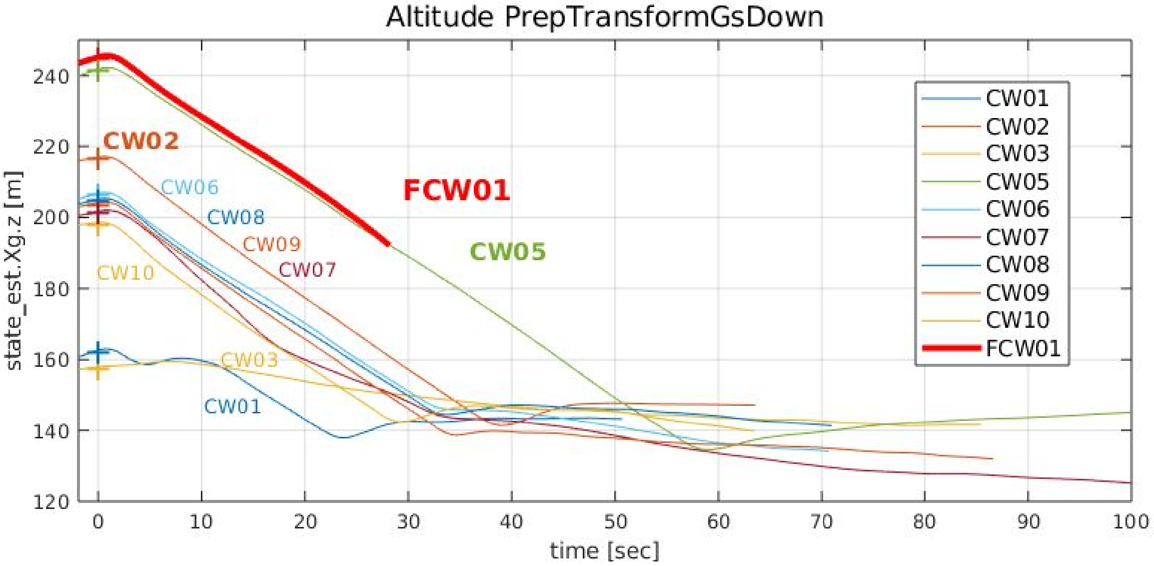


Fig. 14: TransOut Altitudes during PrepTransformGsDown (20m correction applied to FCW-01).

A high TransOut height is bad for four reasons:

1. At higher altitude, the tether pitch angle becomes increasingly negative, reducing the effectiveness of the bridle to apply a stabilizing roll moment. Only when the tether is at right angles relative to the kite's x-axis (tether pitch 0°), all the tether tension is available to counteract the roll moment. As the tether angle inclines towards the kite, bridle exerts less roll moment and more yaw moment.
2. At higher altitude, the kite has to carry more of the tether weight. This reduces the amount of thrust available to generate horizontal tension and to control kite motion and attitude.
3. At higher altitude, higher total tether tension is required to achieve a given horizontal tension component. The horizontal tension component provides the roll stabilization in nominal hover attitude.
4. At higher altitude, the tension or path controller must generate a larger velocity component in the horizontal direction to maintain tautness.

This section discusses the implications of hovering at different altitudes for tension control and bridle geometry based on catenary equations. Catenary equations describe the static shape of the tether suspended between the kite and the attachment point on the ground station [Wikipedia, Tether Catenary and Dynamics]. They also describe the tension exerted by tether, via the bridle, on the kite. Contour plots for tension and tether pitch angles illustrate how tightly the tether has to be stretched at different altitudes and that tether pitch angles to expect. Note that the contour plots do not capture the dynamic behaviour of the kite and the tether: the tether pitch angle will change as the kite actively regulates attitude to follow a hover path; tether and kite motion transients will affect the actual tension at the kite. The contour plots merely give an indication of the operating points for tension and tether pitch angle at different altitudes. Superimposed on the contour plots are the actual trajectories of test flights at Parker Ranch and of FCW-01.

A contour plot of the total tether tension at the kite for a tether of 433 meters with a linear mass density of 0.917 kg/m is shown in Fig. 16 below. Tether tautness is defined as the total effective tether length (including the bridle) divided by the tether radius (the distance between anchor point on the ground and the effective attachment point on the kite, Fig. 6). A transout height of 240 meters requires a tautness of 0.9906 (~4.1 meter slack) for 8 kN tension. A tautness of 0.9805 (~8.4 meter slack) yields 6 kN. This 2kN change in tension corresponds to a change in tether radius of about 4.3 meters. Recall that during FCW-01 the kite closed in on the tether ground anchor point at around 0.5 m/sec for 10 seconds at a time (Fig. 8) and the radius decreased by 7 meters (Fig. 7).

The horizontal tether tension component provides the actual roll stabilization when the kite is hovering in the nominal upright position. It becomes substantially more difficult to generate the horizontal tension at high altitudes since the kite has to carry more of the tether and the tether has to be stretched tauter to achieve a given horizontal tension. The horizontal tension contour plot in Fig.15 below shows the tautness required to maintain horizontal tension at altitude. The contours show at 240 meters a tautness of 0.992 (slack of 3.46 meters) gives a horizontal tension component of 6 kN. At 150 meters, a tautness of 0.987 (slack of 5.6 meters) gives the same tension.

Some flight trajectories during PrepTransformGsDown are plotted on the contour plots.

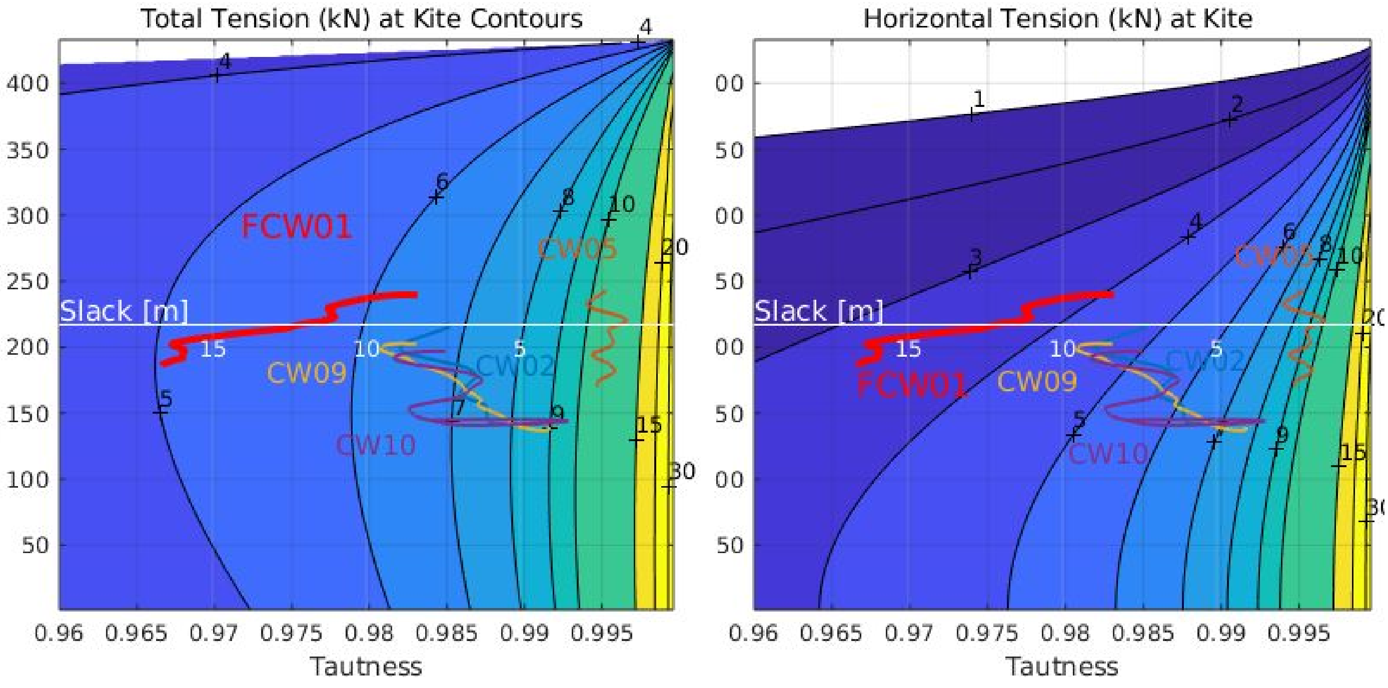


Fig. 15: Tether tension contours from catenary equations.

It is harder to generate horizontal tension at higher altitudes as the bridle geometry becomes less favorable for producing stabilizing roll moments. At 0°, all the tension is in the horizontal direction and works to counter roll. At more inclined angles, the horizontal tension is reduced and tether tension increasingly couples into yaw moment. A tether pitch angle of -45° or better is considered the safe operating region of the kite.

The figure below shows the tether pitch angle predicted by the catenary equations.

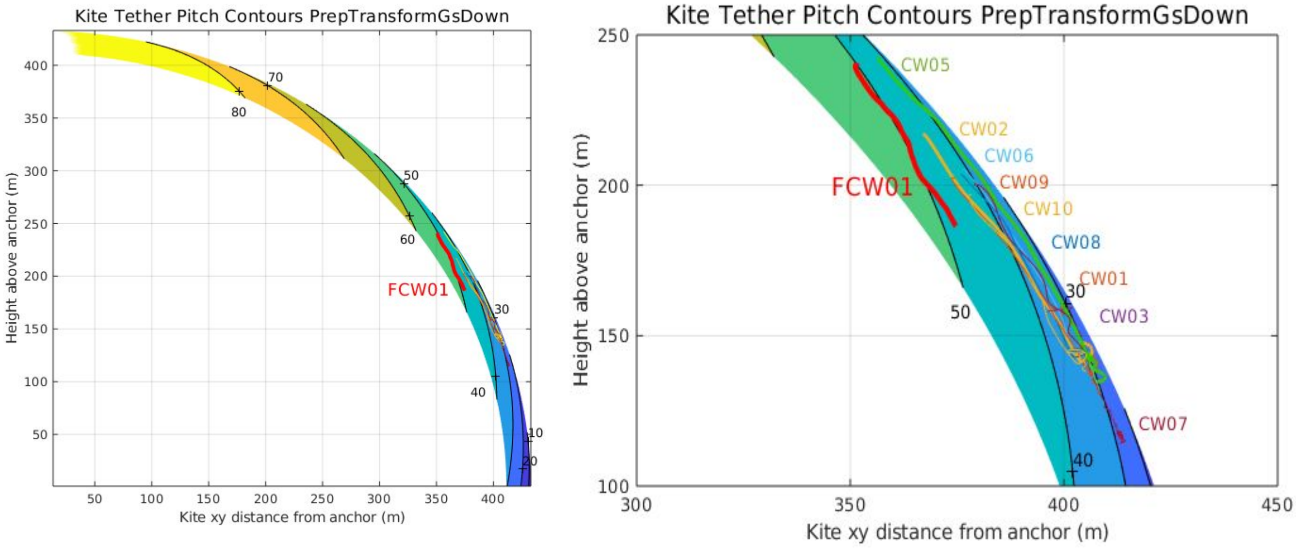


Fig. 16: Tether pitch contours from catenary equations.

CA2 Corrective Action to lower the TransOut altitude

The series of changes that address lowering the TransOut altitude are described in ECR 480. These incorporate changes that cause the kite to transition from crosswind to hover at lower altitudes and at slower speeds. The control strategy during the TransOut flight mode has changed: rather than attempting to control tether tension in the transient phase from crosswind to hover, the hover controller commands a constant pitch.

GPS errors contributed to high TransOut altitude

The kite's control system relies on a combination of inertial sensors, pressure sensors for the pitot tube and five GPS receivers on the kite and the ground station. A state estimator combines the raw sensor signals to determine position, heading and attitude of the kite and the buoy. There were several GPS events during the flight, attributed to multipath interference, that resulted in inaccurate estimates of both kite and buoy altitude. The relative position between the kite and the buoy was estimated accurately.

Plots below show the Ground Station vertical position estimate at the beginning of the flight and at the end of the flight. The nominal height of the kite on the perch is 4.3 m. The estimate immediately before ascending from the perch was 3.9 meters. The position at the end of the flight is -15.9 meters. The kite position when the kite lands in the water is estimated at -32.9 meters. The error in the altitude estimate is between 20 and 37 meters. The altitude plots in this report are corrected by 20 meters.

The incorrect altitude estimate did affect the transition from crosswind to hover. Crosswind path is determined from an elevation angle in g-frame. Altitude errors will affect initial conditions of the transout maneuver. The kite transitioned from crosswind to hover at a higher altitude due to the error. However, the control of the kite motion during transout is determined based on loop angle and airspeed and does involve GPS.

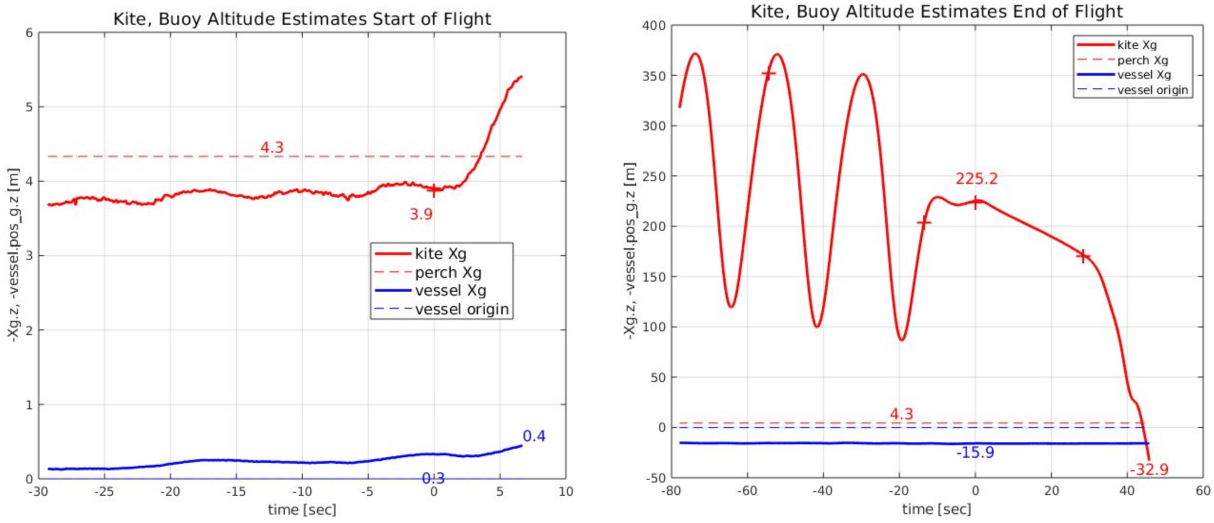


Fig. 17: The GPS measurements introduce errors in the kite altitude estimate.

CA3 Corrective Action to make kite position estimator robust to GPS receiver errors

This has not yet been addressed. The estimate of the altitude of the anchor point was below sea level at the end of the flight. This should be fairly easy to guard against. Several measures under consideration, including a differential GPS measurement to a fixed receiver onshore (see http://b/143561383 Norway 2020: Put a GPS base station on land).

Radial velocity damping counteracts horizontal tension control

As the kite descends to the altitude for the ground station reel-in transformation, the kite must move in the horizontal direction, away from the tether anchor point, to keep the tether taut. The path controller plans the velocity in cylindrical coordinates, but only the vertical component is commanded. The radial damping regulator attempts to regulate the horizontal velocity to zero, while the tension regulator attempts to keep the kite moving along the tether sphere.
FCW-01 descents at 2 meters/sec. The figure below compares the horizontal velocity component required (assuming a fixed anchor point) to maintain tautness to the actual velocity achieved. In the 22

seconds the radial velocity is about 0.5 m/sec less than it should be to maintain the initial tautness at the beginning of PrepTransformGsDown.

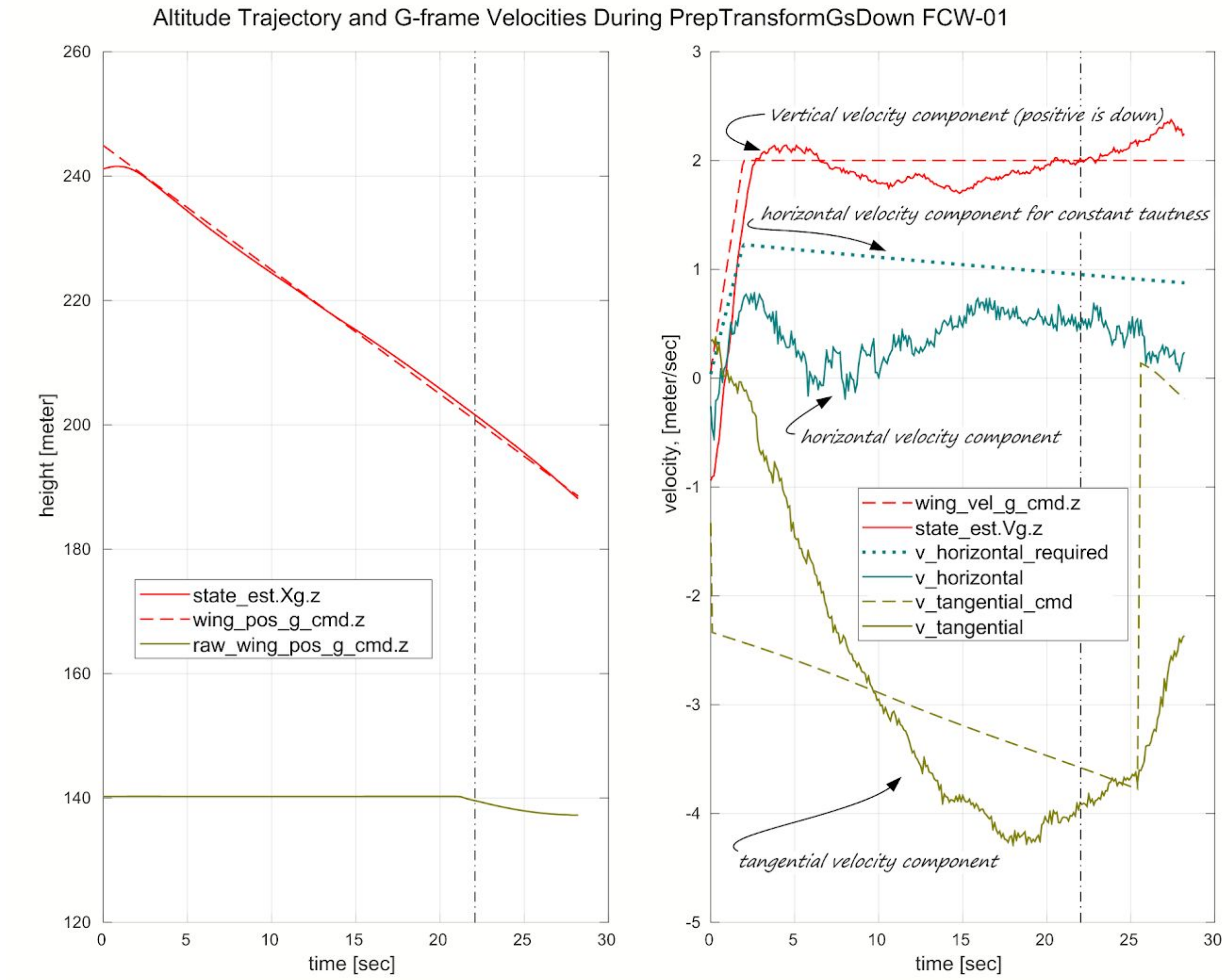


Fig. 18: The radial velocity component required to maintain tautness and actual radial velocity.

CA4 Corrective Action: Explicitly command radial velocity

The change 65620 : hover: Set radial velocity command during PrepTransformDown, described in ECR 473, implements the corrective action illustrated in the figure above.

The C-Sim does not predict rotor thrust induced roll moment

Low tether tension and an unfavorable tether pitch angle reduced roll stability, but what generated the roll moment that actually caused the kite to roll? The bridle moments usually maintain the kite's roll attitude. An exogenous roll moment must be responsible for causing the kite roll angle to diverge. The C-sim does not predict this roll moment and did not warn from hover paths vulnerable to this effect.

Bridle moments

The bridle geometry causes tether tension to create roll moments and yaw moments on the kite. If the tether pitch angle is near zero (tether departing perpendicular to the kite) then the bridle provides roll moments. If the tether pitch angle is near -90 degrees (tether near the kite's tail) then the bridle provides yawing moments. At intermediate tether pitch angle will cause the bridle to provide a combination of roll and yaw moments.

The bridle roll moments are desired because the kite's roll degree of freedom is otherwise uncontrolled. The yaw moments are undesired and must be rejected (balanced by) the rotors. The bridle geometry is such that typical tether tensions observed during hover are sufficient to overpower the rotors' yaw moment control authority if the tether angles at the kite become unfavorable (tether pitch near -90 degrees).

Bridle yaw moments overpowering the rotors caused the kite to rotate away from its usual vertical hover attitude in FCW-01 when the combination of tether pitch, tether roll, and tether tension created more than 15000 Nm of bridle yawing moment on the kite.

Roll moment due to sideslip in the rotor wake

As the kite traversed along the tether sphere into the position for the ground station transformation, it developed a roll moment that counteracted and overcame the restoring bridle moment.

The rotor wake is blown towards the starboard wing as the kite traverses to the position for the ground station transform. This creates an asymmetric lift and induces a roll moment (see Fig. 19).

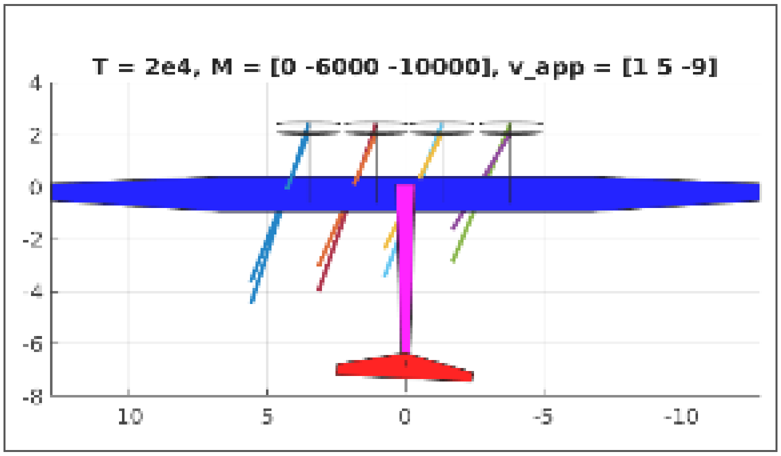


Fig. 19: Sideslip induces roll moment due to asymmetric lift from rotor wake.

CA5 Corrective Action: Extend simulation capabilities to include “phantom roll moment”

The exact formulation for a model for this induced roll moment is still under investigation. Some observations and simulations can be found in Rotor Wake Directions In M600 Hover. It is hypothesized that the roll moment arises due to asymmetric blown lift on the wing. The asymmetry is hypothesized to be caused by both Rotor Yawing Moment and by Kite Sideslip. The related bug is: http://b/139670231 Why did the kite develop a negative roll rate in FCW01 PrepTransformDown?

PA1 Preventive Action: Descend before translate at high transout altitudes.

64421: hover: Descend vertically before traversing implements this change, ECR 473 is the associated ECR.

PA2 Preventive Action: Slow the translation rate during PrepareTransformGsDown from 5 m/s to 2 m/s.

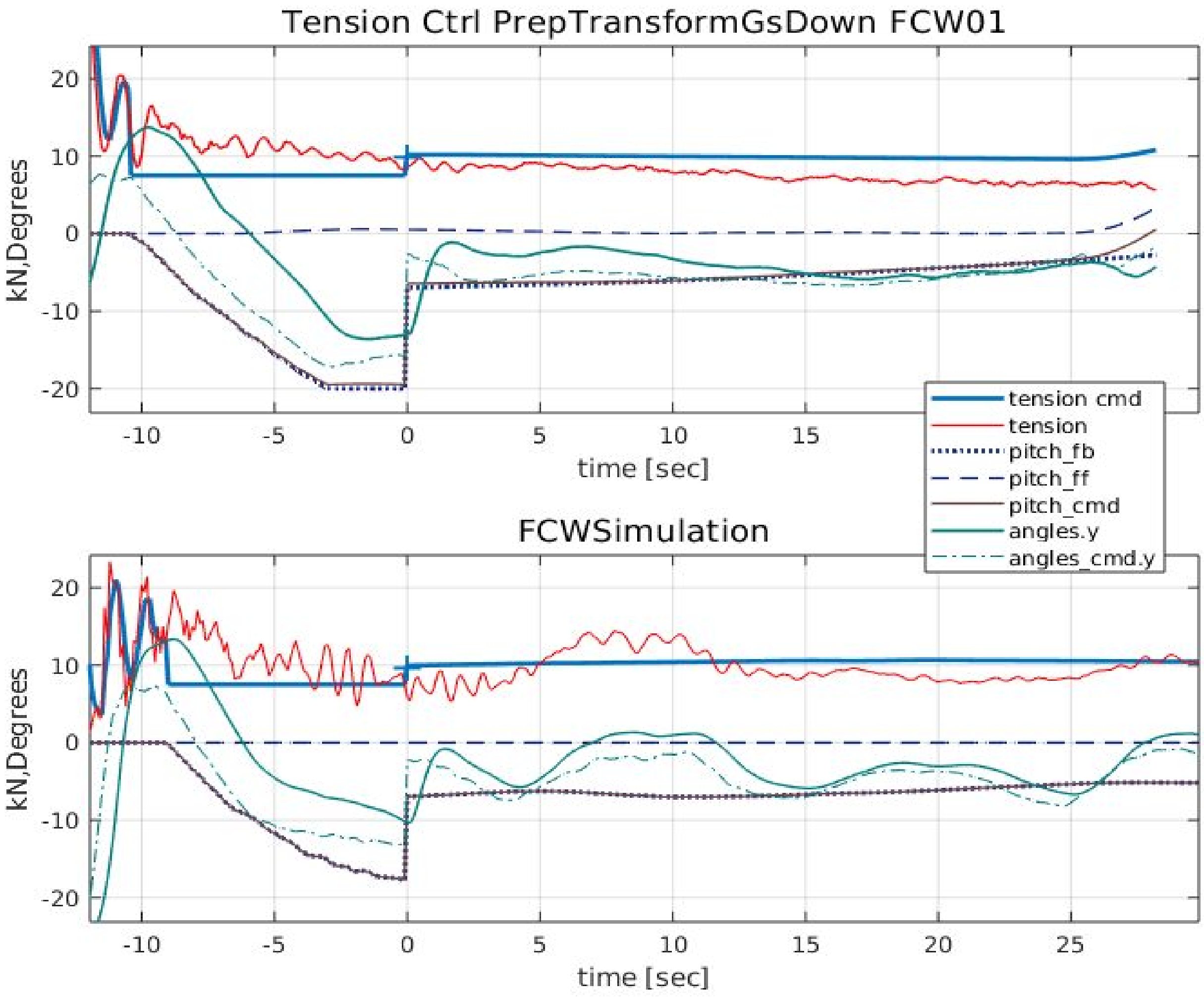
65140: hover: Reduce max tangential speed to 2 m/s implements this preventive action, ECR 473 is the associated ECR.

CA6 Corrective Action: Improve command center monitors to warn about approaching yaw/roll stability limits.

This should follow once the mechanism for the phantom roll moment is better understood (will be developed for of CA5).

The C-Sim does not predict kite-buoy interactions correctly

The C-Sim did not predict the tensions accurately in the TransOut and PrepTransformGsDown flight modes. Below is a plot comparing tension control for the flight and a C-Sim simulation. Tension is fluctuating, but not trending lower.


Tension Ctrl PrepTransformGsDown FCW01

FCWSimulation

Fig. 20: The C-Sim predicts adequate tension during PrepGsTransformDown.

The tether radius simulation is consistent with the tether tension simulation. The kite-to-buoy velocity components in the direction from tether anchor point on the ground station to kite do show a ~2x larger velocity component from the anchor point in the simulation. Significantly, the simulation shows the average relative velocity to be zero, whereas in the actual flight it is negative, indicating a decreasing tether radius. The phasing of the relative motion is substantially different: the simulation shows the distance spreading, increasing tension, at the start of PrepTransformGsDown, whereas in the actual flight the distance was decreasing and dropping.

The C-sim predicts that the buoy retreats faster than was actually observed (49 cm/s vs. 32 cm/s). It does not account for the kite closing in on the buoy. More comparisons between these can be found in FCW-01 Controls Lessons Learned.

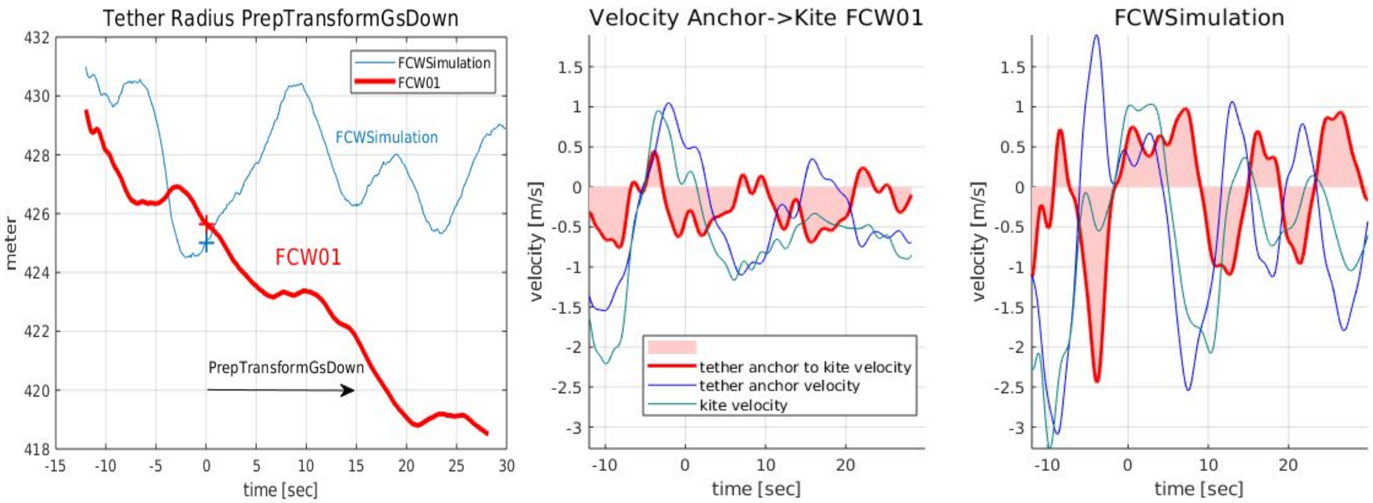


Fig. 21: Components of kite and buoy motion. In the C-sim, there is no net difference in the kite to buoy distance, in the actual flight about 7m accumulates.

The rocking of the buoy in simulation shows an additional frequency component that increases as the kite prepares to transition out of crosswind. This component is not observed in the flight data.

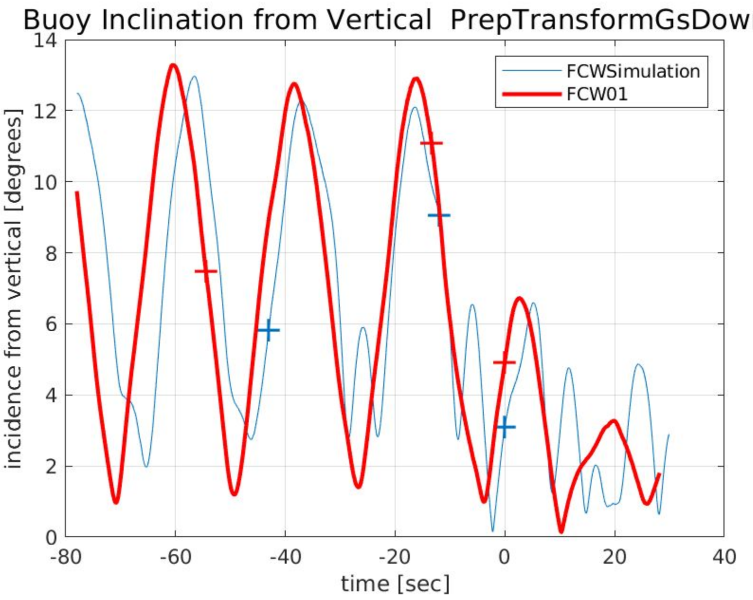


Fig. 22: The inclination from vertical shows an extra component in the C-Sim.

CA7 Corrective Action: Improve fidelity of Buoy-Kite interaction in the C-Sim

The parameters in the C-Sim (for damping, spring constants) should be adjusted based on the observed values in FCW-01 to better predict the kite-buoy interaction.

Summary

This report describes several contributing causes to the loss of kite in FCW-01. Other flights experienced some of these causes without losing control, but the concurrence of all the causes led to the loss of the kite in FCW-01. The additional contributing factor unique to the offshore operation for FCW-01 was that the buoy motion contributed to the slackening of the tether at times during TransOut and PrepTransformGsDown. Flights CW-02 and CW-05 are most similar and are compared to FCW-01 in more detail in Appendix E: FCW-01 comparison with CW-05 and Appendix F: FCW-01 comparison with CW-02.

For all flights, we rely heavily on the capability of the C-Sim to validate controller designs. The “phantom roll moment” was newly observed in FCW-01 and needs to be better understood to inform control strategies for this kite and the next design. The effect of tether and bridle present unique challenges to the flight controller. At present, the fidelity of the C-sim does not predict controller instability for controllers closing the loop around tether dynamics (tension and elevation controllers).

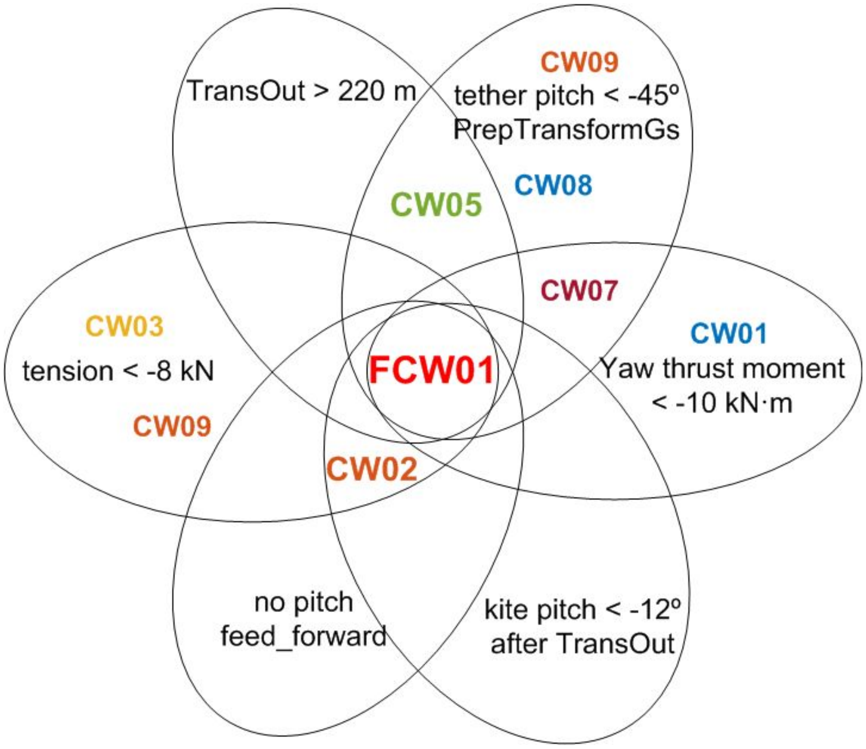


Fig. 23: Contributing causes to the loss of kite in FCW-01.

Appendix A: Wind speed measurements ruled out as contributing factors

The wind provides lift during crosswind and tension during hover. We rely on operating the kite downwind from the ground station that anchors the tether. Wind speed and direction are determined from measurements on the ground station. The kite's path and the operating points for tension are commanded accordingly. A wrong estimate of the wind direction would result in reduced tether tension and hence stability, and at the same time result in increased disturbance forces on the kite. The question was raised if an error in the wind speed estimate contributed to the loss-of-kite event.

Raw wind speed measurements at the ground station

The wind sensor is mounted on the ground station, where it is subject to the 90° rotation during the ground station transformation, the azimuth motion that tracks the kite's crosswind loops, and the motion of the buoy. The processing of the wind data and the correction for these motions is described in the next section.

Fig. 24 shows the amplitude of raw GS wind speed measured along the GS trajectory during FCW-01. The blue arrows are representing the average wind direction during the flight. This figure confirms that the GS drifts down wind during the flight. Also, it can be seen that the measured wind speed gets its minimum value when the GS is drift in the downwind direction. This supports the assertion that the wind data used by the controller is valid and did not contribute to the loss of kite.

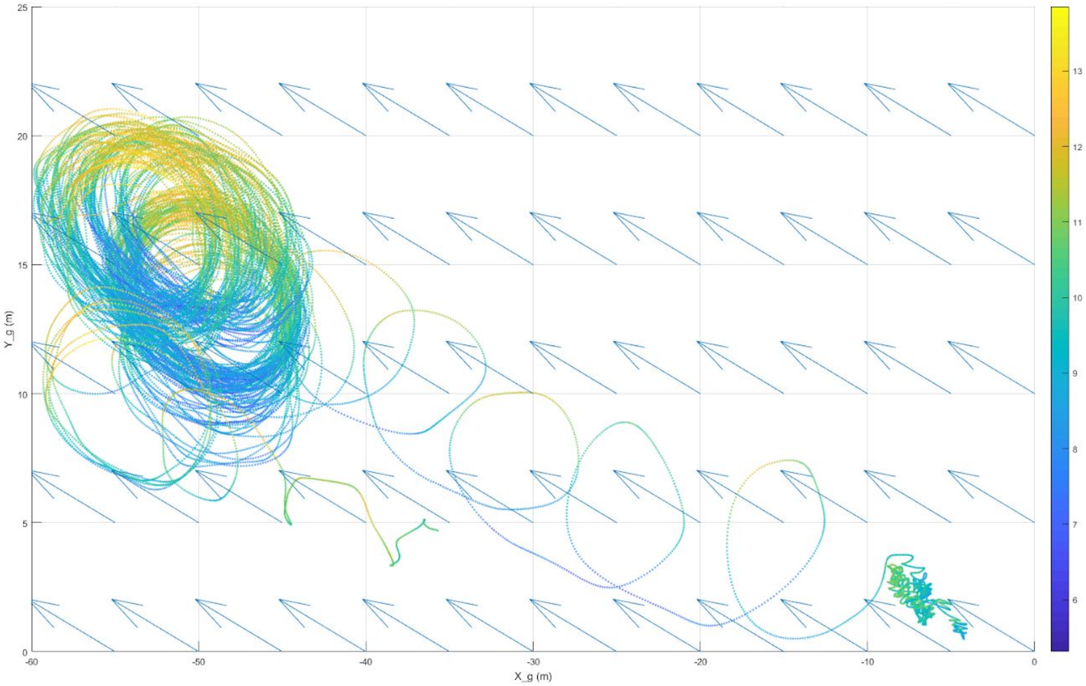


Fig. 24: Raw wind speed measurement along GS trajectory.

Processed wind speed used by the controller

Wind speed and direction are measured by an ultrasonic wind sensor on top of the ground station. The raw data from the wind sensor are in the ground station reference frame. Since the ground station rotated and moved in a circular pattern during crosswind flight due to the interaction with the kite, the raw data reflects the corresponding characteristic wind speed variations shown in Fig. 25.

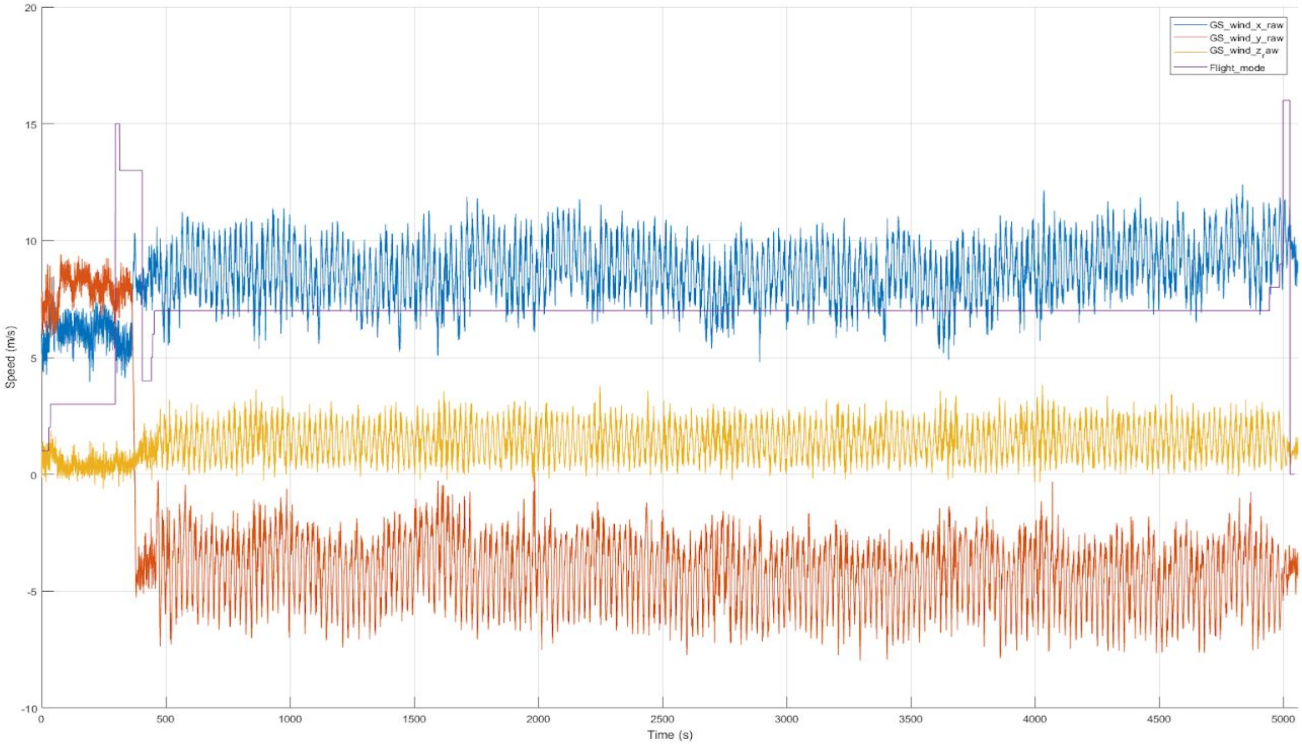


Fig. 25: Raw wind speed measurements during the flight.

Here are some observations from the figure:

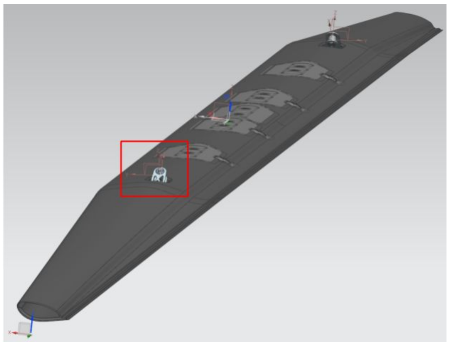
1. There is a step change in both x and y velocity measurement at around 400sec. This was caused by the rotation of the ground station when the kite paid out.
2. There are ringing features when the kite was in crosswind flight mode (flight_mode = 7). This is caused by circular motion of the buoy.
3. After trans-out (at around 5000 sec), the raw wind data returned to those values close to those prior to trans-in (around 440 sec). This suggests the wind speed and direction doesn't change too much during the FCW-01.

The raw data from the wind sensor were fed to the controller which transformed the data into the ground frame. Fig. 26 shows filtered wind data in the ground reference frame. The step change due to ground station rotation and ringing feature during crosswind can't be found in this plot. It implies that the ground station motion was removed from the raw data.

Fig. 26: Wind speed measurements corrected for platform motion.

Appendix B: Tension measurements nominal

The control of the tether tension is an important aspect of system design and operation in an energy kite and it figures prominently in this analysis. Tension is actively regulated based on load cell measurements. For background on the tension sensing system refer to the YM600 Bridle Hardpoint Loadpin Error Investigation. It was determined that the load cells were installed and calibrated correctly and that the tension measurements are accurate to within 2 kN.



The load cells in the YM600-05 kite were originally calibrated by the manufacturer. The data is properly reflected in the configuration file used by the controller. The pre-flight checks which zero load cell values and check for proper direction measurements were done, no deviations were noted. The autochecks monitor was used to confirm the X and YZ axes magnitude/signs looked as expected and had not drifted. Reasonable readings were observed during tightening the tether with the winch.

Based on these observations, we expect the tether tension measurement to be accurate to within 2 kN. Computations of the tension based on tether properties and the observed tether catenary are shown in appendix Appendix B: Tether Catenary Computations. The tension measurements and calculations are consistent within the expected tolerances.

The load cell measurements are also used to calculate tether pitch angles. The pitch angles on the bridles agree to within 10 degrees.

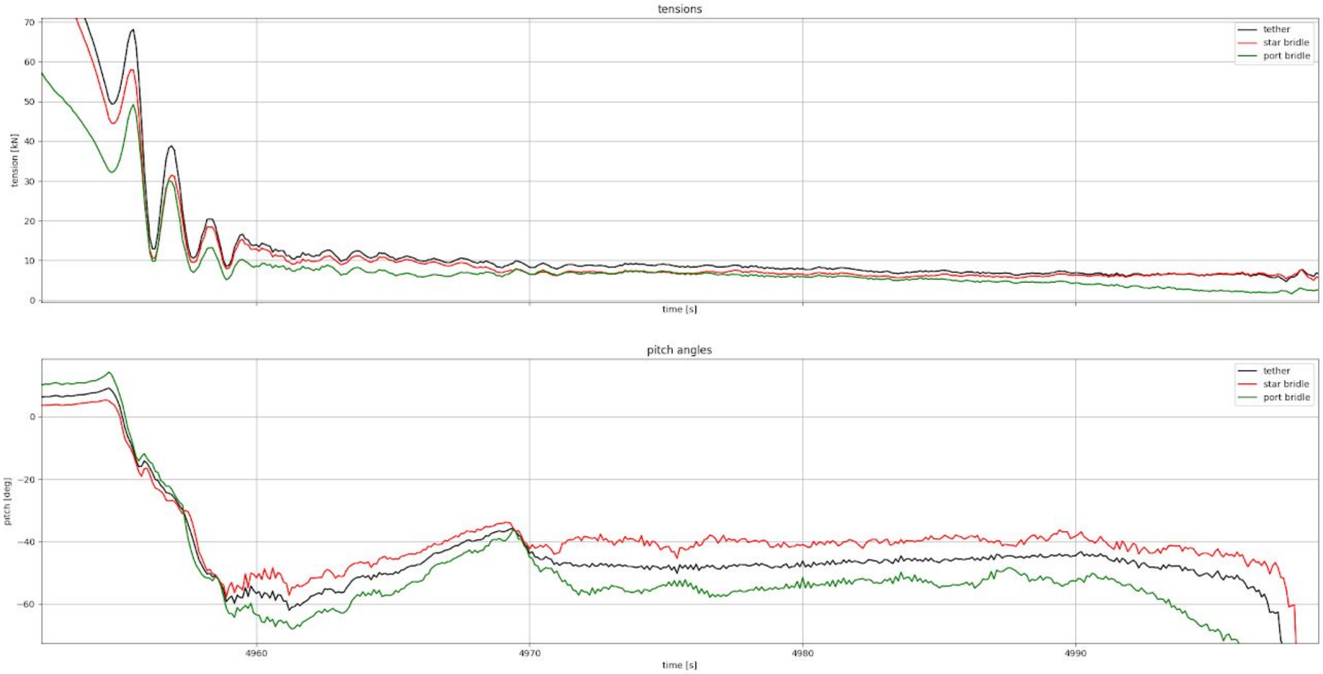


Fig. 27: Load cell measurements and pitch angle computations. The PrepTransformGsDown flight mode begins at time 4969

Appendix C: GPS Performance

The GPS measurements differ by several meters during the flight.

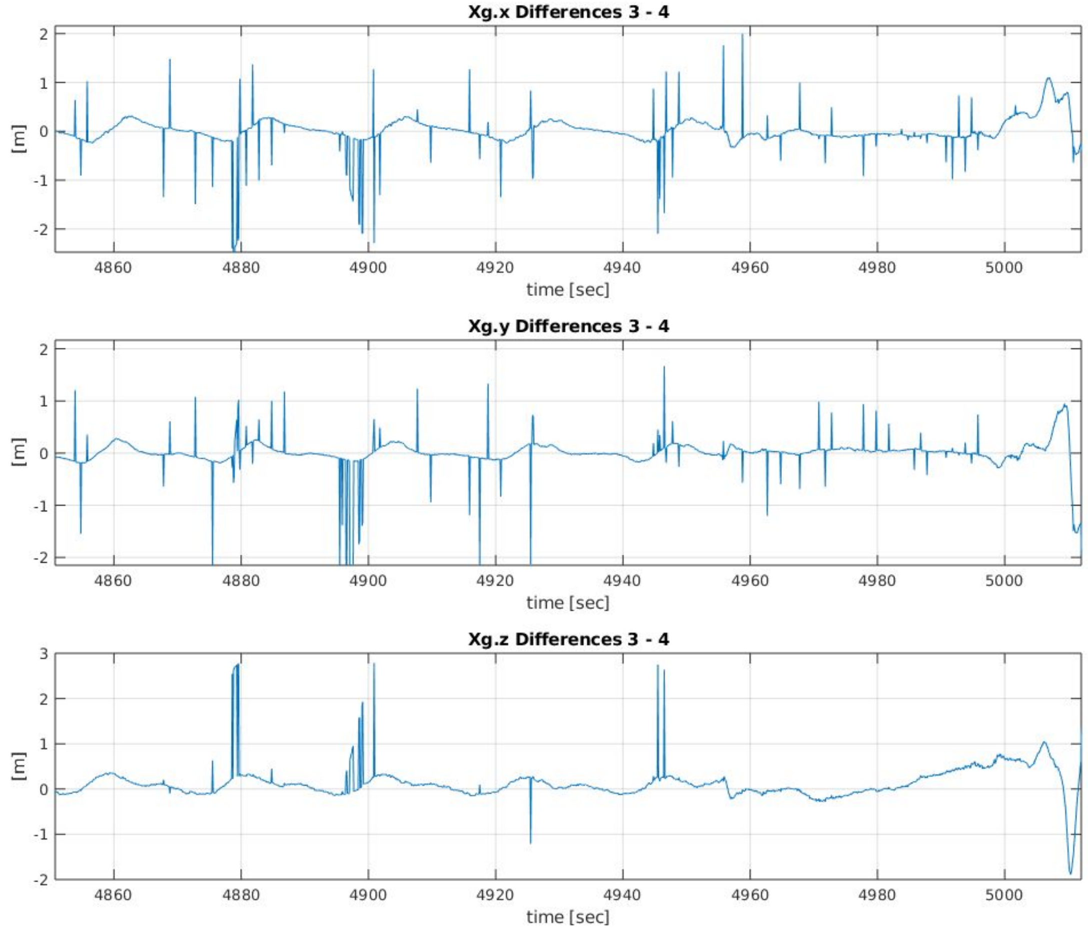


Fig. 28: GPS Errors towards the end of the flight

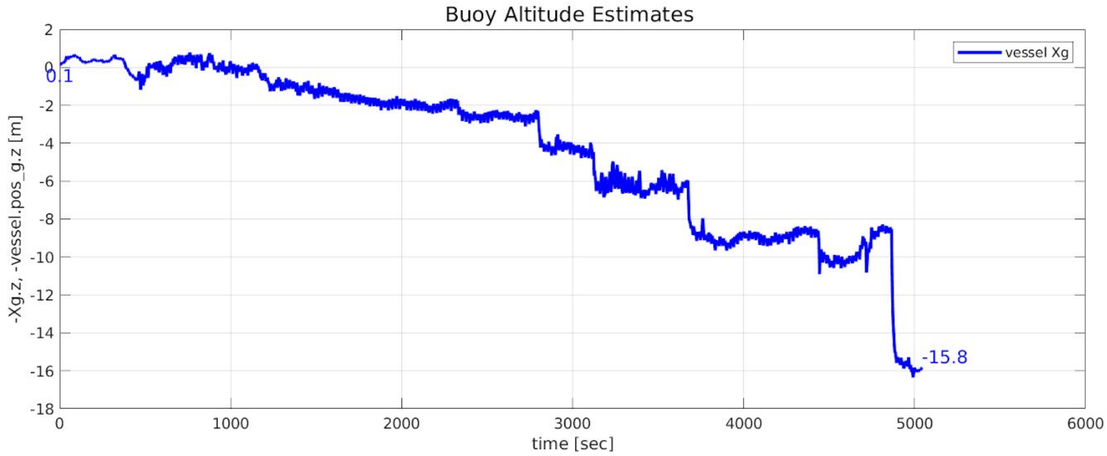


Fig. 29: The buoy altitude estimate drifts below sea level.

Appendix D: Tether Catenary Computations

The figure below shows computation of the tether tension based on the tether catenary. Using the estimated position of the ends of the tether at the kite and at the tether anchor point, the tension is computed.

The 23 seconds starting from 4967 to 4990, the tension drop computed is from 7.5kN to 5.1kN. The computed tension is lower than the estimated tension used on the kite to control tension, but the trend is similar.

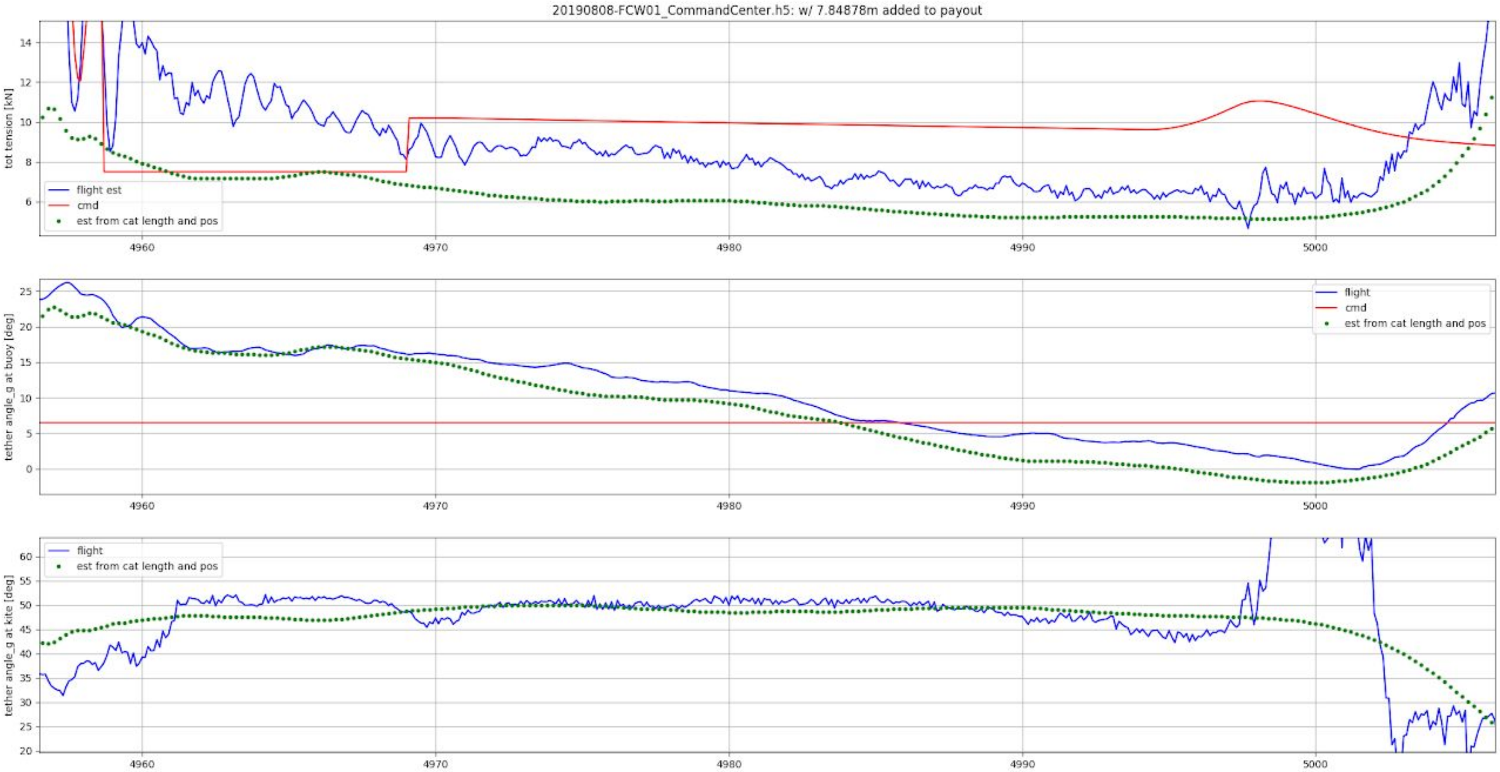


Fig. 30: Tension predicted by catenary equations.

Appendix E: FCW-01 comparison with CW-05

CW-05 and FCW-01 had similar transout height. In this appendix the differences between the flights that allowed CW-05 to maintain control are compared. The wind speed was approximately 8 m/s for CW-05, 11 m/s for FCW-01.

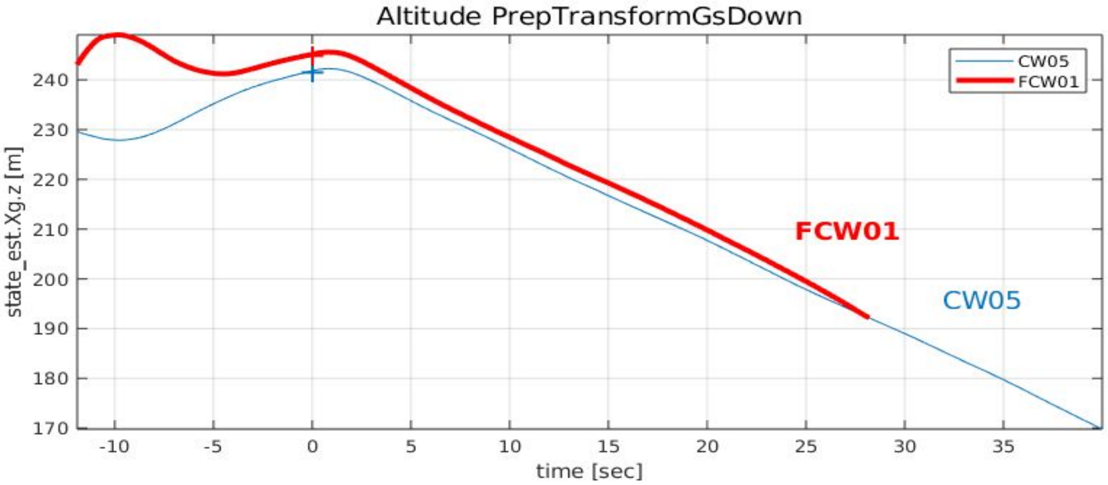


Fig. 31: FCW-01 and CW-05 altitude comparison

The tension for CW-05 was sustained around 10 kN and the hover remained controlled.

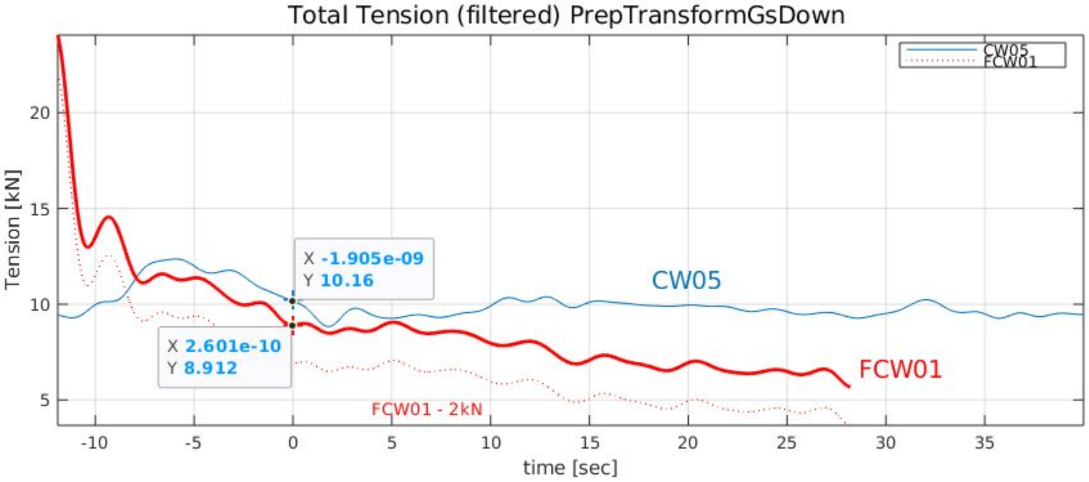


Fig. 32: FCW-01 and CW-05 tension comparison.

CW-05 began PrepTransformGsDown with the kite pitched forward by 7.3°. The tension feed-forward in CW-05 applied a pitch back command through TransOut and PrepTransformGsDown, but not in FCW-01. The tension feedback was similar (and not effective) in both flights, but the combination of feed-forward and feedback resulted in good tension control for CW-05. Notable is also that the TransOut for CW-05 did not have the characteristic pitch jog.

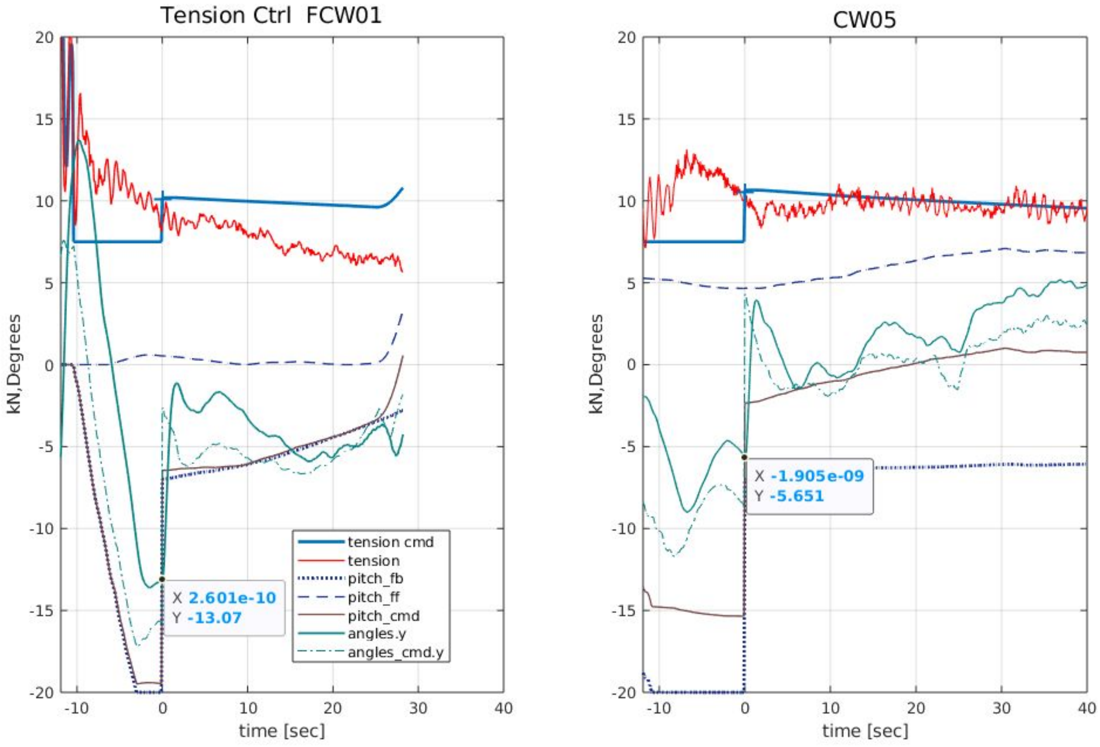


Fig. 33: FCW-01 and CW-05 tension control comparison.

The trajectory of both flights over the catenary equation contour plots indicate a lower tension for FCW-01 at the start of PrepTransformGsDown (~6.5 kN) than the load cell measurements give (8.9 kN). The tether lengths are the same, but the load cells are different.

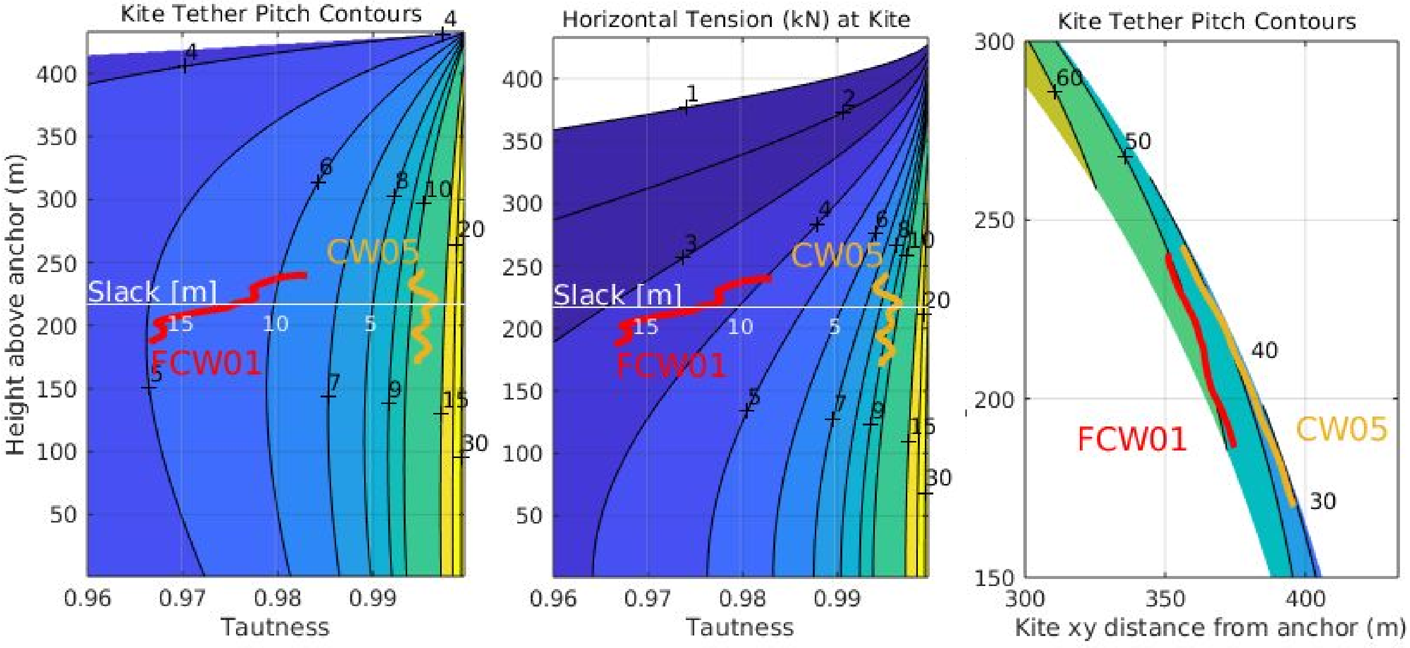


Fig. 34: FCW-01 and CW-05 tension contour plot comparison.

The kite velocities during the descent/translate motion are shown below. CW-05 maintained the horizontal velocity component to keep the tether taut.

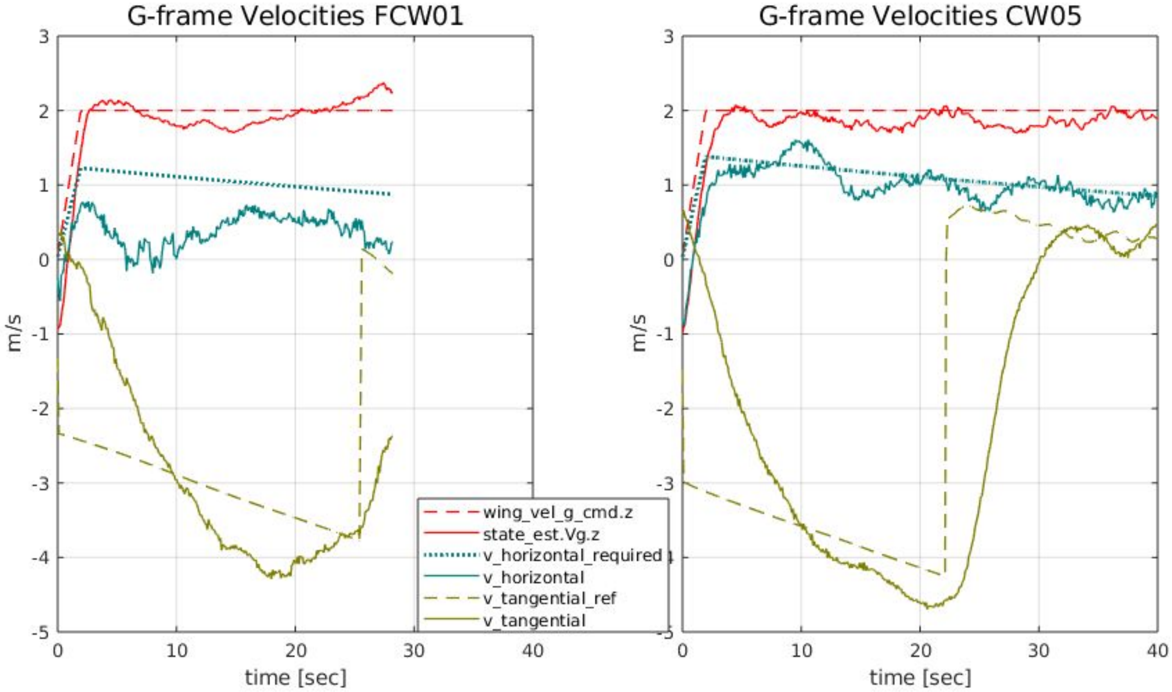


Fig. 35: FCW-01 and CW-05 g-frame hover velocity comparison.

The plots below show that the increased tension allowed the kite to maintain its attitude with similar bridle geometry and yaw thrust moments.

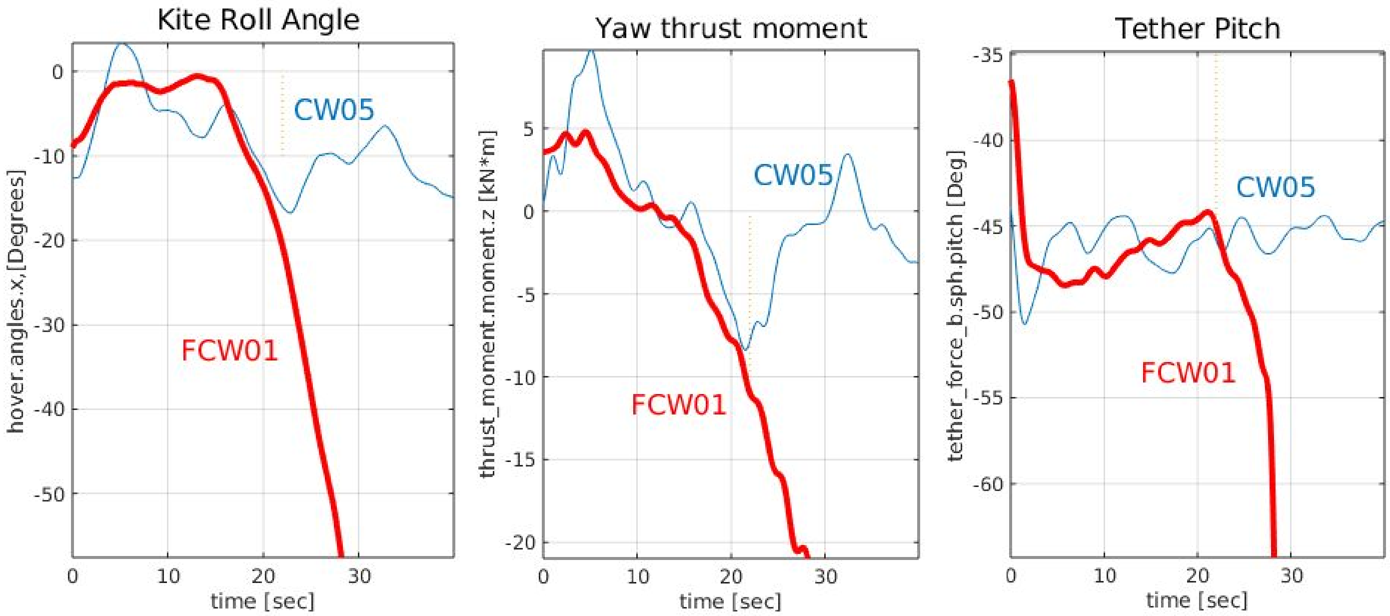


Fig. 36: FCW-01 and CW-05 roll, yaw thrust and tether pitch comparison.

Appendix F: FCW-01 comparison with CW-02

CW-02 had similar initial conditions for the tension controller and similar actions of the tension controller. However, the lower transout height provides better roll stability at lower tension and the flight remained under control. The wind speed was approximately12 m/s for CW-02, 11 m/s for FCW-01.

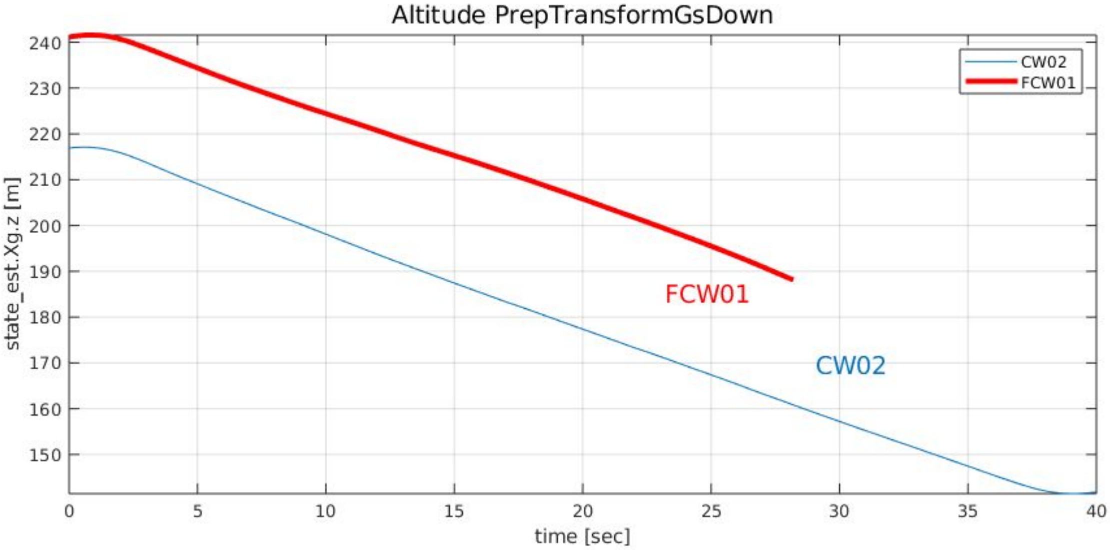


Fig. 37: FCW-01 and CW-02 altitude comparison.

The tension for CW-02, based on (different) load cells was comparable in CW-02 and FCW-01 at the start of PrepTansformGsDown (8 kN CW-02, 9 kN FCW-01). For CW-02 the tension remained around 8 kN (setpoint was ~10 kN).

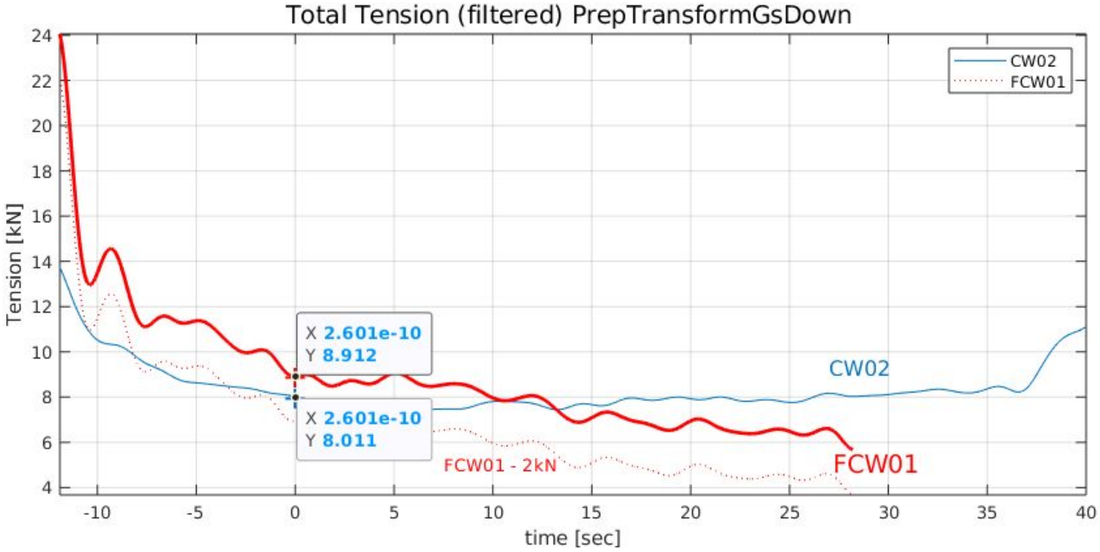


Fig. 38: FCW-01 and CW-02 tension comparison.

The tension controller produced similar control actions for CW-02 and FCW-01. The kite was similarly pitched forward after TransOut, there is similarly no pitch feed-forward, both flights have similar feedback. We can attribute the success of CW-02 to the more favorable bridle geometry at lower altitude, the fact that the buoy did not add slack to the tether and that the radial damping controller did not .

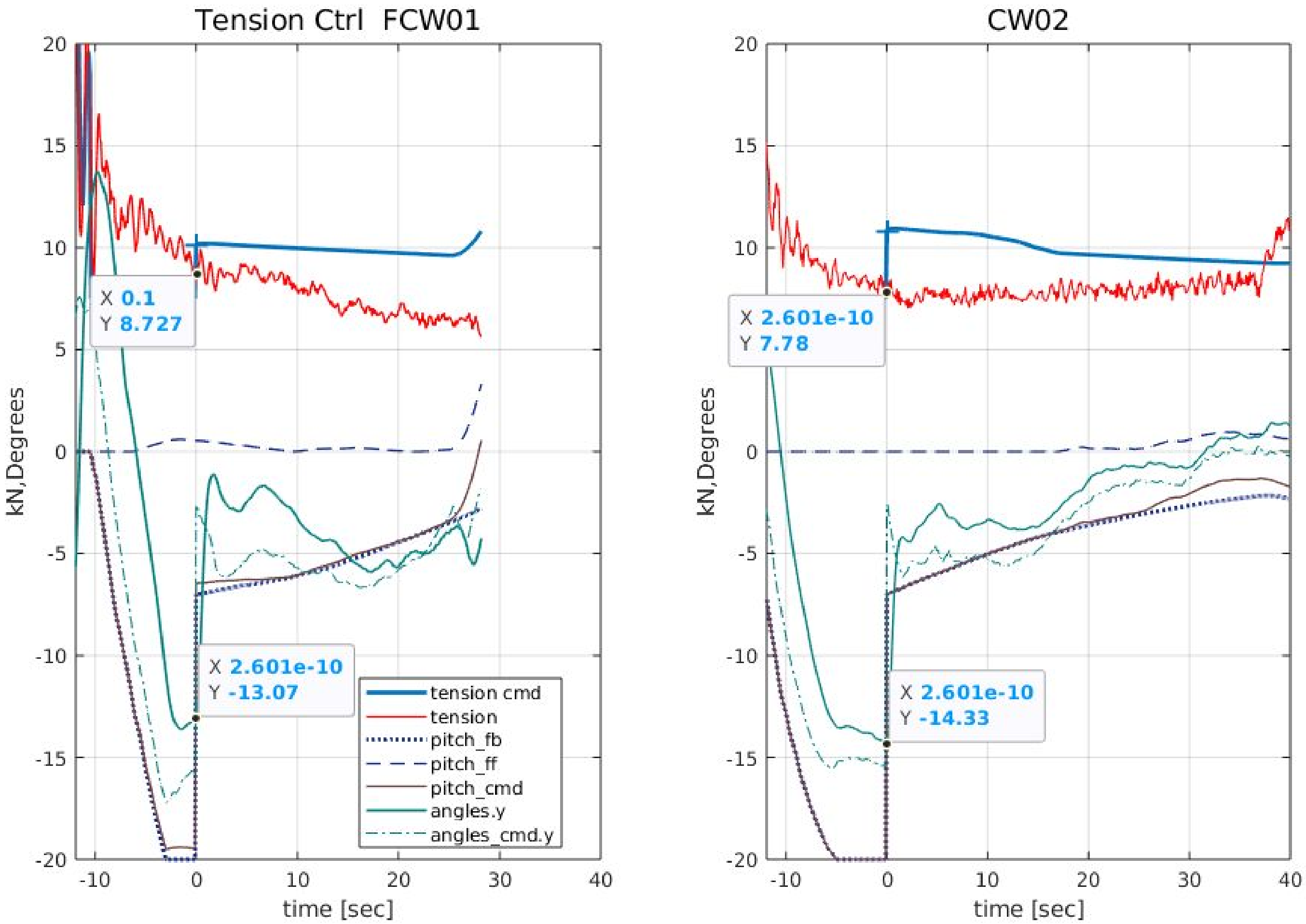


Fig. 39: FCW-01 and CW-02 tension control comparison.

The trajectory of both flights over the catenary equation contour plots indicate a lower tension for FCW-01 at the start of PrepTransformGsDown (~6.7 kN) than the load cell measurements give (8.9 kN). The tether lengths are the same, but the load cells are different.

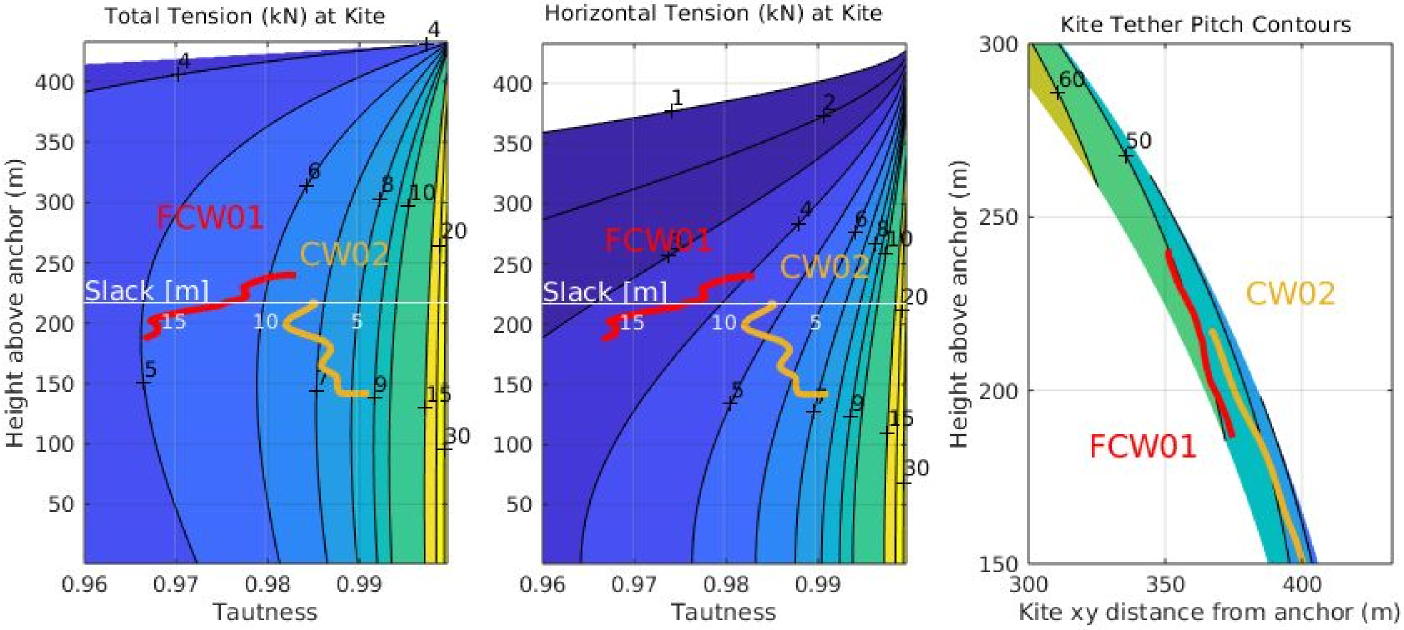


Fig. 40: FCW-01 and CW-02 tension contour plot comparison.

The kite velocities during the descent/translate motion are shown below. CW-02 maintained the horizontal velocity component to stick to the “tether sphere”.

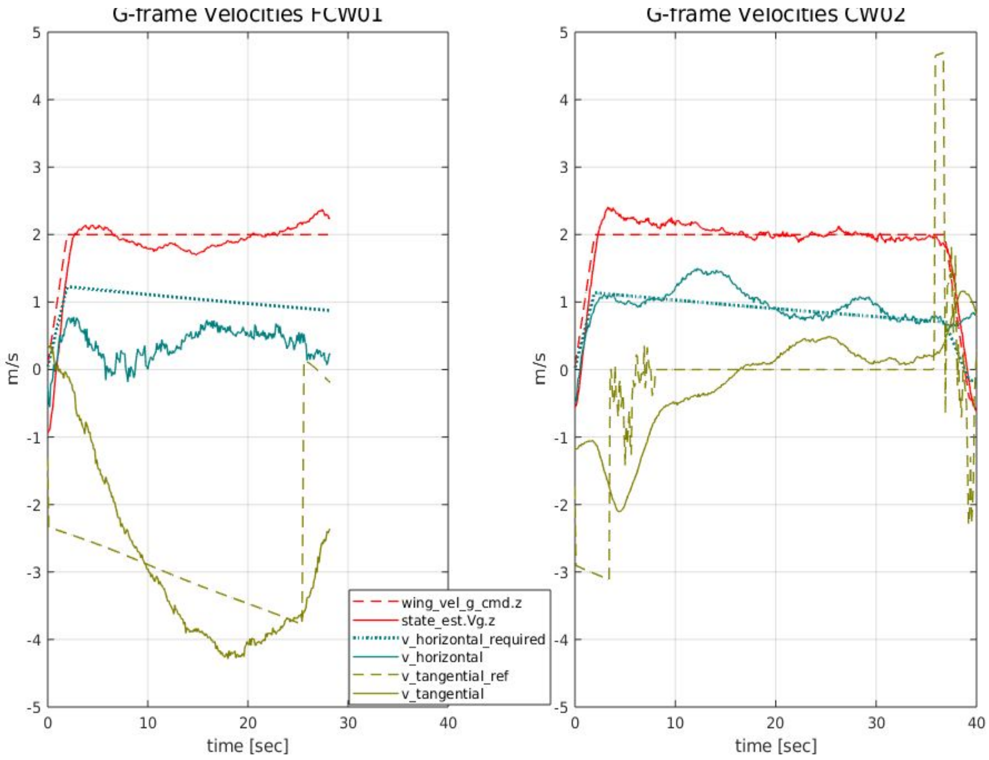


Fig. 41: FCW-01 and CW-02 g-frame hover velocity comparison.

The plots below show that the increased tension allowed the kite to maintain its attitude with similar bridle geometry and yaw thrust moments.

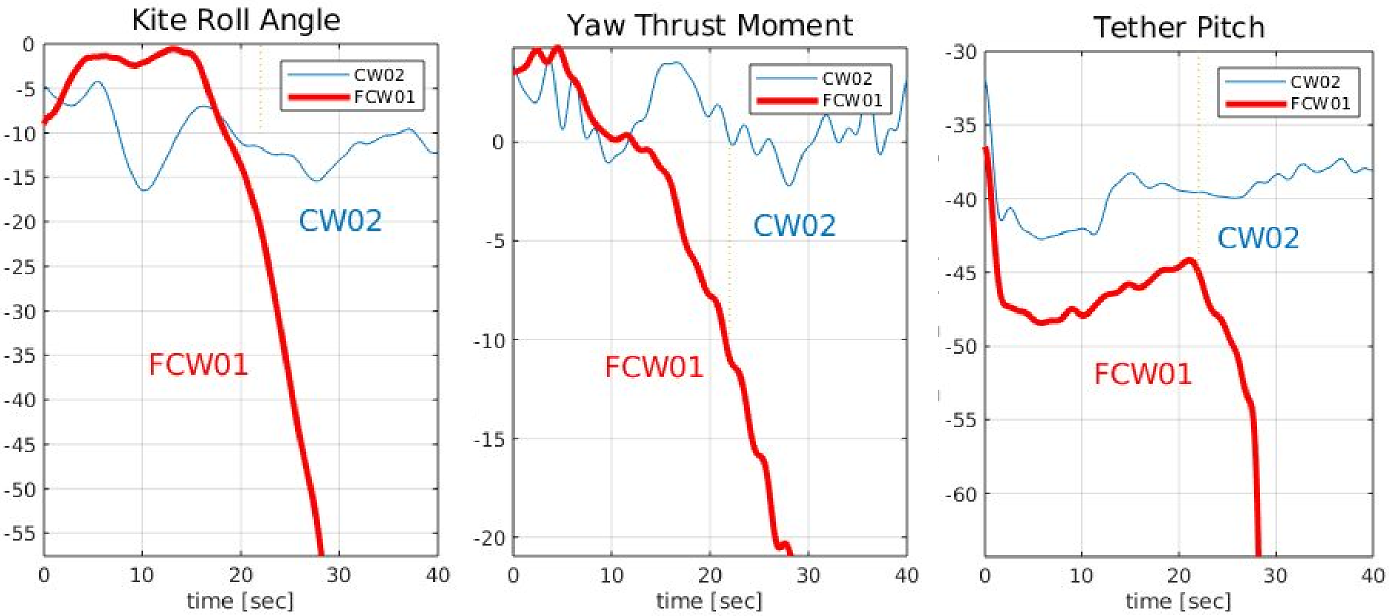


Fig. 42: FCW-01 and CW-02 roll, yaw thrust and tether pitch comparison.

Appendix G: FCW-01 comparison with CW-10

CW-10 had a lower TransOut height. It achieved good tension control due to the pitch feed-forward offsetting the pitch feedback. The wind speed was approximately 9.5 m/s for CW-10, 11 m/s for FCW-01.

Fig. 43: FCW-01 and CW-10 altitude comparison.

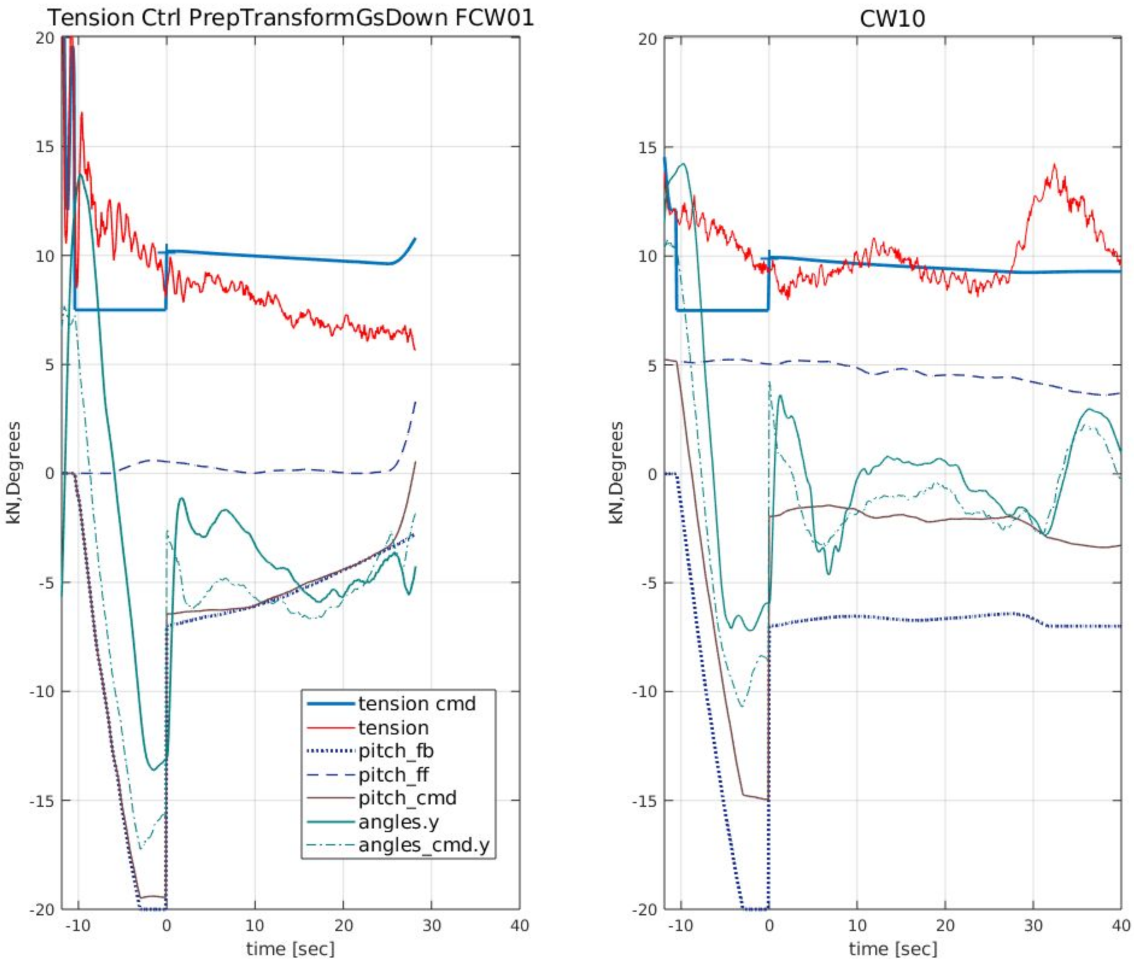


Fig. 44: FCW-01 and CW-10 tension control comparison.

EDITORIAL NOTE: Makani's timeline of engagement with the FAA

In December 2011, the FAA published a Notice and Comment memo (Federal Register vol. 76, No 235 / Dec 7th 2011 / page 76333 *et seq*) on Airborne Wind Energy Systems, seeking AWE developer comments on the possible application of 14 CFR (77): "SAFE, EFFICIENT USE, AND PRESERVATION OF THE NAVIGABLE AIRSPACE."

Makani began working with the FAA very early in our test program, but the story of the following documents begins in February 2014, when we demonstrated the Wing 7 prototype in flight at Sherman Island, in the Sacramento river delta area. An operational lighting demonstration with standard aircraft anti-collision lights was conducted in early August of 2014, with a temporary Determination of No Hazard issued for a year, starting August 18th, 2014 (ASN# 2014-WTW-1596-OE through 2014-WTW-1599-OE). The DNH determined that Wing 7 did *not* exceed obstruction standards for this location, but required the following:

- NOTAM issued during operation
- Marking:
    - Wing: conspicuous colors
    - Base station: white
    - Tether: no requirement
- Lighting:
    - Kite: two standard ACL strobes
    - Base station: L-865
    - Tether: none
- No nighttime operation permitted

In October of 2014, Makani submitted our proposed M600 installation at Parker Ranch for obstruction evaluation. Due to the greatly increased size of the M600 system, it would exceed obstruction standards. Thus began a series of technical meetings and evaluations between Makani and the FAA OEG, to determine a proposed initial lighting and marking scheme.

In May of 2015, there was an initial technical review held at the FAA offices in Washington, D.C. In September, there was a lighting and marking guidance meeting held at the FAA William J Hughes Technical Center in Atlantic City, NJ. Makani presented our proposed lighting scheme at this time, and the decision was taken that this would suffice for FAA observation flights to evaluate conspicuity. Also at this meeting, the FAA presented a proposed set of alternatives for tether marking, followed by an observational conspicuity test using tether test samples suspended below a helicopter.

Makani constructed the proposed set of alternative tether markings, and the tether conspicuity demonstration was successfully conducted in January 2016 at the FAA technical center. The FAA selected the most conspicuous of the marking options.

On June 14th 2016, the FAA issued a temporary Determination of No Hazard for the Parker Ranch installation, valid for 18 months (ASN# 2014-WTW-7734-OE through 2014-WTW-7737-OE). This study determined that the proposed installation *does* exceed the obstruction standards, but would not be a hazard to air navigation if the following requirements were met:

- NOTAM issued during operation
- An FAA authorized TFR would be required for operation above 201 feet AGL for the first time, during which time FAA observers would verify conspicuity
- Upon successful completion of the conspicuity test, the TFR would be terminated, and further operation would be permitted subject to compliance with the (possibly modified) requirements stated by the FAA
- Marking:
    - Wing: conspicuous colors
    - Base station: white
    - Tether: alternating 150 foot bands of white and aviation orange
- Lighting:
    - Kite: two standard ACL strobes
    - Base station: L-865
    - Tether: none
- No nighttime operation permitted, except during FAA observation

The 2016 DNH was revised and renewed twice, on February 15 2018, and again on February 20, 2019, to support the FAA observation flight. The revision stipulated that *four* strobes would be mounted at wingtips and on the top and bottom of the tail, each with a full-hemisphere viewing aperture, to ensure at least two ACL's would be visible in *any* orientation of the kite, from *any* angle of approach. These are no longer standard ACL lights, and Makani designed and prototyped the required hemispherical viewing aperture strobes and installed them.

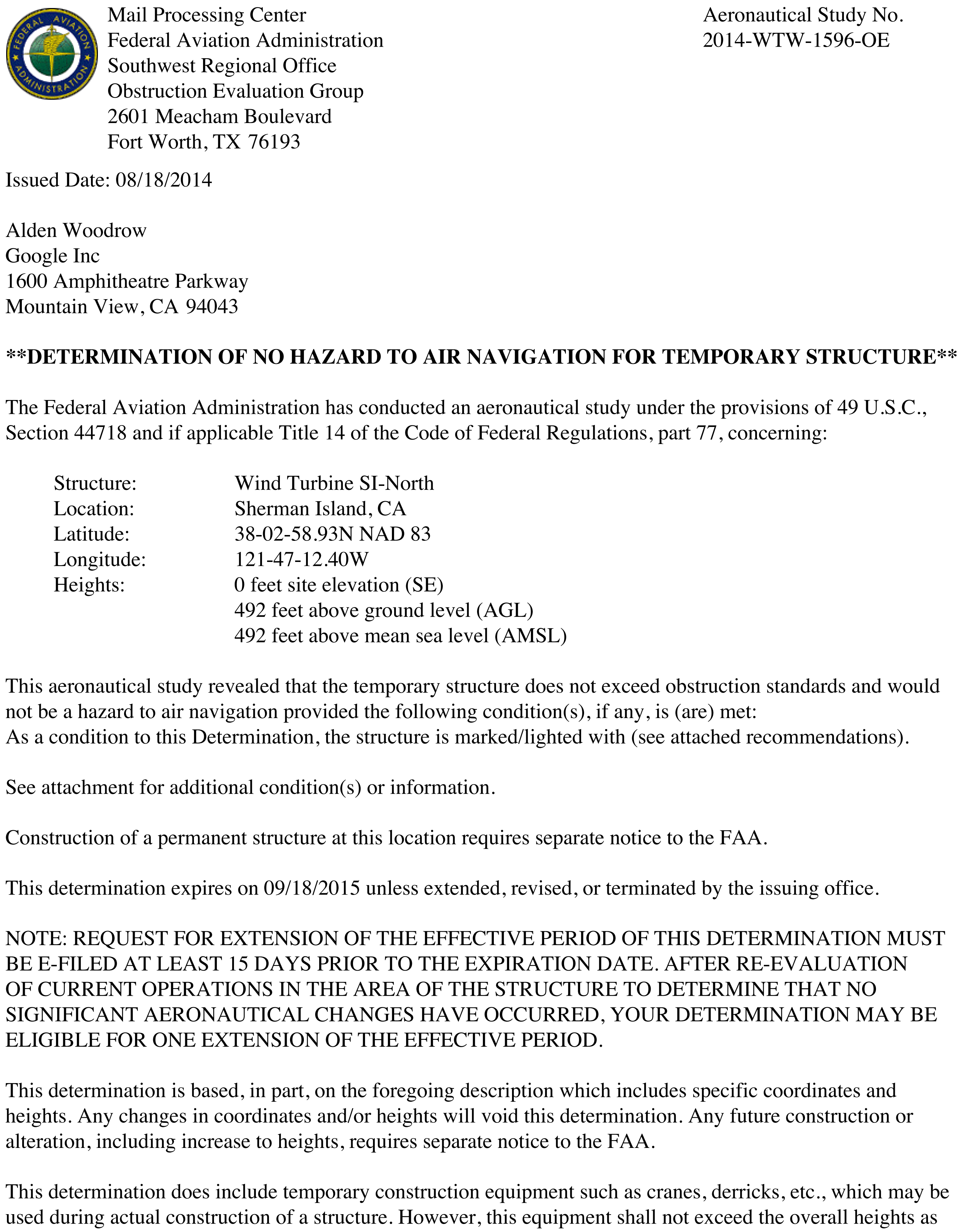
The daytime conspicuity verification flights, CW-01 and CW-02, were executed at Parker Ranch in December of 2018, with the nighttime segment following in May of 2019.

After the conspicuity verification flights, a new DNH was issued on December 13 2019, valid for 18 months (ASN# 2019-WTW-4744-OE through 2019-WTW-4747-OE), with the most up-to-date lighting requirements, and relaxing the TFR requirement and the restriction on nighttime flight. The final requirements:

- NOTAM issued during operation
- No TFR required

- Marking:
    - Wing: conspicuous colors
    - Base station: white
    - Tether: alternating 150 foot bands of white and aviation orange
- Lighting:
    - Kite: four enhanced hemispherical ACL strobes
    - Base station: L-865
    - Tether: none
- Nighttime operation permitted

This DNH was intended as a bridge, until the FAA could develop permanent rulemaking. Unfortunately, as of the date of Makani’s wind down, no such permanent rule had been issued. We include here the first Sherman Island DNH and the final and most up-to-date DNH issued, in the hopes that they may be useful for other developers seeking to navigate the waters (or “winds”) of FAA regulation of Airborne Wind Energy.



Mail Processing Center
Federal Aviation Administration
Southwest Regional Office
Obstruction Evaluation Group
2601 Meacham Boulevard
Fort Worth, TX 76193

Aeronautical Study No.
2014-WTW-1596-OE

Issued Date: 08/18/2014

Alden Woodrow
Google Inc
1600 Amphitheatre Parkway
Mountain View, CA 94043

****DETERMINATION OF NO HAZARD TO AIR NAVIGATION FOR TEMPORARY STRUCTURE****

The Federal Aviation Administration has conducted an aeronautical study under the provisions of 49 U.S.C., Section 44718 and if applicable Title 14 of the Code of Federal Regulations, part 77, concerning:

Structure: Wind Turbine SI-North
Location: Sherman Island, CA
Latitude: 38-02-58.93N NAD 83
Longitude: 121-47-12.40W
Heights: 0 feet site elevation (SE)
492 feet above ground level (AGL)
492 feet above mean sea level (AMSL)

This aeronautical study revealed that the temporary structure does not exceed obstruction standards and would not be a hazard to air navigation provided the following condition(s), if any, is (are) met:
As a condition to this Determination, the structure is marked/lighted with (see attached recommendations).

See attachment for additional condition(s) or information.

Construction of a permanent structure at this location requires separate notice to the FAA.

This determination expires on 09/18/2015 unless extended, revised, or terminated by the issuing office.

NOTE: REQUEST FOR EXTENSION OF THE EFFECTIVE PERIOD OF THIS DETERMINATION MUST BE E-FILED AT LEAST 15 DAYS PRIOR TO THE EXPIRATION DATE. AFTER RE-EVALUATION OF CURRENT OPERATIONS IN THE AREA OF THE STRUCTURE TO DETERMINE THAT NO SIGNIFICANT AERONAUTICAL CHANGES HAVE OCCURRED, YOUR DETERMINATION MAY BE ELIGIBLE FOR ONE EXTENSION OF THE EFFECTIVE PERIOD.

This determination is based, in part, on the foregoing description which includes specific coordinates and heights. Any changes in coordinates and/or heights will void this determination. Any future construction or alteration, including increase to heights, requires separate notice to the FAA.

This determination does include temporary construction equipment such as cranes, derricks, etc., which may be used during actual construction of a structure. However, this equipment shall not exceed the overall heights as indicated above. Equipment which has a height greater than the studied structure requires separate notice to the FAA.

This determination concerns the effect of this temporary structure on the safe and efficient use of navigable airspace by aircraft and does not relieve the sponsor of compliance responsibilities relating to any law, ordinance, or regulation of any Federal, State, or local government body.

Any failure or malfunction that lasts more than thirty (30) minutes and affects a top light or flashing obstruction light, regardless of its position, should be reported immediately to (877) 487-6867 so a Notice to Airmen (NOTAM) can be issued. As soon as the normal operation is restored, notify the same number.

A copy of this determination will be forwarded to the Federal Aviation Administration Flight Procedures Office if the structure is subject to the issuance of a Notice To Airman (NOTAM).

If you have any questions, please contact our office at (816) 329-2525. On any future correspondence concerning this matter, please refer to Aeronautical Study Number 2014-WTW-1596-OE

Signature Control No: 210250986-227234966 (TMP -WT)
Donna O'Neill
Specialist

Attachment(s)
Additional Information
Map(s)

Additional information for ASN 2014-WTW-1596-OE

The project consists of the four corners of an area that will be used to operate an Airborne Wind Energy System (AWES) that would be located approximately 9.47-9.62 nautical miles (NM) southwest of the Rio Vista Municipal Airport (O88), Rio Vista, CA, at a site known as Sherman Island. Sherman Island is located in the Sacramento River near Suisun Bay. This area is a VFR (Visual Flight Rules) flyway for fixed and rotary wing aircraft between the San Francisco Bay area and the San Joaquin Valley. The four corner of this area have been studied under Aeronautical Study No. 2014-WTW-1596 through 1599-OE. The AWES does not exceed any 14 CFR Part 77 obstruction standard. However, due to its operating height and special characteristics the following conditions apply during its operations.

1) The proponent shall ensure that a Notice to Airmen (NOTAM) is issued each time prior to the beginning of operations and shall be cancelled each time when operations end. The NOTAM should include the latitude/longitude, radial, and distance from Scaggs Island (SDG) VORTAC and Sacramento (SAC) VORTAC, and the operating area including radius distance from center point and maximum altitude (AMSL) of the vehicle. For NOTAM purposes the vehicle should be referred to as an Airborne Wind Energy System (AWES).

2) The lighting and marking plan for the proposed AWES at Sherman Island will be considered preliminary/temporary as part of a research and development effort with the FAA's Airport Technology R&D Branch, ANG-E26. As part of this effort, the FAA will be working with the developer to determine the optimal marking and lighting techniques for AWESs, and adopt these findings as a national standard. For this determination, the AWES should be marked and lighted (for daytime operation) as follows:

Marking: The AWES should be painted and/or marked with areas of contrasting colors that will provide sufficient contrast against terrain and the sky. High-visibility orange or high visibility green may be suitable colors. The ground station should be marked with white paint to provide contrast against terrain. The tether, at this time, does not require any marking.

Lighting: The AWES should be lighted with high-output white strobe lights, mounted on the wing tips, programmed to flash when the AWES reaches its highest and lowest points when in orbit. When the AWES is not in orbit and is in straight flight, the high-output white strobe lights should flash at 30 flashes per minute until it is either docked at the ground station or enters into orbit. The ground station should be equipped with a FAA Type L-865 white strobe light that will be programmed to flash in unison with the wing-tip lights of the AWES. The tether, at this time, does not require any lighting.

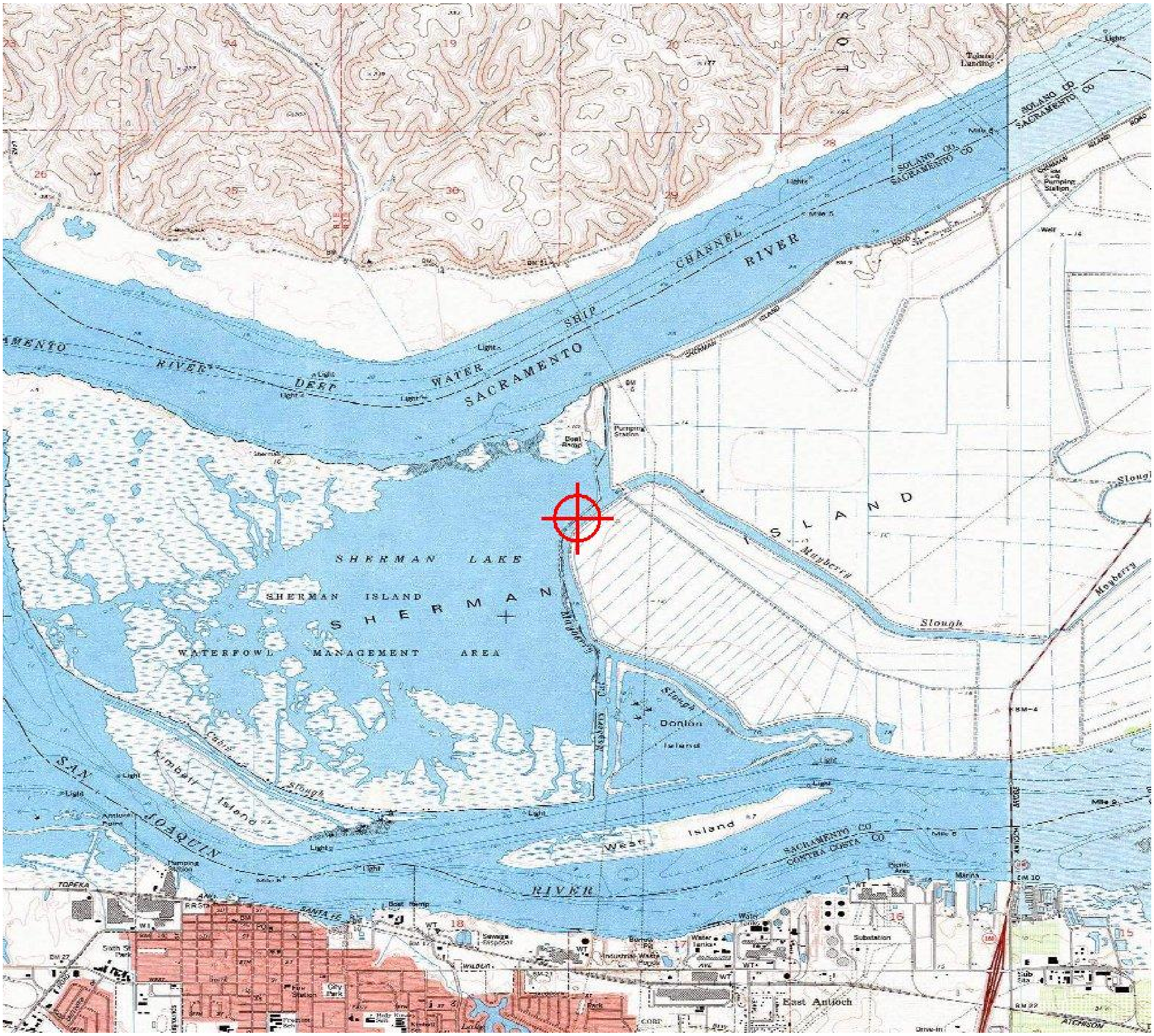
Daytime/Nighttime: At this time, details for nighttime lighting and marking have not been determined. Night time operations are prohibited. Further research will be needed to make that determination.

Duration of preliminary/temporary lighting and marking plan: This plan shall be valid for a period of one year. If at anytime during this period the FAA determines that the preliminary/temporary lighting and marking plan implemented under this determination is unsafe or that safety is being compromised due to insufficient lighting/marking, the operation of the AWES shall be suspended until a remedy is identified.

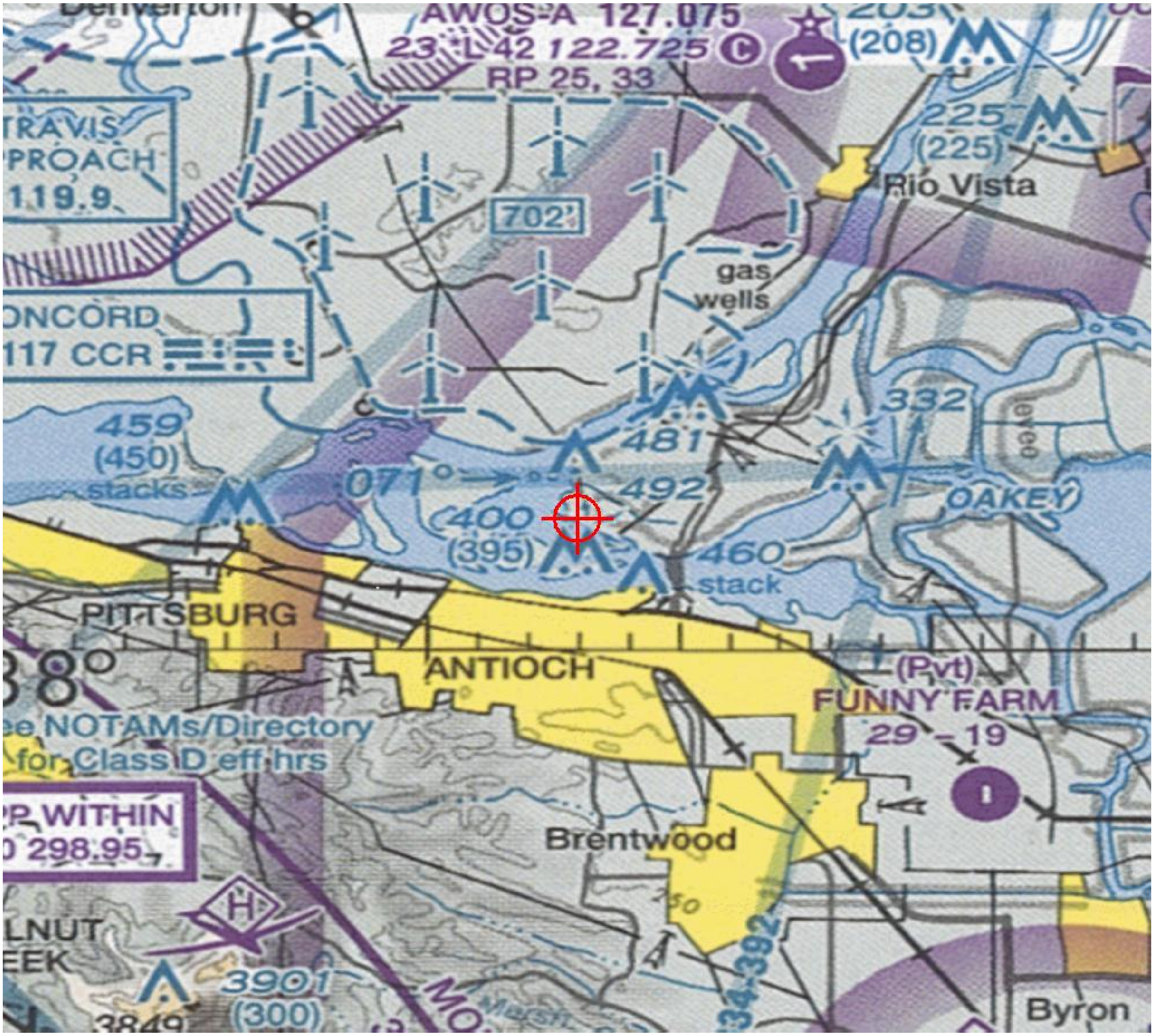
Light Outages: Due to the limited number of lights being utilized, operation of the AWES without all lights functioning is not permitted.

Research Provisions: The FAA Airport Technology R&D Branch may, at their discretion, request that the AWES, the ground station, or the tether be fitted with lighting and/or marking with different characteristics to assist with identifying the optimal technique for identifying AWESs. As part of this determination, the developer agrees to assist the FAA with this research and be as accommodating as possible, should such a request be received. It must be understood that the marking and lighting plan described in this determination is considered preliminary/temporary as part of a research and development effort. While the intent is to identify a final lighting and marking configuration during this research effort, the final configuration that will be described in FAA Advisory Circular 70/7460-1 (AC) may or may not be the same as described in this determination. Once a final marking and lighting configuration is made and identified in the AC, the developer understands that they may be required to change the existing, interim marking and lighting to be in accordance with the AC.

TOPO Map for ASN 2014-WTW-1596-OE



Sectional Map for ASN 2014-WTW-1596-OE



Mail Processing Center
Federal Aviation Administration
Southwest Regional Office
Obstruction Evaluation Group
10101 Hillwood Parkway
Fort Worth, TX 76177

Aeronautical Study No.
2019-WTW-4744-OE

Issued Date: 12/13/2019

Neal E. Rickner
Google Inc
1600 Amphitheatre Parkway
Mountain View, CA 94043

DETERMINATION OF NO HAZARD TO AIR NAVIGATION FOR TEMPORARY STRUCTURE

The Federal Aviation Administration has conducted an aeronautical study under the provisions of 49 U.S.C., Section 44718 and if applicable Title 14 of the Code of Federal Regulations, part 77, concerning:

Structure:	Wind Turbine PR-North
Location:	Kamakoa Gulch, HI
Latitude:	19-56-09.76N NAD 83
Longitude:	155-38-42.19W
Heights:	2955 feet site elevation (SE)
	1484 feet above ground level (AGL)
	4439 feet above mean sea level (AMSL)

This aeronautical study revealed that the temporary structure does exceed obstruction standards but would not be a hazard to air navigation provided the condition(s), if any, in this letter is (are) met:

SEE ATTACHMENT FOR ADDITIONAL CONDITION(S) OR INFORMATION

This determination cancels and supersedes prior determinations issued for this structure.

This determination is based, in part, on the foregoing description which includes specific coordinates and heights. Any changes in coordinates and/or heights will void this determination. Any future construction or alteration, including increase to heights, requires separate notice to the FAA.

This determination does include temporary construction equipment such as cranes, derricks, etc., which may be used during actual construction of a structure. However, this equipment shall not exceed the overall heights as indicated above. Equipment which has a height greater than the studied structure requires separate notice to the FAA.

This determination did not include an evaluation of the permanent structure associated with the use of this temporary structure. If the permanent structure will exceed Title 14 of the Code of Federal Regulations, part 77.9, a separate aeronautical study and FAA determination is required.

This determination concerns the effect of this temporary structure on the safe and efficient use of navigable airspace by aircraft and does not relieve the sponsor of compliance responsibilities relating to any law, ordinance, or regulation of any Federal, State, or local government body.

A copy of this determination will be forwarded to the Federal Aviation Administration Flight Procedures Office if the structure is subject to the issuance of a Notice To Airman (NOTAM).

If you have any questions, please contact our office at (816) 329-2526, or bill.kieffer@faa.gov. On any future correspondence concerning this matter, please refer to Aeronautical Study Number 2019-WTW-4744-OE

Signature Control No: 404837550-425249765 (TMP -WT)
Bill Kieffer
Specialist

Additional Condition(s) or Information for ASN 2019-WTW-4744-OE

Proposal: To construct and/or operate a(n) Wind Turbine to a height of 1484 feet above ground level, 4439 feet above mean sea level.

Location: The structure will be located 4.11 nautical miles south of MUE Airport reference point.

Part 77 Obstruction Standard(s) Exceeded and Aeronautical Impacts, if any:

Preliminary FAA study indicates that the above mentioned structure would:
have no effect on any existing or proposed arrival, departure, or en route instrument flight rules (IFR) operations or procedures.
have no physical or electromagnetic effect on the operation of air navigation and communications facilities.
have no effect on any airspace and routes used by the military.

Based on this aeronautical study, the structure would not constitute a substantial adverse effect on aeronautical operations or procedures because it will be temporary. The temporary structure would not be considered a hazard to air navigation provided all of the conditions specified in this determination are strictly met.

As a condition to this Determination, the structure is to be marked/lighted with See Additional Information.

Any failure or malfunction that lasts more than thirty (30) minutes and affects a top light or flashing obstruction light, regardless of its position, should be reported immediately to (877) 487-6867 so a Notice to Airmen (NOTAM) can be issued. As soon as the normal operation is restored, notify the same number.

This determination expires on 06/13/2020 unless extended, revised, or terminated by the issuing office.

NOTE: REQUEST FOR EXTENSION OF THE EFFECTIVE PERIOD OF THIS DETERMINATION MUST BE E-FILED AT LEAST 15 DAYS PRIOR TO THE EXPIRATION DATE. AFTER RE-EVALUATION OF CURRENT OPERATIONS IN THE AREA OF THE STRUCTURE TO DETERMINE THAT NO SIGNIFICANT AERONAUTICAL CHANGES HAVE OCCURRED, YOUR DETERMINATION MAY BE ELIGIBLE FOR ONE EXTENSION OF THE EFFECTIVE PERIOD.

Additional information for ASN 2019-WTW-4744-OE

THIS AMMENDED TEMPORARY DETERMINATION IS NOT ELIGIBLE FOR EXTENSION AND EXPIRES ON 06/13/2020.

The proposed temporary construction is an Airborne Wind Energy System (AWES) that consists of an airborne wind energy kite connected to a ground station by a 1500 foot tether (cable). The cable would allow the energy kite to maneuver within 1500 feet of the ground station depending upon the prevailing winds. The AWES would be located approximately 4.11 - 4.57 nautical miles south of the Waimea-Kohala airport (MUE), Kamuela, HI. The four corners of this operating area were submitted for study under aeronautical study numbers 2019-WTW-4744 through 2019-WTW-4748-OE. The height of the terrain underlying the AWES varies and the tether would restrict the AWES to a maximum height of 4439 feet above mean sea level within the operating area.

The temporary structure is identified as an obstruction under the standards of 14 CFR, part 77, as follows:

Section 77.17(a)(1): A height more than 499 feet above ground level (AGL). The proposed structure would exceed by the following amounts for each corner of the operating area.

2019-WTW-4744-OE / 985 feet
2019-WTW-4746-OE / 909 feet
2019-WTW-4747-OE / 908 feet
2019-WTW-4748-OE / 1001 feet

Section 77.17(a)(2): A height that is 200 feet AGL, or above the established airport elevation, whichever is higher, within 3 nautical miles of the established reference point of an airport, excluding heliports, with its longest runway more than 3,200 feet in actual length, and that height increases in the proportion of 100 feet for each additional nautical mile from the airport up to a maximum of 499 feet. The proposed structure would exceed by the following amounts for each corner of the operating area.

2019-WTW-4744-OE / 1173 feet
2019-WTW-4746-OE / 1067 feet
2019-WTW-4747-OE / 1051 feet
2019-WTW-4748-OE / 1173 feet

The AWES would be located on the edge of traffic pattern airspace for category D aircraft that may utilize the Waimea-Kohala airport. Category D aircraft are those aircraft with an approach speed of between 141-165 knots. Aeronautical study disclosed no known or forecasted category D aircraft conducting operations at the Waimea-Kohala airport. The AWES would be located outside traffic pattern airspace for all aircraft that would normally utilize the Waimea-Kohala airport.

Aeronautical study disclosed that the temporary structure would have no effect on any existing or proposed arrival, departure, or en route Instrument Flight Rules (IFR) operations or procedures.

Study for possible Visual Flight Rules (VFR) effect disclosed that the temporary structure would not have a substantial adverse effect on any existing or proposed arrival or departure VFR operations or procedures. It would not conflict with airspace required to conduct normal traffic pattern operations at Waimea-Kohala airport or any other known public use or military airports. Aeronautical study for VFR en-route effect disclosed that it would be necessary for the AWES to be satisfactorily marked/lighted to ensure conspicuity so that aircraft could safely navigate around the structure.

Due to this being an initial introduction of an emerging technology to the National Airspace System, additional conditions and notification procedures must be necessary prior to operation of the Makani M600 Airborne Wind Energy System (AWES).

Weather requirements:

The weather requirement for operation of the AWES must be a ceiling/visibility minimum of 1,500 feet above ground level and 3 statute miles at the base station.

NOTAM requirements:

Notify the Kona Operations Center, (808)-329-1083 at least one hour prior to the beginning of operation and again when operation has suspended for the day so that a local Notice to Airmen (NOTAM) can be issued. Provide to the operations center the latitude/longitude, direction, and distance in nautical miles from Waimea-Kohala airport (PHMU) and the operating area including radius distance in feet from center point (groundstation). For NOTAM purposes the vehicle should be referred to as an "Airborne Wind Energy System."

The lighting and marking plan for the proposed AWES at Kamakoa Gulch/Parker Ranch will be considered preliminary/temporary as part of a research and development effort with the FAA's Airport Technology R&D Branch, ANG-E26, Obstruction Evaluation Group, and Flight Standards Service - Flight Procedure Standards Branch. As part of this effort, the FAA will be working with the developer to determine the optimal marking and lighting techniques for AWESs, and possibly adopt these findings as a national standard. For this determination, the AWES should be marked and lighted as follows:

Marking requirements:

The tether for the energy kite must be painted and/or marked with areas of contrasting colors that will provide sufficient contrast against terrain and the sky. Alternating 150 foot bands of aviation orange and white are chosen to be tested; however this recommendation remains preliminary and is subject to change based on the results of the final airborne conspicuity testing. The ground station should be marked with white paint to provide contrast against terrain. The wing on the kite for this test is overall painted white with orange and yellow painted wing tips.

Lighting requirements:

The energy kite must be lighted with four flashing white strobe lights that meet or exceed the photometric specifications of FAA approved aircraft anti-collision lights (specified in Title 14 CFR Part 23.1397), mounted on the wing tips and tail, as necessary to provide 360 degree visual coverage. The ground station must be equipped with an FAA Type L-865 white strobe light that will be programmed to flash in unison with the wing-tip lights of the energy kite. It is desirable that the strobes be adjustable during the test to determine if different flash rates, number of flashes or positions to flash in the orbit of the vehicle add to the vehicles conspicuity. The tether, at this time, does not require any lighting.

Light Outages: Due to the limited number of lights being utilized, operation of the airborne wind energy system without all lights functioning is not permitted.

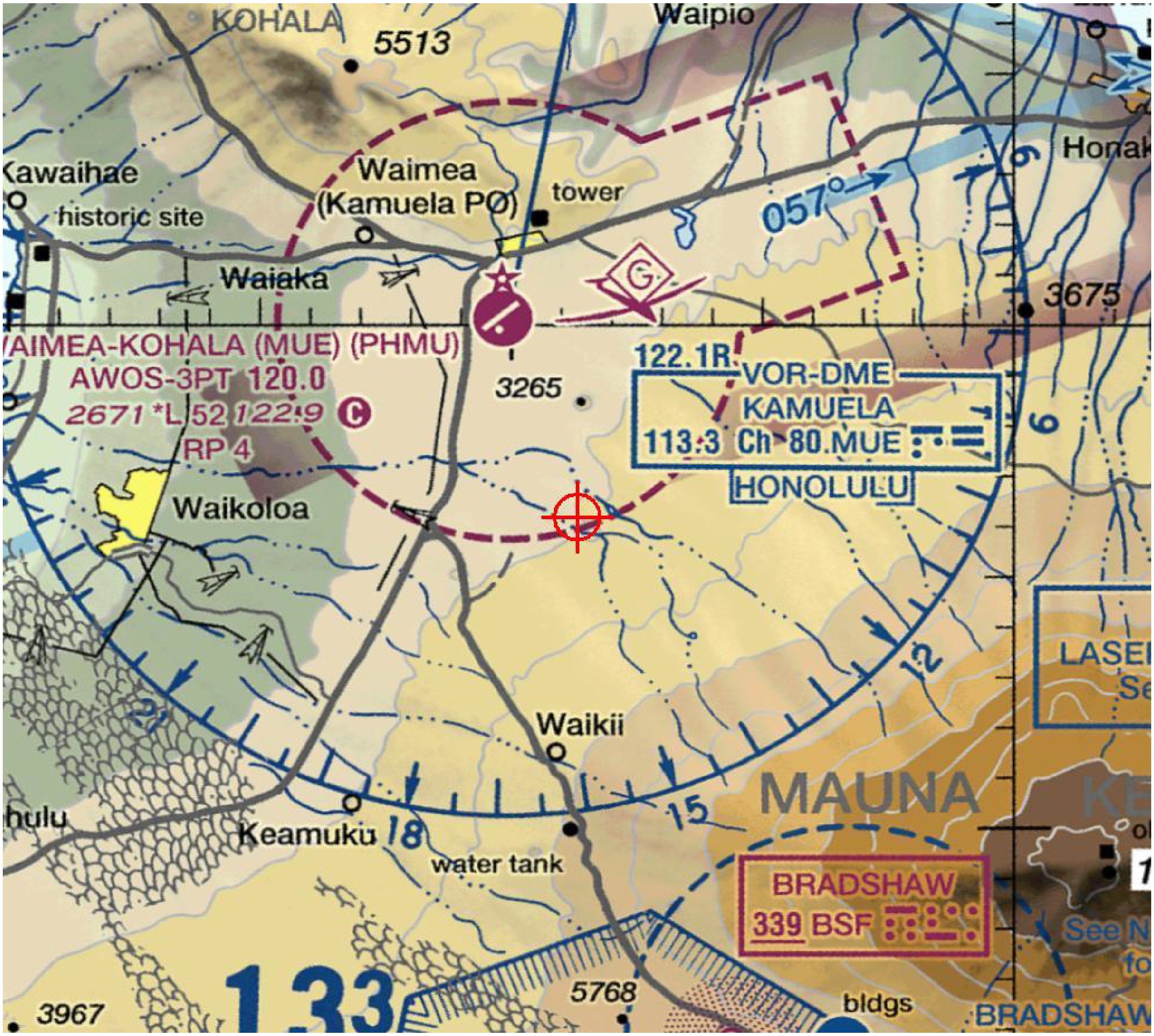
Research Provisions:

The FAA may, at their discretion, request that the AWES, the ground station, or the tether be fitted with lighting and/or marking with different characteristics to assist with identifying the optimal technique for identifying AWESs. As part of this determination, the developer agrees to assist the FAA with this research and be accommodating, should such a request be received. It must be understood that the marking and lighting plan described in this determination is considered preliminary/temporary as part of a research and development effort. While the intent is to identify a final lighting and marking configuration during this research effort, the final configuration that will be identified may or may not be the same as described in this determination. Once a final marking and lighting configuration is made the developer understands that they may be required to change the existing, interim marking and lighting.

The cumulative impact of the proposed temporary structure, when combined with other proposed and existing structures, is not considered to be significant. Study did not disclose any adverse effect on existing or proposed public-use or military airports or navigational facilities, nor would the proposal affect the capacity of any known existing or planned public-use or military airport.

Therefore, it is determined that the proposed temporary structure would not have a substantial adverse effect on the safe and efficient utilization of the navigable airspace by aircraft or on any air navigation facility and would not be a hazard to air navigation provided the conditions set forth in this determination are met.

Sectional Map for ASN 2019-WTW-4744-OE



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Date:	**Our reference**:	**Your reference**:
2018-01-19	Makani Kite_20180119	PO 425360

Googles Makani Energy Kite

Revision	Date	Content
0	2018-01-19	First issuance

CONTENTS

1. EXECUTIVE SUMMARY

This document contains the summary of the work carried out by DNV GL together with Google describing a possible design basis for the verification/certification of the tethered Makani Energy Kite. The design basis will utilise relevant parts of existing standards mainly the IEC 61400 series standards for wind turbines. For areas not covered by existing standards, an approach using technology qualification methods is suggested, see Section 5.

Both the tethered Makani Energy Kite and the corresponding ground station system are considered in this report.

Germanischer Lloyd Industrial Services GmbH
Registered Office Hamburg No. HRB 86804. VAT Reg. No. DE 228 282 604
Managing Directors: Dr. Kim Mørk, Tobias Rosenbaum.
Place of performance and jurisdiction is Hamburg. The General Terms and
Conditions of DNV GL apply. German law applies. www.dnvgl.com

It has been found that the IEC 61400 series wind turbine standards are applicable or partly applicable for some components and aspects, see Appendix A for the overview table.

For aspects not covered by existing standards, it is suggested that Technology Qualification methods are applied.

DNV GL applied templates developed for the Technology Qualification method described in the DNV GL document RP A203:2013 as a format for our detailed reporting.

The DNV GL work was based on:

- The kick-off teleconferences between Makani and DNV GL
- Individual expert teleconferences with Makani and DNV GL
- Regular email correspondence
- DNV GL internal workshops evaluating IEC standards and technology classes
- Documentation package of presentations provided by Makani to DNV GL

2. CERTIFICATION SCHEME

The certification scheme according to DNVGL-SE-0441 should be applicable for the Makani Energy Kite in terms of the organizational setup of certification. The DNVGL-SE-0441 is a further development of IEC 61400-22 and GL Guidelines and it allows for assessment of new technology. However, the technical content needs to be adapted for the application in question.

3. REVIEW AND EVALUATION

Individual expert teleconferences have been initiated within the time period of June until September 2017 on the following disciplines:

- Loads
- Avionics and control system
- Electromechanical tether and electrical installations
- Hybrid rotors
- Wings and planform
- Ground station and mechanical components
- Commissioning procedure
- Prototype measurements

During the teleconferences the technical concept, design parameters, methodologies and principles have been presented to DNV GL and discussed between DNV GL and the customer allowing identification of applicable standards based on IEC 61400 series.

After completion of the individual expert teleconference for respective disciplines, DNV GL has carried out internal workshops for the evaluation of the applicable standards and related technology classes.

The results of this work have been summarized, see Appendix A. In general, if an IEC 61400 series wind turbine standard was directly applicable per DNV GL opinion, this standard has been mentioned within the column for “Standard or new aspect”.

4. TECHNOLOGY CLASSES

Technology classes have been defined for components and aspects.

In combination with the setting for whether the application is known or not, the definition for Technology Class was established. The Technology Class has been completed by setting the Technology Status on either "proven", "limited field history" or "new/unproven" Technology for the respective component.

Consequently, the final identification of the Technology Class was possible for the components in question.

	Technology Status		
Known Application	Proven	Limited field history	New/unproven
yes	1	2	3
no	2	3	4

Table 1: Technology Status definition

The following table gives an overview of the Technology Class definition.

Technology Class	Definition
1	No new technical challenges
2	New technical uncertainties
3	New technical challenges
4	Demanding new challenges

Table 2: Technology Class definition

The individual definition of the Technology Class has been supported by DNV GL comments and observations/assumptions.

5. ELABORATION OF A CERTIFICATION/VERIFICATION PROCESS

For evaluating aspects to which existing standards do not apply, the process addressed within DNVGL-SE-0441 should be applied.

- Conceptual Design
- Technology Qualification including Prototype Testing

The verification of the Conceptual Design will be concluded with a statement/report as well as a certification/verification plan addressing required Technology Qualification activities.

If the Technology Qualification process has been finalized successfully a statement/report will be issued.

6. SUMMARY AND CONCLUSIONS

The concept design of the Makani Energy Kite was presented and explained to DNV GL. A list of components and aspects has been prepared containing references to applicable IEC 61400 series standards and Technology Classes.

It has been found that the IEC 61400 series standards for wind turbines are applicable or partly applicable for some components and aspects.

The plan for evaluating aspects to which existing standards do not apply was developed.

7. REFERENCES

/1/ DNVGL-SE-0441, Service Specification for Type and Component Certification of Wind Turbines

/2/ DNVGL-RP-A203, Recommended Practice for Technology Qualification

/3/ IEC 61400-22:2010, Wind turbines - Part 22: Conformity testing and certification

List of documents from the customer:

Document No.	Revision and Date	Title
Presentation 1	-, 2017-06-30	Makani, Energy Kite – Overview
Presentation 2	-, 2017-07-05	Makani, Energy Kite – Overview
Presentation 3	-, 2017-07-17	Makani, M600A Airframe
Presentation 4	-, 2017-08-03	Makani, Controls, Avionics, GS, Safety System
Presentation 5	-, 2017-09-07	Makani, Prototype Testing and Commissioning
Presentation 6	-, undated	Makani, Tether - Appendix

Sincerely

for Germanischer Lloyd Industrial Services GmbH

i.V. Reinhard Schleeßelmann i.A. Kay-Uwe Fruhner

APPENDIX A – OVERVIEW STANDARDS AND EVALUATION ASPECTS

See latest Revision of:

Makani Kite_Appendix A_2018-01-19

Developer: Makani 49468
Turbine: Makani Energy Kite Vx
Appendix A: Overview standards and evaluation aspects

Components and functions in the design module

ID					Component	Function	Standard or new aspect	Known Application		Technology			Technology Class	Comments	Observations
								yes	no	Known	L. hist.	New			
1					**Loads**										
	1	1			simulation tools	load simulation and/or prediction of parameters for load simulation model, aeroservoelastic instabilities, fluttering predictions (rotor, tail)	New application, integration of tools and interfaces, change of operating modes (from operating to recovery for example), integration of winch operations with flight condition		x			x	4	Validation of in-house codes are required, also overall validation of integration of tools to be performed looking at prototype testing results.	Tools are partly well known, partly unknown to DNV GL
					Aeroelastic simulation tools ASWING, CSIM, STAR-CCM+, NASTRAN, RCAS, Kite-FAST, in-house MATLAB codes, XFOIL, MSES, VSAERO										
					Structures Response Simulation										
					Rotor Response Simulation										
					Tether Response simulation										
					Aeroservoelastics Simulation										
	1	2			load measurements, operation parameters, turbine behaviour and simulation validation	validation of simulation tools and design conditions (for example deployment operating, extreme, accidental and retrieval conditions)	Parts of IEC 61400-11(noise), -12-1(power curve), -13 (mechanical loads), -21 (power quality)		x		x		3	Adaptation of the requirements in IEC 61400 (including definitions eg hub height) will be needed to focus on the main areas of uncertainty and translate the different application to the kite	
	1	3			load case definition	Define envelop conditions that will be used to design all systems	IEC 61400-1 (including edition 4, sections 6+7, Table 2 for load case definition and Table 3 for proposed target probability of failures) and DNVGL-ST-0437		x		x		3	Please note that IEC 61400 considers a return period of 50 years for extreme external conditions	The FMECA will allow the identification of risks and criticalities throughout the systems and components. Target probability of failures compatible with renewable sector are proposed. Different safety levels with associated annual probability of failures such as Low (10E-03 annual prob failure), Normal (10E-04), High (10E-05) safety levels may be considered depending on consequences of failure. Based on the target probability of failures, simulations and measurements can be used to determine the load effects and to perform a calibration of load factor compatible with the target probability of failure.
	1	3	1		Deployment Phase		Controls for transition		x		x		3		
	1	3	2		Operating Phase		Controls for transition		x		x		3		
	1	3	3		Retrieval Phase		Controls for transition		x		x		3		
	1	3	4		Stand still at ground (including survival condition)		Derivation of loads, identification of critical connections, extreme loading definition		x	x			2		
	1	3	5		Construction, installation, maintenance and repair		Use IEC 61400-1 DLC 8.X. Adaption by developing the related load case table for the energy kite application.		x		x		3		
	1	4			load safety factor strategy	Ensure sufficient safety margin baased on variability of loads	Based on IEC 61400-1 section 7, Table 3		x			x	4		The FMECA will allow the identification of risks and criticalities throughout the systems and components. Target probability of failures compatible with renewable sector are proposed. Different safety levels with associated annual probability of failures such as Low (10E-03 annual prob failure), Normal (10E-04), High (10E-05) safety levels may be considered depending on consequences of failure. Based on the target probability of failures, simulations and measurements can be used to determine the load effects and to perform a calibration of load factor compatible with the target probability of failure.

Developer: Makani 49468
Turbine: Makani Energy Kite Vx
Appendix A: Overview standards and evaluation aspects

Components and functions in the design module

ID					Component	Function	Standard or new aspect	Known Application		Technology			Technology Class	Comments	Observations
								yes	no	Known	L. hist.	New			
2					**Avionics and Control system**		**Application transferred to wind turbine technology**							**To check with FMECA results**	**It is assumed that this is adapted from other industries.**
	2	1			Flight computers	Control all phases of operation and fault handling			x	x			2		
	2	2			Kite avionics buses and communication nodes	Control execution			x	x			2		
	2	3			Kite-to-ground communication (fiber optic) and long-range radio communication for off-tether fault cases	Transfer of flight control signals and operation data to ground			x		x		3		
	2	3	1		Polymer (Plastic) Optical Fiber				x		x		3		
	2	4			Flight control sensors										
	2	4	1		gyros, accelerometers, compass	atitude, direction, acceleration, velocity			x	x			2		
	2	4	2		static pressure	vertical position, altitude			x	x			2		
	2	4	3		total pressure	airspeed			x	x			2		
	2	4	4		alpha (indirect measurement?)	angle of attack			x	x			2		
	2	4	5		beta (indirect measurement?)	angle of sideslip			x	x			2		
	2	4	6		load cells	Tension for control, backup position, tether roll and pitch			x	x			2		
	2	4	7		GSG encoders	Position backup			x	x			2		
	2	4	8		GPS	Position, velocity			x	x			2		
	2	4	9		GPS TRK	Precision relative position			x	x			2		
	2	4	10		Additional position measurement	Position, velocity			x	x			2		
	2	5			Closed-loop control software for all modes	Control all phases of operation and fault handling	Interconnection with power optimisation and flight control		x			x	4		
	2	6			Actuators	Implement flight controls									
	2	6	1		Ailerons actuators				x	x			2		
	2	6	2		Rudder actuators				x	x			2		
	2	6	3		Elevator actuators				x	x			2		
	2	6	4		Flaps actuators				x	x			2		
3					**Electromechanical tether and electrical installations**										
	3	1			Tether	fixing the kite and transmission of electrical power and communication									
	3	1	1		Control and Instrumentation Cables	Transmits typically analogue and/or digital control signals, as well as monitoring data	IEC 60227, IEC 60228, IEC 60332 etc.		x	x			2	It is assummed that of the shelf cables will be used	Design life, the type of cable and any environmental / vibration motions., etc that are imposed in the cables - To be clarified to identify novelty, uncertainty
	3	1	2		Power Cables (4 to 16 separetly insulated conductors)	Transmit power (MV)	IEC 60502-2		x	x			2	It is assummed that of the shelf cables will be used	Design life, the type of cable and any environmental / vibration motions., etc that are imposed in the cables - To be clarified to identify novelty, uncertainty Configuration to be clarified.
	3	1	3		Structural										see line 6.10 in section structural
	3	1	4		Terminations	Interface Tether to Reel and to Bridle									
	3	1	4	1	Terminations (mechanical)				x			x	4		
	3	1	4	2	Connectors (electrical)		Electrical HV terminations acc. IEC 60502-4		x			x	4		
	3	1	5		Bridles	Connection Bridle to Kite (allow for roll and pitch motion)									
	3	1	5	1	Mechanical				x			x	4		For definition of Tech Class, further information is required.
	3	1	5	2	Electrical				x			x	4		For definition of Tech Class, further information is required.
	3	1	6		Profile	Drag reduction and stability of tether								Assumed UV resistant, erosion resistant, flexible	How the profile will not interfer with the reeling in / out, segmentation and continuity of the lightning ground path?

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						yes	no	Known	L. hist.	New			
3	1	7	Lightning ground path	Ligthning protection through path to ground	IEC 61400-24 + IEC 62305 series		x			x	4	Lightnig stroke hitting the kite shell shall be conducted down to earth in a "controled" manner. A defined down conducting path shall be available to protect sensitive equipment or other parts from electro-magnetic impacts. Outer structural parts shall be used preferably. A standardized earth electrode shall be provided at the ground station to allow for this. Lightning stroke testing of kite and sub-assemblies most probably required for verification of e.g. attachment points/receptors	Lightning strike could hit tether directly (cable inside) Integrity of the path that is uncertain (slip ring/ de-twisting, segmets of profile, termination, etc) Operational profile (restriction during thunderstorms?)
3	2		Kite Power										
3	2	1	Motor / generators	Power generation and thrust (for control of kite operation)	IEC 60034 series		x			x	4	Description of changing the operation mode from motorisation to generation not known at this time	Axial flux, twin-rotor, 36 teeth, 30 poles, edge-wound coils, sandwich bonded assembly, "wet stator" with dielectric coolant, casing laminate G-10. Stack design
3	2	3	MV Bus		IEC 62271 for switchgear	x		x			1		
3	2	4	MV to LV Converter		IEC 62477		x			x	4	Self-designed equipment, not industry proven, shall undergo a well defined testing procedure based in applicable international standards	
3	3		LV System		IEC 60364 series	x		x			1		
3	3	1	LV Bus			x		x			1		
3	3	2	Servos		IEC 61800 series	x		x			1		Assumed off-the-shelf components and operating, maintnained within parameters of Tech Class 1
3	3	3	Battery			x		x			1		Assumed off-the-shelf components and operating, maintnained within parameters of Tech Class 1
3	3	4	Avionics (Covered in item 2)										
3	4		Ground Power										
3	4	1	Inverter (stacked)		IEC 62477	x				x	3		6 250kW inverters • DC series connected • Inverter section is floated • Custom designed, high isolation transformer • Needs work to meet regulatory requirements for insulation
3	4	2	Battery			x		x			1		
3	4	3	Switchgear		IEC 61439 / IEC 62271	x		x			1	The results of internal arcing and related pressure to cabinets and structures have be investigated, escpeially for the kite.	
3	4	4	Slip ring		no standard	x				x	3	More information about the slipring itself and qualification/testing required. Even industry proven slip-rings from known manufactures are prone to shot-cicuits or other failures e.g. depending on environmental aspects.	Lightning down conductor included?

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						yes	no	Known	L. hist.	New			
4			**Hybrid rotors**										
	4	1	2.3m Diameter rotor 5 Fixed-Pitch blades	Generate lift for take off and convert wind energy in rotational energy	IEC 61400-1 in combination with DNVGL-ST-0376 for the composite parts		x	x			2		separate blades
	4	2	Electro-thermal de-icing	ensures aerodynamic perfomance and safety relavant	IEC 61400-1 in combination with DNVGL-ST-0076 for electrotechnical systems		x	x			2		Inductive power transfer to avoid slipring
	4	3	Lightning protection		IEC 61400-24		x	x			2		Aluminum conductive mesh
	4	4	Leading edge erosion protection	extends life time	Aerospace standards	x		x			1	New to Wind industry	Electro-formed nickel
	4	5	Hub, shaft and rotor bearing		Machinery Standards, DNVGL-ST-0361	x		x			1		
5			**Wings and Planform**										
	5	1	Wings	Keeps Kite spinning	IEC 61400-1 in combination with, DNVGL-ST-0376 for the composite parts and DNVGL-ST-0361 for machinery components		x	x			2	Loading (see Item 1) and item 9 (safety factors)	
	5	2	Pylons	mounting of engine/turbine to the kite	IEC 61400-1 in combination with, DNVGL-ST-0376 for the composite parts and DNVGL-ST-0361 for machinery components		x	x			2	Loading (see Item 1) and item 9 (safety factors)	
	5	3	Fuselage	Main body of the kite	IEC 61400-1 in combination with, DNVGL-ST-0376 for the composite parts and DNVGL-ST-0361 for machinery components		x	x			2	Loading (see Item 1) and item 9 (safety factors)	
	5	4	Tail plane	Steering and Stability	IEC 61400-1 in combination with, DNVGL-ST-0376 for the composite parts and DNVGL-ST-0361 for machinery components		x	x			2	Loading (see Item 1) and item 9 (safety factors)	
	5	5	Housing and cut-outs		IEC 61400-1 in combination with, DNVGL-ST-0376 for the composite parts and DNVGL-ST-0361 for machinery components		x	x			2	Loading (see Item 1) and item 9 (safety factors)	

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ID						Component	Function	Standard or new aspect	Known Application		Technology			Technology Class	Comments	Observations
									yes	no	Known	L. hist.	New			
6						**Ground station structure and mechanical components**	ground attachment for kite (reliability (single point failures), cross wind tension (190kN / Provide launch and land capability for kite (land up to 25m/s), Wind change up to 30 deg in 6s, survive 35.8m/s with kyte parked, 50,1m.s gust / minimize maintnenace and repair cost over 20y system life									
	6	1				Ground-side gimbal (GSG)	Fixation point of tether at lower end.	Loading uncertain, load cycles and maintenance regime uncertain / different from traditional application. Including events with failures (abnormal and accidental)		x		x		3	redundant de-twist drive, predominantly post-machined casting, strength driven by crosswind tether tension, bearing size driven by cross ind tether tension and system life	
	6	1	1			Gimbal Bearing	Freedom of rotation for tether	ISO 76 / ISO 281 / DNVGL-ST-0361 / IEC 61400-1		x	x			2		For all components: See line 9.1.
	6	1	2			Gimbal structural parts	Cardan joint for tether	DNVGL-ST-0361 / IEC 61400-1		x	x			2		For all components: See line 9.1.
	6	1	3			Gimbal de-twist drive	Electrical drive for rotating the gimbal	DNVGL-ST-0361 / IEC 61400-1		x	x			2	Design is unknown. It is assumed that the technology is known	For all components: See line 9.1.
	6	2				Winch	Winching the tether.	Loading uncertain, load cycles and maintenance regime uncertain / different from traditional application. Including events with failures (abnormal and accidental)		x		x		3		hydraulic friction brake, electric motors
	6	2	1			Winch arm	Structureal part that holds the gimbal, positioning of the tether on the drum at beginning of winch action.	DNVGL-ST-0361 / DNVGL-ST-0126 / IEC 61400-1		x	x			2		For all components: See line 9.1.
	6	2	2			Winch bearing	Freedom of rotation for the winch drum	ISO 76 / ISO 281 / DNVGL-ST-0361 / IEC 61400-1		x	x			2		For all components: See line 9.1.
	6	2	3			Winch ring gear	Gear fixed to the drum of the winch.	DNVGL-ST-0361 / IEC 61400-1		x	x			2		For all components: See line 9.1.
	6	2	4			Winch reduction gearbox and interface pinion	Parts of the drive for the drum	DNVGL-ST-0361 / IEC 61400-1		x	x			2	Design is unknown. It is assumed that the technology is known	For all components: See line 9.1.
	6	2	5			Drum	Holding the tether when winching.	DNVGL-ST-0361 / IEC 61400-1	x		x			1		For all components: See line 9.1.
	6	2	6			Brake	Brake for the drum.	DNVGL-ST-0361 / IEC 61400-1	x		x			1		For all components: See line 9.1.
	6	3				Sensors	Identify where the tether is pointing									see line 10.3 in section Instrumentation
	6	4				Levelwind	Function of this component seems to be to direct the tether onto the drum.	DNVGL-ST-0361 / IEC 61400-1		x		x		3	Design and functionality not clear	For all components: See line 9.1.
	6	5				Azimuth unit	Turning the winch unit about the horizontal axis to follow the wind.	Loading uncertain, load cycles and maintenance regime uncertain / different from traditional application. Including events with failures (abnormal and accidental)		x		x		3		hydraulic friction brake, electric motors, rolling bearing
	6	5	1			Azimuth ring gear	Gear fixed to the azimuth unit.	DNVGL-ST-0361 / IEC 61400-1		x	x			2		For all components: See line 9.1.
	6	5	2			Azimuth reduction gearbox and interface pinion	Parts of the drive for the azimuth unit.	DNVGL-ST-0361 / IEC 61400-1		x	x			2		For all components: See line 9.1.
	6	5	3			Brake	Bake for the azimuth unit.	DNVGL-ST-0361 / IEC 61400-1		x	x			2		For all components: See line 9.1.
	6	5	4			Azimuth bearing	Freedom of rotation for the azimuth unit.	ISO 76 / ISO 281 / DNVGL-ST-0361 / IEC 61400-1		x	x			2		For all components: See line 9.1.
	6	6				Frame	Structural connection of azimuth unit and winch.	DNVGL-ST-0361 / DNVGL-ST-0126 / IEC 61400-1	x		x			1	Steel structures (maybe moving to casting) / Once loading is known than the design and construction is traditional	For all components: See line 9.1.
	6	7				Tower	Structural connection of foundation and azimut unit.	DNVGL-ST-0361 / DNVGL-ST-0126 / IEC 61400-1	x		x			1	Once loading is known than the design and construction is traditional	For all components: See line 9.1.
	6	8				Perch	Fixation of the kite at the ground.	DNVGL-ST-0361 / DNVGL-ST-0126 / IEC 61400-1 / Loading uncertainty including local forces such as docking forces		x		x		3	Steel with shock absorption system or composite, kite not carrying shock absorption gear, steel perch panel, large landing zone	For all components: See line 9.1.

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								yes	no	Known	L. hist.	New			
	6	9			Slip rings (for - cross wind operation & - deployment / retrieval & - communication signals)	Transmission of power and communication signals in rotating parts	no standard available		x			x	4	Sliprings are not carrying mechanical loads	Detailed design, location and implementation not clear to DNV GL.
	6	10			Tether, structural	Transfer Load from kite to ground	Loading uncertainty, construction / materials		x			x	4		For all components: See line 9.1.
7					**Commissioning procedure**										
	7	1			Commissioning of the whole energy kite	Safe commencement of the operation phase. All phases and systems, records and post-commissioning activities to be covered.	IEC 61400-1, chapter 13		x	x			2	Procedure and application of the standard needs to be adapted.	
8					**Prototype measurements**										
	8	1			Assessment of terrain at test site	ensure undisturbed inflow conditions or site calibration of inflow conditions	IEC 61400-12-1 (2017) e.g. Annex A, Annex B / Much higher hub height and much larger rotor area than traditional wind turbine		X	X			2		
	8	2			Ambient conditions air speed (at ground station 80m metmast and LIDAR)	measurement of inflow conditions (wind speed, wind direction, inflow angle, wind speed gradients, air density, …)	Parts of IEC 61400-12-1 (2017) - Power performance measurements / Different magnitude of measurement area / height than traditional wind turbine		X		X		3	Adaptation of the requirements in IEC 61400-12-1 will be needed to focus on the main areas of uncertainty and translate the different application to the kite	Does not meet IEC requirements. It will be use a second site to achieve the requirements using a LIDAR to identify the wind measurements all across the circle of the kite trajectory (LIDAR like other Remote sensing Devices (RSD) only for non-complex sites, see IEC 61400-12-1 section 7.2.4). LIDAR range maybe up 400m height. to Use average across the disk formed by the circle (200m to 300m diameter and center at around 180m). 80m met mast planned. Kite equipped with Pitot tubes.
	8	3			Control system commmands and wind turbine behaviour	Measure/validate the behaviour including emergency response	Safety and Function Test See IEC 61400-22 section 8.4.2 and Annex D		x	x			2	Safety and Function Test procedure needs to be adapted.	
	8	4			Load measurements	for validation of simulation tools and design conditions (for example deployment operating, extreme, accidental and retrieval conditions)	Parts of IEC 61400-13 (2015) - Measurements of mechanical loads / Different configuration from wind turbinie structure requiring different measurements to be taken from different locations Linking of site conditions and loading on kite		X			X	4	Adaptation of the requirements in IEC 61400-13 will be needed to focus on the main areas of uncertainty and translate the different application to the kite	MLCs adopted according to ID 1.3 of this sheet
	8	4	1		Airframe aerodyn loads										Wing Loads Envelope, Vibration envelpe, Wind-fuse Loads;
	8	4	2		Rotor thrust and torque										Crosswind performance: torque correlation
	8	4	3		Tether tension										
	8	4	4		Ground station										
	8	4	5		Accelerometers and position / orientation measurements										
	8	5			Power performance	provide power curve measured under consistent, accurate and reproducable conditions	Parts of IEC 61400-12-1 (2017) - Power performance measurements / Linking of site conditions and performance of kite and comparison with equivalent wind turbine		X			X	4	Adaptation of the requirements in IEC 61400-12-1 will be needed to focus on the main areas of uncertainty and translate the different application to the kite	
	8	6			Noise	provide noise emission values measured under consistent, accurate and reproducable conditions	Based on IEC 61400-11 (2012) - Acoustic noise measurement techniques / Linking of site conditions and noise characterisation of kite and comparison with equivalent wind turbine		X		X		3	Adaptation of the requirements in IEC 61400-11 will be needed to focus on the main areas of uncertainty and translate the different application to the kite	
	8	7			Long duration operation	Measure/test availability	IEC TS 61400-26-1		x	x			2	Measurement/Test procedure needs to be adapted.	

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						yes	no	Known	L. hist.	New			
	8	8	Probabilistic capability envelope concept	Allows for in-situ risk management based on objective data analysis Ability to accelerate development at bounded risk Translation of failure rate targets into capability envelope that are established via multiples of standard deviation of test data			X			X	4		
9			**Standards/Technical Specifications**										
	9	1	Safety Level (Reliability Level)	Calibration of partial safety factors in order to meet required safety level and reliability level.	background documents available but no direct IEC 61400 standard		x			x	4	background documents to be used for orientation due to limited experiences with turbine type in question	Evaluation if partial safety factors can be used from IEC standards or if re-calibration is necessary. Annual failure probability (reliability level) to be defined for the entire system. Load uncertainty to be considered. Assumptions by designer to be discussed and agreed. Based on limit state function (e.g. Monte Carlo simulation) the safety factors are to be derived.
	9	2	Hierarchy of Standards	Indicate the applicable standards and which one is ruling in case of conflict.	IEC 61400-22 plus break down of applicable standards ordered by hierarchy.		x	x			2	definition of applicable hierarchy	
10			**Instrumentation (other than flight control)**										
	10	1	Health Sensors	Important components and systems monitor/report their health status.	Individual standards for the respective components		x		x		3	Most of the components are used in other application.	
	10	2	Data acquisition	Aquire data and store in kite's computer system.	IEC 61400-25 series on communication		x	x			2	In most parts of the kite standard SCADA (Supervisory Control And Data Acquisition) system are used.	
	10	3	Sensors at ground station	Sensors for position, speed, environment, … (Including identify where the tether is pointing)	Individual standards for the respective sensors	x		x			1		

Bird and Bat Conservation Plan – Makani Energy Kite Project, South Kohala District, Island of Hawaiʻi, Hawaiʻi

BUSINESS CONFIDENTIAL INFORMATION

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1 Introduction

Makani, a project of X, an Alphabet Company, is proposing to test a utility-scale energy kite on privately owned property on Parker Ranch, Waimea, Island of Hawaiʻi. This research project is aimed at testing this new technology to validate its efficacy in generating renewable energy on a utility-sized scale.

As part of its due diligence, Makani has conducted biological surveys on the Parker Ranch site, and has identified several avian and mammalian species which may use resources on and around the proposed facility. In keeping with the voluntary Land-Based Wind Energy Guidelines published by the U.S. Fish and Wildlife Service in 2012 (WEG, or “the Guidelines”), Makani has prepared this Bird and Bat Conservation Plan (BBCP) to document its environmental due diligence and risk modelling efforts, to avoid and minimize impacts on local wildlife, and in the unlikely event that a listed species or migratory bird is downed, injured or killed by project activities, to ensure that the appropriate emergency response and reporting protocols are in place as part of Makani’s Standard Operating Procedures (SOPs).

2 Regulatory Background and BBCP Scope

The Endangered Species Act of 1973 (16 U.S.C. §§ 1531 et seq.; ESA), among other provisions, prohibits the unauthorized take[1] of certain listed species. The Migratory Bird Treaty Act (16 U.S.C. § 703 et seq.; MBTA), among other provisions, prohibits the take[2] of listed migratory birds. As part of its implementation of these and other statutes, and to advance its broader mission to “conserve, protect and enhance fish, wildlife, plants and their habitats,” the U.S. Fish and Wildlife Service (FWS) has prepared voluntary Guidelines for wind energy facilities aimed at addressing risks to species of concern (WEG, 1).

The Guidelines primarily contemplate long-term, commercial-scale wind energy facilities based on wind turbines of conventional design, as reflected in their five-tiered framework spanning multiple years of planning, construction, and operation (WEG, 5). However, because of the close alignment between the goals of the Makani project and the Guidelines’ stated goals of promoting compliance with law, conserving species of concern, and improving the state of the art in data gathering and risk mitigation, Makani intends to follow the recommendations set forth in the Guidelines to the extent applicable, and to work with FWS to tailor its approach to the circumstances of the Parker Ranch site in Hawaiʻi.

Because of the research and development nature of the Makani project, described in Section 4, not all recommendations of the Guidelines are applicable, as summarized in

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[1] “The term ‘take’ means to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct.” 16 U.S.C. § 1532.

[2] Here, “to pursue, hunt, shoot, wound, kill, trap, capture, or collect, or attempt to pursue, hunt, shoot, wound, kill, trap, capture, or collect.” 50 CFR 10.12

the table below. In the event of any significant expansion or extension of the testing program (including deployment of additional energy kites or operations beyond the anticipated testing period), Makani will revise this BBCS in coordination with FWS.

Tier 1 – Preliminary site evaluation (landscape-scale screening of possible project sites)	*Applicable in part*
Tier 2 – Site characterization (broad characterization of one or more potential project sites)	*Applicable in part*
Tier 3 – Field studies to document site wildlife and habitat and predict project impacts	*Applicable in part*
Tier 4 – Post-construction studies to estimate impacts	*Applicable in part*
Tier 5 – Other post-construction studies and research	*Not applicable*[3]
Best Management Practices (WEG, ch. 7)	*Applicable in part*
Mitigation (WEG, ch. 8)	*Applicable in part*
Advancing Use, Cooperation, and Effective Implementation (WEG, ch. 9)	*Applicable in part*
Formal consultation or permitting under Sections 7(a)(2) and 10(a)(1)(B) of the ESA	*Not applicable*[4]

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[3] Tier 5 consists of follow-up studies and improvements to risk mitigation that have proved necessary following data collection in Tier 4 studies, which are themselves expected to last at least one year (WEG, 34). Because the Makani project will only conduct operations for a limited one-year testing program, Tier 5 would not be applicable absent an expansion or extension of the testing program.

[4] Following a meeting with officials in the Pacific Region FWS office in Honolulu on April 20, 2015, Makani determined that, because of the very low risk of a take of a threatened or endangered species, the Section 10 “incidental take permit” process would not be appropriate for the testing program activities contemplated in this BBCP.

3 Technology Overview & Development History

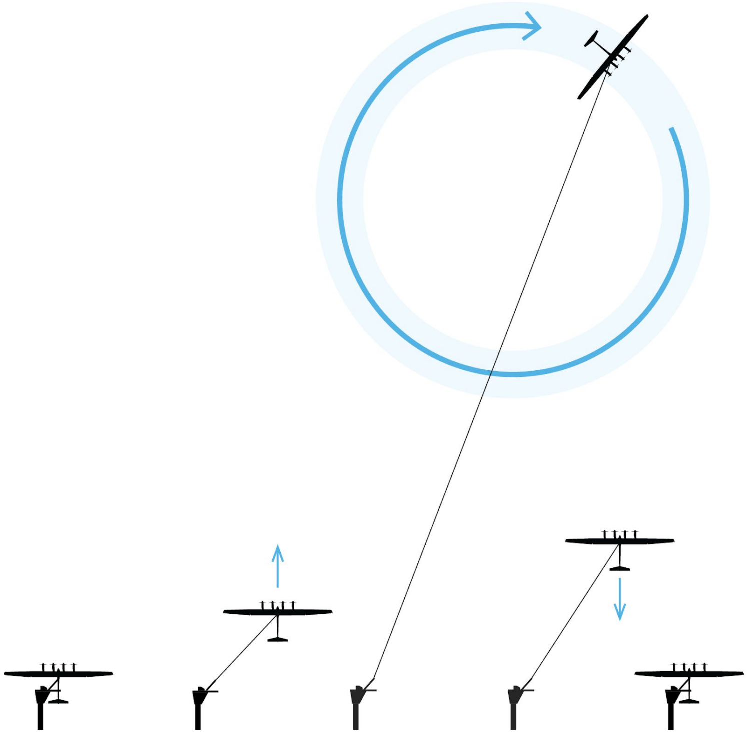
Makani is developing energy kites that use a wing tethered to a ground station to efficiently harness energy from the wind, generating electricity at utility-scale.

As the kite flies in loops, rotors on the wing spin as the wind moves through them. Our latest prototype, the “M600,” is designed to transfer up to 600 kilowatts of electrical power generated onboard down the tether to the grid—enough to power about 300 homes.

Makani has been researching and developing energy kites since 2006. Beginning with soft fabric kites that powered generators on the ground, Makani’s researchers found out early on that rigid kites could more efficiently harness energy from the wind. From 2012-2015, the team fabricated and tested “Wing 7,” which is a subscale prototype to the M600. Wing 7 validated the concept for controls, aerodynamics and power generation and operated for roughly 100 hours. In December 2016, Makani first generated electricity in crosswind flight with the M600 at a test site located on the China Lake Naval Air Weapons Station in California’s Mojave desert.

Layered photographs of the kite in flight around different points on the crosswind loop illustrate the flight path of Makani’s “Wing 7” 20kW prototype operating in California, 2013.

Makani's "M600" 600kW prototype operating in California, 2018.



The graphic to the left illustrates the kites modes of operation. First the ground station positions the kite downwind. Then the kite uses electricity from the grid to climb vertically to an altitude dictated by the flight controller. Next the kite transitions into power generating crosswind flight. As the kite flies in circles rotors on the wing spin as the wind moves through them, generating electricity onboard that is sent down the tether to the grid. To end a flight, the kite transitions out of looping crosswind flight and hovers back down to its perch while the ground station reels in the tether.

4 General Site and Project Description

Makani is planning to continue testing its 600 kW energy kite prototype on Parker Ranch pasture lands north and east of the intersection of Māmalahoa Highway (State Route 190) and the Saddle Road (State Route 200). Unlike more traditional wind turbines, the energy kite consists of an airfoil that is tethered to a base station with a conductive cable. The kite produces power by driving onboard generators with propellers that are spun by the wind as the kite flies in circles at the end of its tether.

The three basic parts of the energy kite are the ground station, the tether, and the kite. The ground station is ~5 meters tall, the tether is ~434 meters long, and the kite is ~24 meters long. The typical maximum operational height of the kite is ~325 meters. The project area is composed of pastureland on a relatively flat area in the plains South of Waimea, at an elevation of approximately 925 meters above mean sea level. As a part of the project we have also upgraded an approximately 3.2-kilometer long four-x-four road to access the site.

Vegetation on the site is best characterized as pasture land predominately vegetated with a mix of alien pasture grasses and weedy species typical of pasture lands in the general Waimea area on the Big Island.

The Makani test site on Parker Ranch Pasture land, 2017

5 Species Addressed in the Plan

This plan addresses the following four bird species and one bat species:

- Nēnē (*Branta sandvicensis*)
- Hawaiian Petrel (*Pterodroma sandwichensis*),
- Newell's Shearwater (*Puffinus newelli*).
- Band-rumped Storm-Petrel (*Oceanodroma castro*)
- Hawaiian hoary bat (*Lasiurus cinereus semotus*)

6 Species Background

6.1 Nēnē

Nēnē, or Hawaiian Goose, are the lone extant Hawaiian endemic goose remaining in the Islands. This endangered species is found on Hawaiʻi, Maui, Molokaʻi and Kauaʻi and has recently been reported on Lānaʻi and Oʻahu.

Nēnē, are an iconic species and are easily identified even by the most untrained of observers (Figure 1).

Figure 1 – Adult Nēnē

The Nēnē population on the Island of Hawaiʻi is doing well, and has recently been augmented by several hundred birds translocated by the State of Hawaiʻi, Department of Land and Natural resources, Division of Forestry and Wildlife (DOFAW) from a golf course on the Island of Kauaʻi to the Big Island. Although Nēnē were not recorded on the site during the biological surveys, this species is expanding on the Big Island and nests at several locations south and southwest of the project site. Nēnē are curious birds, and will investigate promising foraging or nesting sites. There is the potential that this species could show up on the site at some point during construction or operation of the testing program.

6.2 Seabirds - Hawaiian Petrel, Newell's Shearwater, Band-rumped Storm-Petrel

It is probable that the endangered Hawaiian Petrel, the threatened Newell's Shearwater (and the federally proposed Band-rumped Storm-Petrel over-fly the project area in small numbers between April and the middle of December each year. All three of these pelagic seabird species nest high in the mountains in burrows. There is no suitable nesting habitat for any of these three seabird species in the project site or for that matter in the larger Waimea plains area.

Unlike Nēnē the only real likelihood that construction personnel or facility operators are likely to see one of these three seabird species, is in the event that one is downed by natural causes or by interaction with the project device as these three species pass over the general project area during nighttime hours.

On the ground the species are distinctive, though can be difficult to identify to species level by an untrained observer. The following four images depict these species on the ground or in the hand.

Figure 2 – Newell's Shearwater, note it is a black over white bird with a long relatively narrow bill and black and blue feet.

Figure 3 – Hawaiian Petrel note the relatively larger size than the previous species, heavier, thicker bill and less clean demarcation between the black and white areas on the bird

Brenda Zaun, USFWS

Figure 4 – Hawaiian Petrel note the relatively larger and shorter bill size than the previous species. Also note the less defined demarcation between black and white parts of the bird

Figure 5 – Band-rumped Strom-Petrel, note the tiny size, totally dark coloration, small tubenosed bill.

6.3 Hawaiian Hoary Bat

It is probable that the endangered Hawaiian hoary bat overfly the general project area on a seasonal basis. As there are no suitable bat roosting trees within or even close to the site, any usage of the site by this endangered species is likely to be animals transiting the site while going elsewhere, or potentially foraging for insects over the project area on a seasonal basis.

The Hawaiian hoary bat is a subspecies of the continental hoary bay (*Lasiurus cinereus*) and as such is a typical lasiurine bat. They are a foliage roosting, over-dispersed species that is usually found roosting in leaves singly and widely separated from other members of the population. They are widely distributed on the Island of Hawaiʻi and are found on a seasonal basis in almost any area that still has tree cover.

Currently it is thought that this is the only bat species present in the Hawaiian Islands though two new scientific papers suggest that there are in fact two species—to the layperson differentiating between these two putative species is likely impossible.

The following two images depict Hawaiian hoary bats, the first is a bat photographed on the Big Island and the second is of a young bat on Kauaʻi that was being rehabilitated.

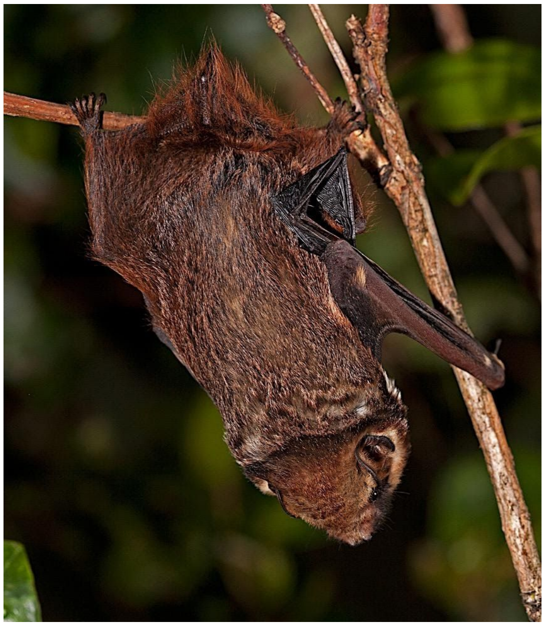


Figure 6 – Adult Hawaiian hoary bat

Figure 7 – Sub-adult Hawaiian hoary bat

7 Potential Risks to Protected Species

7.1 Nēnē

The principal potential risks that the construction and operation of the device poses to Nēnē should they appear on the site are associated with the clearing, grubbing and construction phases of the project as vegetation is removed, and later following build-out, the potential that Nēnē could be attracted to the site and potentially be hit by vehicles. With that said the risks are extremely low, as this species is not currently known to frequent the site.

Construction activity has the potential to destroy Nēnē nests or to disturb sitting birds sufficiently that they abandon their nests, eggs or potentially chicks. Nēnē, are curious birds that are attracted to activity and are naïve as to the risks that humans and other mammals potentially pose to them. Nēnē, in the greater project area are potentially acclimated to humans as the bulk of the birds use resources and nest on and adjacent to the several golf courses in south Kohala and north Kona districts. Nēnē that have become habituated to humans often begging for food, human food is not good for Nēnē; they should be feeding on grass and other vegetation.

7.2 Seabirds

The principal potential impacts that construction and operation of the device poses to protected seabirds fall into two categories, lighting and physical contact with the kite and/or the tether. As this is relatively new technology, which as yet has not been used in the Hawaiian Islands there is no existing data as to the rate of collision with a device such as this. Seabird passage rates recorded by ornithological radar conducted at the site recorded very low seabird passage rates.

Lighting Impacts

Exterior lighting during the seabird fledgling season poses an increased threat that birds will be downed after becoming disoriented by lights associated with the project during the nesting season. The two main areas that outdoor lighting could pose a threat to these nocturnally flying seabirds is if, 1) during construction it is deemed expedient, or necessary to conduct nighttime construction activities, 2) following build-out, the potential operation of security lighting during the seabird nesting season. It should be noted that seabird fledglings do fallout naturally on their first flight out to sea—a period when high natural levels of mortality occur.

Wing and Tether Impacts

Seabirds can also collide with anthropogenic structures including power lines, utility poles, standard wind generator rotor blades and/or associated infrastructure. The potential risk is heightened if exterior lighting is present. As mentioned above it cannot be ruled out that protected seabirds could potentially interact with the tether and/or kite if it is flown during crepuscular and nighttime hours.

7.3 Hawaiian Hoary Bat

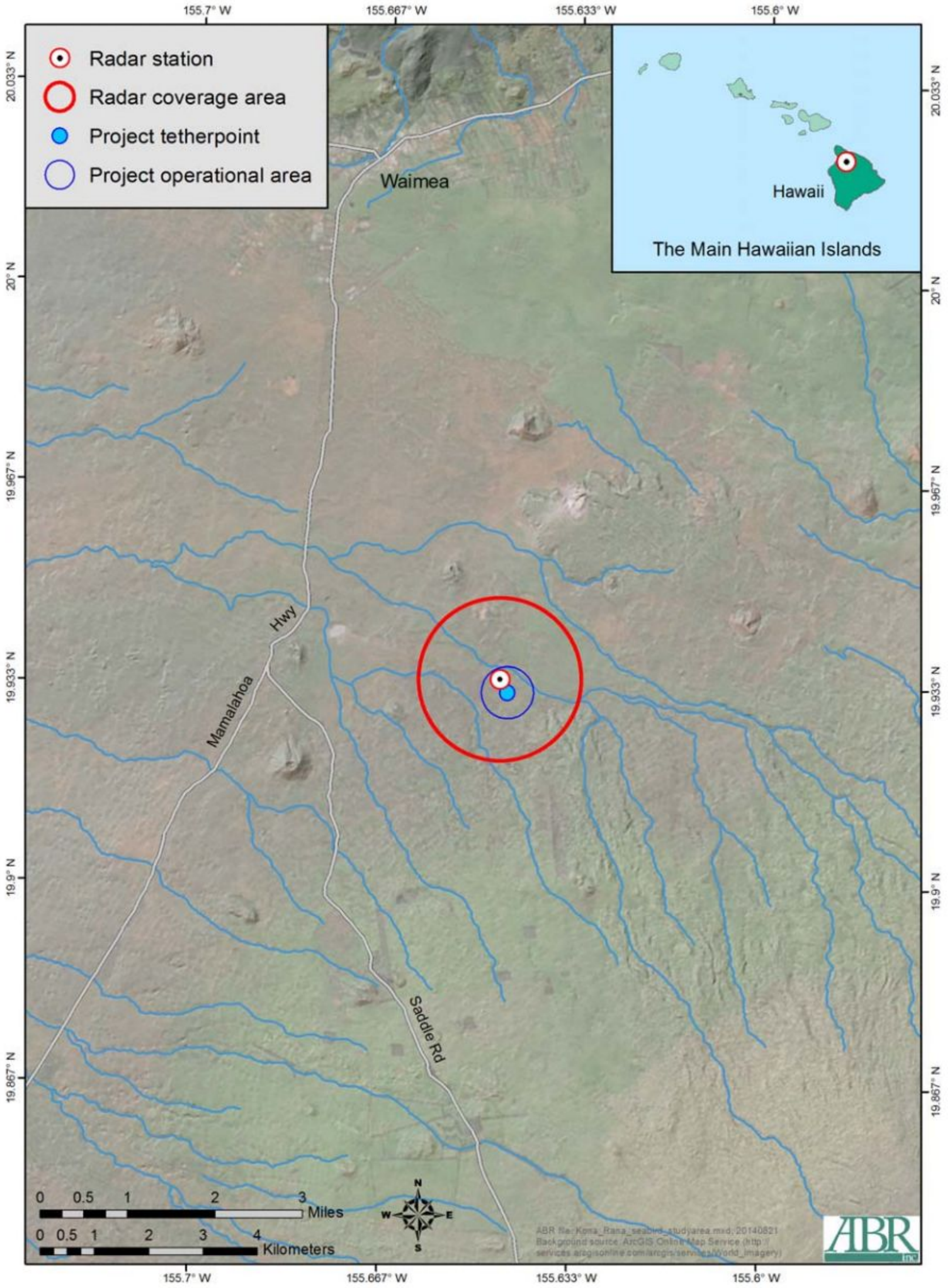
The principal potential impacts that construction and operation of the proposed energy kite poses to Hawaiian hoary bats is the potential that bats may be attracted to, or just fly into the kite and tether sweep area and collide with one or both. As with protected seabirds Hawaiian hoary bats have been killed by standard wind turbine generators, usually by being struck by the rotor blade, often when apparently chasing the blade.

As there are no suitable bar roost trees anywhere close to the project site potential impacts to roosting bats that construction activity poses to rooting bats in many other areas in the Hawaiian Islands will not occur.

8 Pre-Construction Data Collection and Monitoring

As part of the early development of the test project, Makani engaged third party experts to guide siting in an area of low avian activity. Detailed monitoring of passage rates for relevant species was then conducted by ABR. A summary of ABR's methodology follows.

> We used marine radar and binoculars and night-vision optics to collect radar and audiovisual (AV) data on the movements, passage rates, flight behaviors, and flight altitudes of seabirds for ten nights in summer 2014 (8 July–17 July). These sampling dates were selected to correspond with one of the main activity periods of the Hawaiian Petrel and Newell's Shearwater breeding season. Specifically, the summer sampling dates overlap with the incubation/early chick-rearing periods of both species (Ainley et al. 1995, Simons and Hodges 1998, Deringer 2009).
> The daily sampling effort consisted of a 3-hour (h) period beginning at sunset each evening (i.e., ~1900–2200 h) and the 2 h period beginning two hours prior to sunrise each morning (~0350–0550 h). Our daily sampling periods were selected to correspond with the evening and morning peaks of movement of petrels and shearwaters, as described near breeding colonies on Kauaʻi (Day and Cooper 1995, Deringer 2009).
> During sampling, we collected radar and AV data concurrently so the radar operator could provide locations and flight directions of incoming targets to help the AV observer locate targets (i.e., birds) for species identification. In return, the AV observer provided information to the radar operator on the identity and flight altitude of any targets observed. For the purpose of recording data, a calendar day began at 0701 h and ended at 0700 h the following morning; that way, an evening and the following morning were classified as occurring on the same sampling day



Map of study area and test site location.

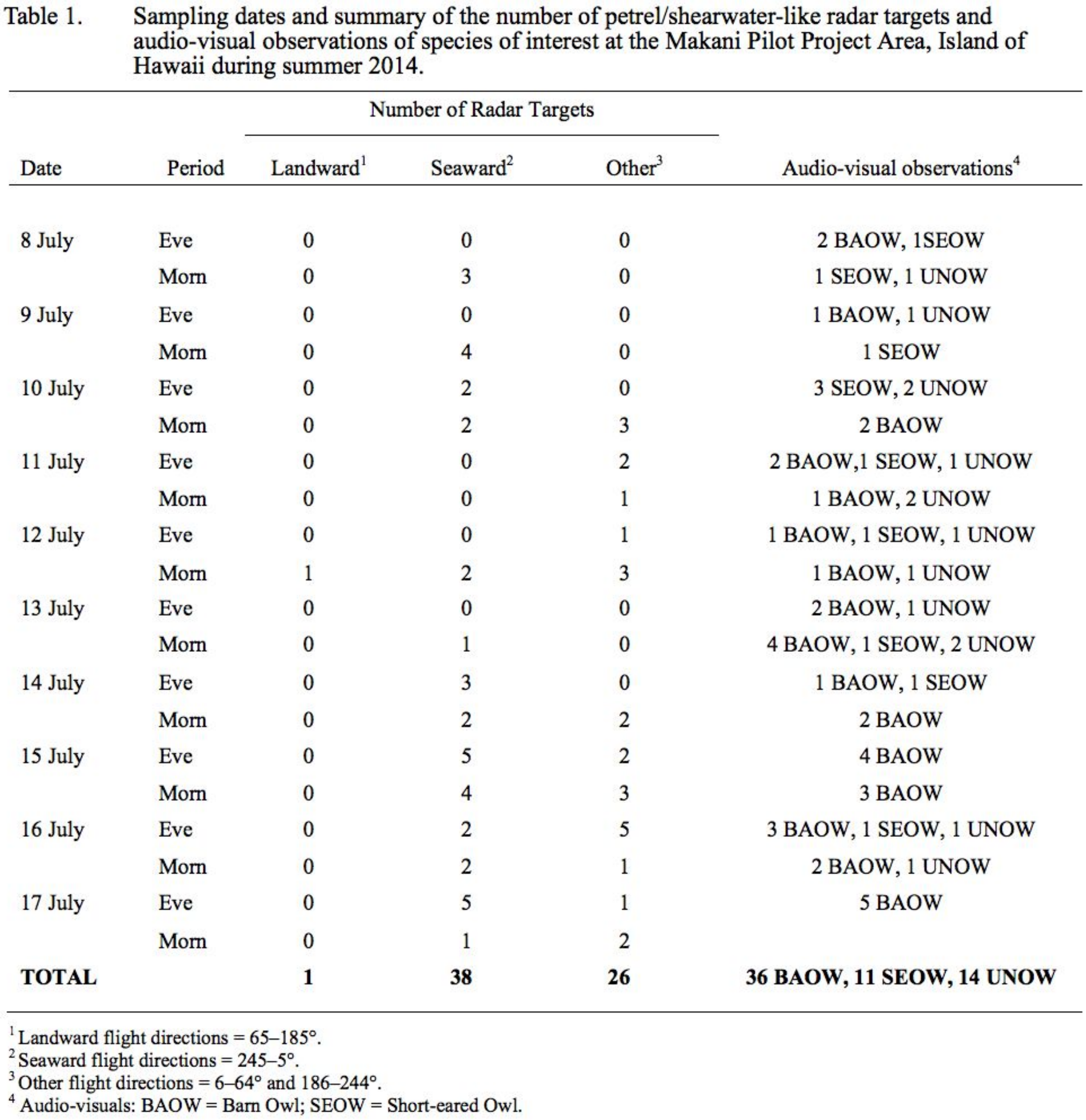


Table 1. Sampling dates and summary of the number of petrel/shearwater-like radar targets and audio-visual observations of species of interest at the Makani Pilot Project Area, Island of Hawaii during summer 2014.

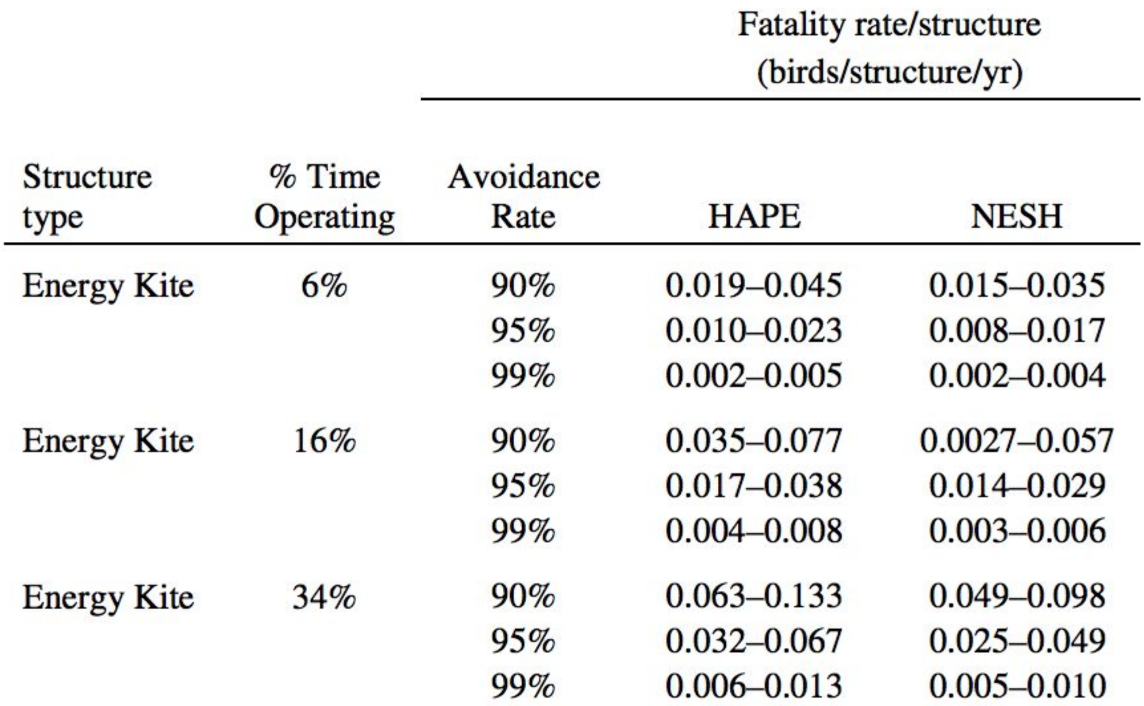
		Number of Radar Targets			
Date	Period	Landward[1]	Seaward[2]	Other[3]	Audio-visual observations[4]
8 July	Eve	0	0	0	2 BAOW, 1SEOW
	Morn	0	3	0	1 SEOW, 1 UNOW
9 July	Eve	0	0	0	1 BAOW, 1 UNOW
	Morn	0	4	0	1 SEOW
10 July	Eve	0	2	0	3 SEOW, 2 UNOW
	Morn	0	2	3	2 BAOW
11 July	Eve	0	0	2	2 BAOW,1 SEOW, 1 UNOW
	Morn	0	0	1	1 BAOW, 2 UNOW
12 July	Eve	0	0	1	1 BAOW, 1 SEOW, 1 UNOW
	Morn	1	2	3	1 BAOW, 1 UNOW
13 July	Eve	0	0	0	2 BAOW, 1 UNOW
	Morn	0	1	0	4 BAOW, 1 SEOW, 2 UNOW
14 July	Eve	0	3	0	1 BAOW, 1 SEOW
	Morn	0	2	2	2 BAOW
15 July	Eve	0	5	2	4 BAOW
	Morn	0	4	3	3 BAOW
16 July	Eve	0	2	5	3 BAOW, 1 SEOW, 1 UNOW
	Morn	0	2	1	2 BAOW, 1 UNOW
17 July	Eve	0	5	1	5 BAOW
	Morn	0	1	2	
TOTAL		**1**	**38**	**26**	**36 BAOW, 11 SEOW, 14 UNOW**

[1] Landward flight directions = 65–185°.
[2] Seaward flight directions = 245–5°.
[3] Other flight directions = 6–64° and 186–244°.
[4] Audio-visuals: BAOW = Barn Owl; SEOW = Short-eared Owl.

Above: Summary of study results.

ABR then conducted modeling to estimate the potential risk to the species of concern using their typical simulations for conventional wind turbines, adapted to reflect the operational profile and geometry of Makani's energy kite. Three scenarios were used to model the potential risk: low, medium, and high operational cases. The low case (6% operating time) corresponds to approximately 500 hours of testing over the course of the year. The high case (34%) corresponds to approximately 3000 hours of testing. The medium case (16%) is Makani's best estimate of operational time in the first year of testing. Because this is an early stage R&D project, it is difficult to project total operational time, but it is unlikely to be greater than what is reflected in the high case scenario. Each of these scenarios was also modeled with three avoidance rates: 90%, 95%, and 99%

In all scenarios, the risk to the relevant species from one year of operation of the single energy kite prototype is very low.



Structure type	% Time Operating	Avoidance Rate	Fatality rate/structure (birds/structure/yr) HAPE	Fatality rate/structure (birds/structure/yr) NESH
Energy Kite	6%	90%	0.019–0.045	0.015–0.035
		95%	0.010–0.023	0.008–0.017
		99%	0.002–0.005	0.002–0.004
Energy Kite	16%	90%	0.035–0.077	0.0027–0.057
		95%	0.017–0.038	0.014–0.029
		99%	0.004–0.008	0.003–0.006
Energy Kite	34%	90%	0.063–0.133	0.049–0.098
		95%	0.032–0.067	0.025–0.049
		99%	0.006–0.013	0.005–0.010

Above: ABR's summary of potential risk at various operating frequencies.

Simultaneously, ABR has installed and maintained an acoustic monitoring system to characterize bat activity at and near the test site. ABR will deliver a comprehensive report detailing a year of monitoring in 2016, and will be reflected in an updated version of this document. In the interim, a summary of bat activity through from December 2014 to May 2015 follows.

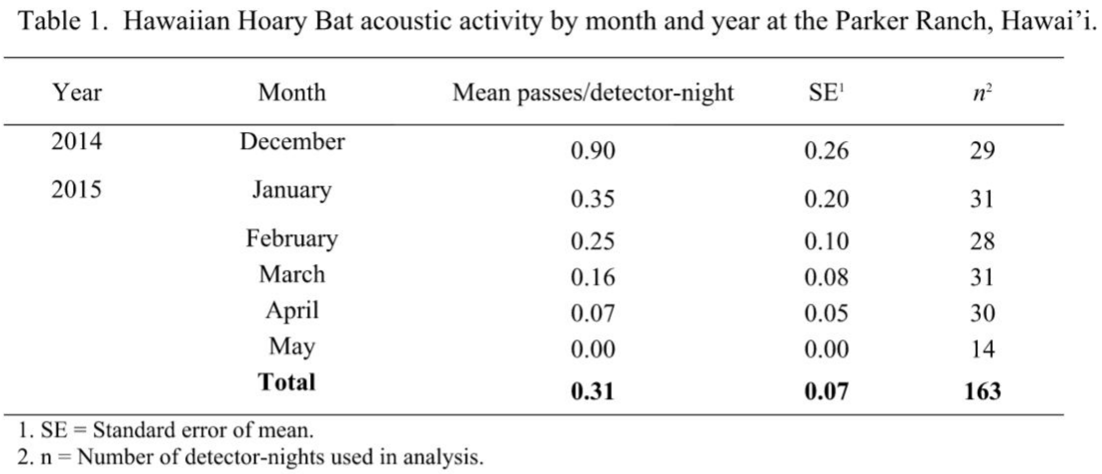


Table 1. Hawaiian Hoary Bat acoustic activity by month and year at the Parker Ranch, Hawai'i.

Year	Month	Mean passes/detector-night	SE[1]	n^2
2014	December	0.90	0.26	29
2015	January	0.35	0.20	31
	February	0.25	0.10	28
	March	0.16	0.08	31
	April	0.07	0.05	30
	May	0.00	0.00	14
	Total	**0.31**	**0.07**	**163**

1. SE = Standard error of mean.
2. n = Number of detector-nights used in analysis.

Above: Summary of bat activity.

9 Specific BMPs and Minimization Measures

9.1 Construction

During the construction phase of the project the only protected species that construction personnel potentially could encounter are Nēnē. The following minimization measures will be implemented to ensure that construction activities do not result in deleterious impacts to Nēnē.

- Makani’s primary construction contractor will be responsible for endangered species conditions compliance and response in the event of an incident with an endangered species.
- No pets will be allowed on property. Mammalian predators pose a threat to Nēnē and also may scavenge downed, injured or dead animals that potentially could occur on the site.
- Closed trash receptacles food and beverage container disposal will be provided. All food and beverage supplies consumed on site will be disposed of in the closed containers. Food and beverage trash can attract mammalian predators and may attract Nēnē.
- No feeding of birds, especially Nēnē will be permitted on the site.
- In the event that a downed, injured or dead protected bird or bat species is encountered the endangered species lead will immediately follow the Downed, Injured or Dead Protected Species Emergency Response Protocols outlined in the next section of the document.

9.2 Post-construction Device Operation

Following build-out facility operators will follow the following minimization guidelines to ensure that facility operation activities do not result in deleterious impacts to Nēnē, Newell’s Shearwater, Hawaiian Petrel or Hawaiian hoary bats.

- Facility operators will undergo endangered species awareness training prior to starting work on the project.
- One person will be identified as being the lead for endangered species conditions compliance and emergency response in the event of an incident involving an endangered species.
- The project will maintain a service agreement in place for the duration of the project with the Hawaiʻi Wildlife Center to provide care, rehabilitation and other services for any downed or injured protected bird or bats that may be recovered on the site.
- No household pets will be allowed on property. Mammalian predators pose a threat to Nēnē and also may scavenge downed, injured or dead protected animals that potentially could occur on the site. Note: Parker Ranch routinely

uses trained dogs to herd cattle on the project site, but additional dogs or other pets will not be permitted.
- Closed trash receptacles for all staff food and beverage container disposal will be provided. Food and beverage trash can attract mammalian predators and may attract Nēnē.
- No feeding of birds, especially Nēnē will be permitted.
- On a regular basis the site will be inspected for any downed, injured or dead seabirds or bats.
- Monitoring activities will be recorded and the data archived following the protocols outlined in the Monitoring and Data Management section of this document.
- In the event that a downed, injured or dead protected bird or bat species is encountered the endangered species lead will immediately follow the Downed, Injured or Dead Protected Species Emergency Response Protocols outlined in the next section of the document.

10 Monitoring and Inspection During Operation

Makani's testing program in Parker Ranch is an early stage R&D effort to test and improve our technology, and thus we have an opportunity to undertake approaches to monitoring that are uncommon for traditional wind projects. Makani will implement a monitoring plan that ensures consistent inspection and allows for operational flexibility, while taking advantage of increased human and technical surveillance during operation. The plan consists of the following components:

1. Monitoring for bird and bat impacts will take place continuously throughout the test program.
    a. The kite, tether, and ground station will be under live visual observation by Makani’s testing team at all times during tests. The testing team will watch for potential avian interactions with the kite and will follow the protocols outlined below in the case of an incident.
    b. Audio-visual recording will take place during all test operations from multiple camera angles. Testing and engineering teams regularly reviewing video will watch for potential avian interactions.
    c. The kite, tether, and ground station will be regularly inspected while shut down outside of testing operations for damage. The testing team will watch for evidence of any impact to relevant species. Any indication of an incident based on inspection will trigger a comprehensive review of footage and data to identify a potential impact.
2. Third party monitoring may also be used to complement Makani’s on site program.
    a. Makani may hire expert biologists to continue acoustic monitoring of bats throughout the test program, with regular analysis to understand if and how bat activity is impacted by energy kite testing

   b. Makani may hire expert biologists to conduct radar studies of the kind described above during the testing program to better understand if and how energy kite testing impacts avian behavior
   c. Makani may partner with an organization that provides professionally trained dogs to search the project area for relevant species. The animals would be used regularly to detect potential incidents. Any identification of an injured or killed bird will trigger a comprehensive review of footage and data to identify a potential impact.
3. If an incident is confirmed through any of these means, operation of the kite will immediately be curtailed in order to allow for further investigation and reporting protocols outlined below will be followed.

11 Downed or Injured Protected Species Emergency Response Protocols

A Threatened and Endangered Species Recovery Kit consisting of the following supplies will be maintained on site at all times and will be replenished as needed.

1. Medium pet carrier
2. 6 clean towels
3. 6 pairs nitrile gloves
4. 6 T&E Incident forms
5. 2 Pens

In the event that a downed, or injured protected species is encountered on the site, contact the Makani wildlife conservation leads who will implement the following protocols immediately.

1. The animal or carcass will be photographed from several angles to ensure correct identification to species. Seabirds in particular can be difficult to identify to species by a layperson.
2. Deploy the T&E Species Recovery Kit.
3. Slowly approach the injured or downed animal and gently wrap it in a clean towel, place it into the pet carrier and put the pet carrier in a shaded location before transporting it to the operations and maintenance tent on site.
4. Immediately call Hawaiʻi Wildlife Center for instructions on pick up
5. Record the position of the incident, and fill in an incident log sheet with all of the data required on that form.
6. Transfer the animal to Hawaiʻi Wildlife Center technician, per their instructions.
7. Turn in the completed incident reporting form to test site manager for data entry and archiving.
8. Any equipment or supplies used to recover an animal will be cleaned or replaced following an incident.

12 Monitoring and Data Management

Monitoring of the site for downed, injured or dead birds and bats is essential to determine whether the operation of the device results in impacts to protected bird and bat species. In the event that it does result in impacts these data will assist in formulating a solution to future such incidents.

The site will be inspected for any downed, injured, dead seabirds or bats every morning following operation of the device the night before. A monitoring checklist will be filled out for each monitoring event and turned in to the flight testing program manager for data entry and archiving.

Data gathered during monitoring events and any protected species incidents will be entered into a database and maintained by the company. These data will be used for any agency reporting that is deemed necessary and will also be used to develop additional minimization measures should the need arise in the future.

13 Reporting Loop

In the event that a protected species incident occurs on the project site the Project will report those incidents to the US Fish & Wildlife Service (USFWS) and the State of Hawaiʻi Division of Forestry and Wildlife (DOFAW) promptly. Any instructions that are received from either or both agencies will be complied with.

Current contact information for the two agencies is as follows:

USFWS	Diane Sether Alternative Energy Coordinator Hawaiʻi and Maui Nui Geographic Team
Phone #	(808) 792-9458
Email	diane_sether@fws.gov

DOFAW	Glenn Metzler
Phone #	(808) 587-4149
Email	glenn.m.metzler@hawaii.gov