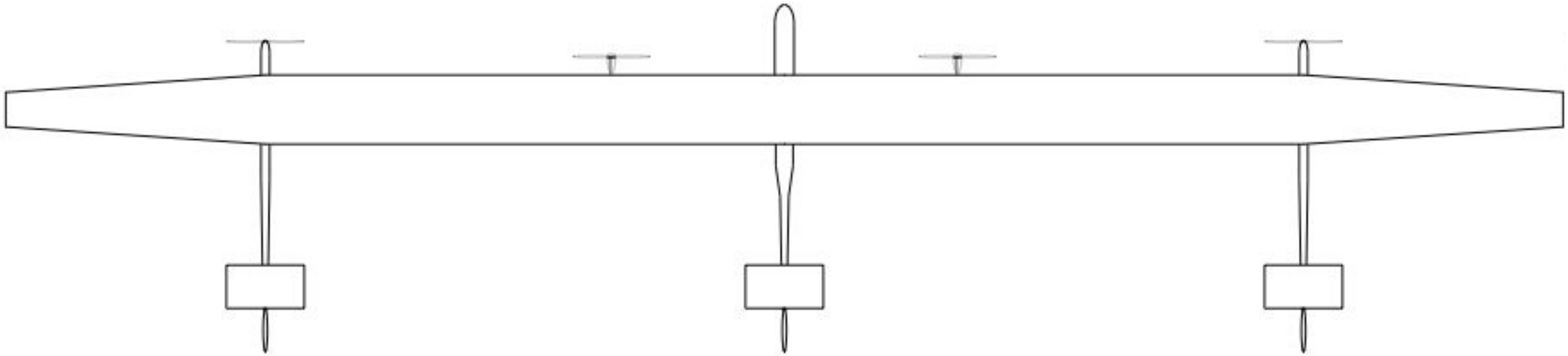
16.82 Critical Design Review

Presenting *"Dawn"*



Brent A. Avery, Nicholas Bain, Diego Barea, Kevin Carlson, Annick Dewald, KJ Hardrict, Timmy Hussain, Bjarni Örn Kristinsson, Dongjoon Lee, Jacqueline Liao, Trevor Long, Mohammed Nasir, Codrin Oneci, Alexander Peraire-Bueno, Peter Sharpe, Michelle Xu, José Zavala

Mission Objective

Carry instrumentation for free radicals research in the lower stratosphere in order to understand the ozone layer thinning.

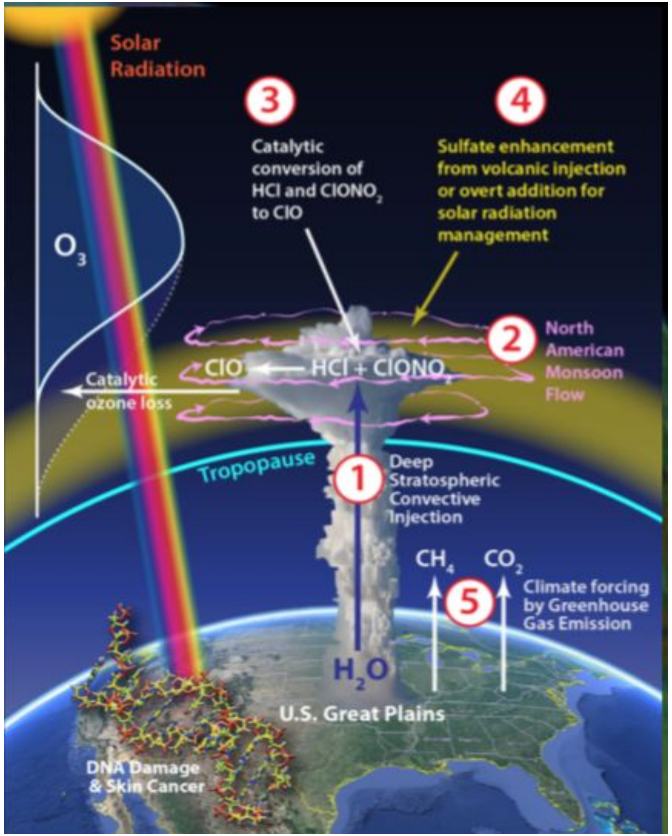
Scientific Objective:

Investigate free radical kinetics in stratospheric storms.

Mission Objective:

Carry a scientific payload in stratospheric storms for 6 weeks of summer over CONUS. This will be done using a solar aircraft.

Done in collaboration with Harvard/MIT center for Environmental Monitoring

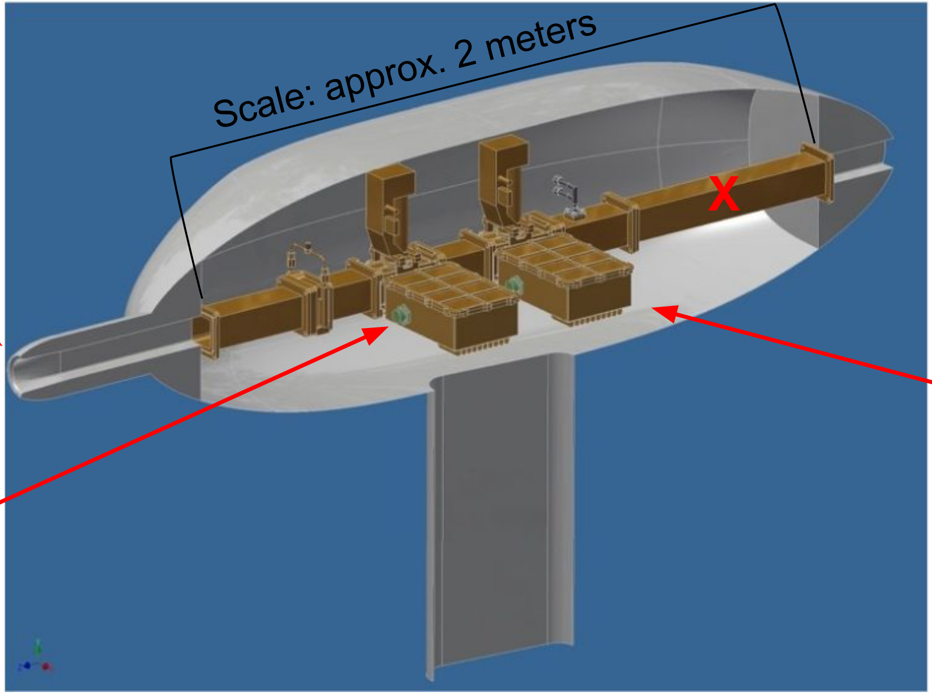


Source: Jim Anderson

Payload

Undisturbed air required for free radical measurement

First optical system engages atomic resonance scattering to detect Cl atoms following chemical conversion of ClO· to Cl



Source: Jim Anderson

Weight = 30 kg

Second optical axis engages atomic resonance scattering to detect Br atoms following chemical conversion of BrO^- to Br

Requirements

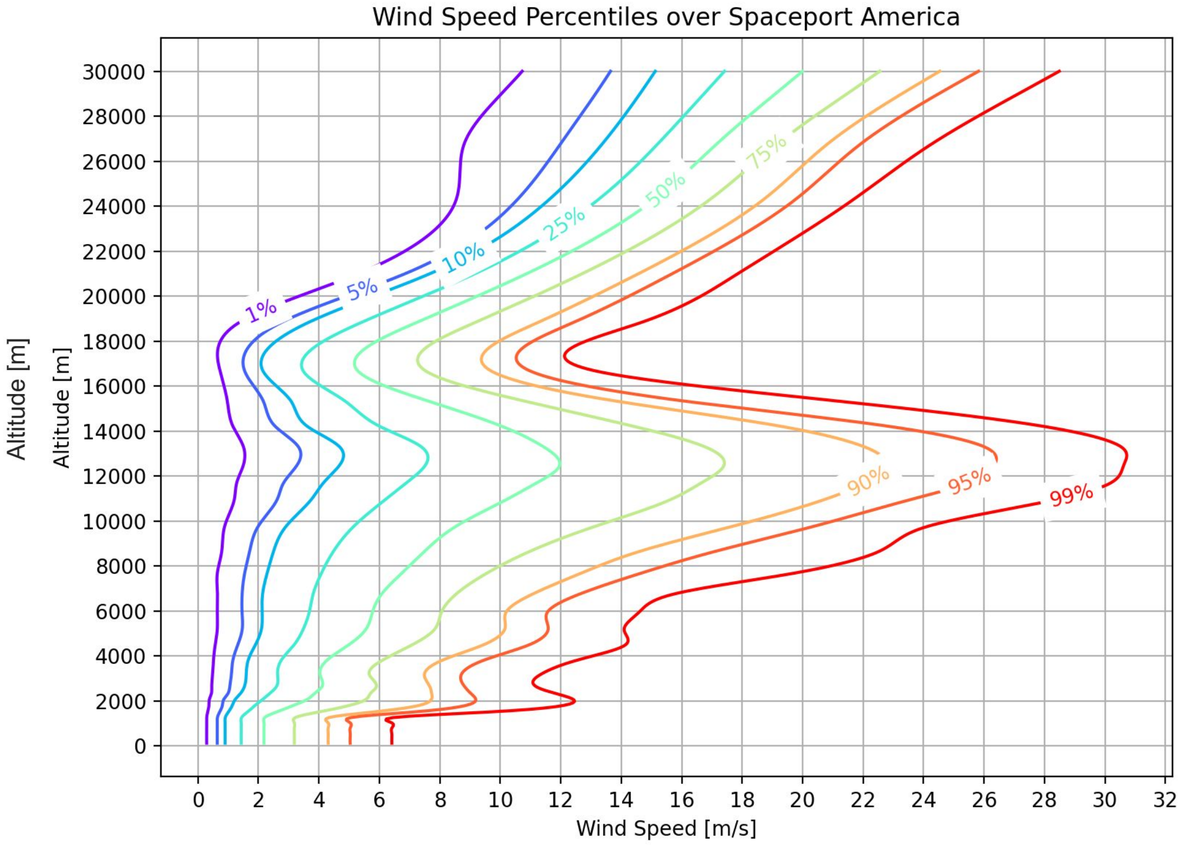
Specification	Customer Requirement
Payload Weight	66 lbs (30 kg) minimum, 110 lbs (50 kg) desired
Payload Power	500 W day, 150 W night
Payload Volume	~1 cubic meter
Speed	Capable of station keeping and storm tracking
Endurance	6 weeks, July - Aug, CONUS
Altitude	65,000 ft (19812 m) minimum altitude (higher altitudes desirable)
Control	Autonomous with mission targets designated from the ground
Communications	Payload data downlink, C2, ATC

Source: Jim Anderson

Specification	Inferred Requirement
Stationkeeping	Ability to stationkeep for 24 hours at 99th percentile winds (~20 m/s) within CONUS
Latitude	Capable of performing mission between 26N and 49N latitude (CONUS)
Vertical Gusts	Vehicle can withstand up to 2 m/s vertical gusts
Day of Year	Capable of performing mission until Aug. 31 (lowest solar insolation) at 65,000 ft
Transportation	Vehicle can be disassembled and transported across the CONUS

Models: Atmosphere and Wind

- Atmosphere
  - 1976 COESA model
  - Sutherland viscosity
- Wind speed modeling
  - 50 years of data from ECMWF ERA5 database
  - CONUS and Spaceport America
- Takeaways:
  - 99% wind speeds at cruise altitude in July-Aug. are ~20 m/s
  - Stronger winds in troposphere (esp. during day)



Operational Categories

Track Storm

- Loiter over a storm
- UAV moves with storm

Stationkeep

- Be able to maintain average constant position over ground

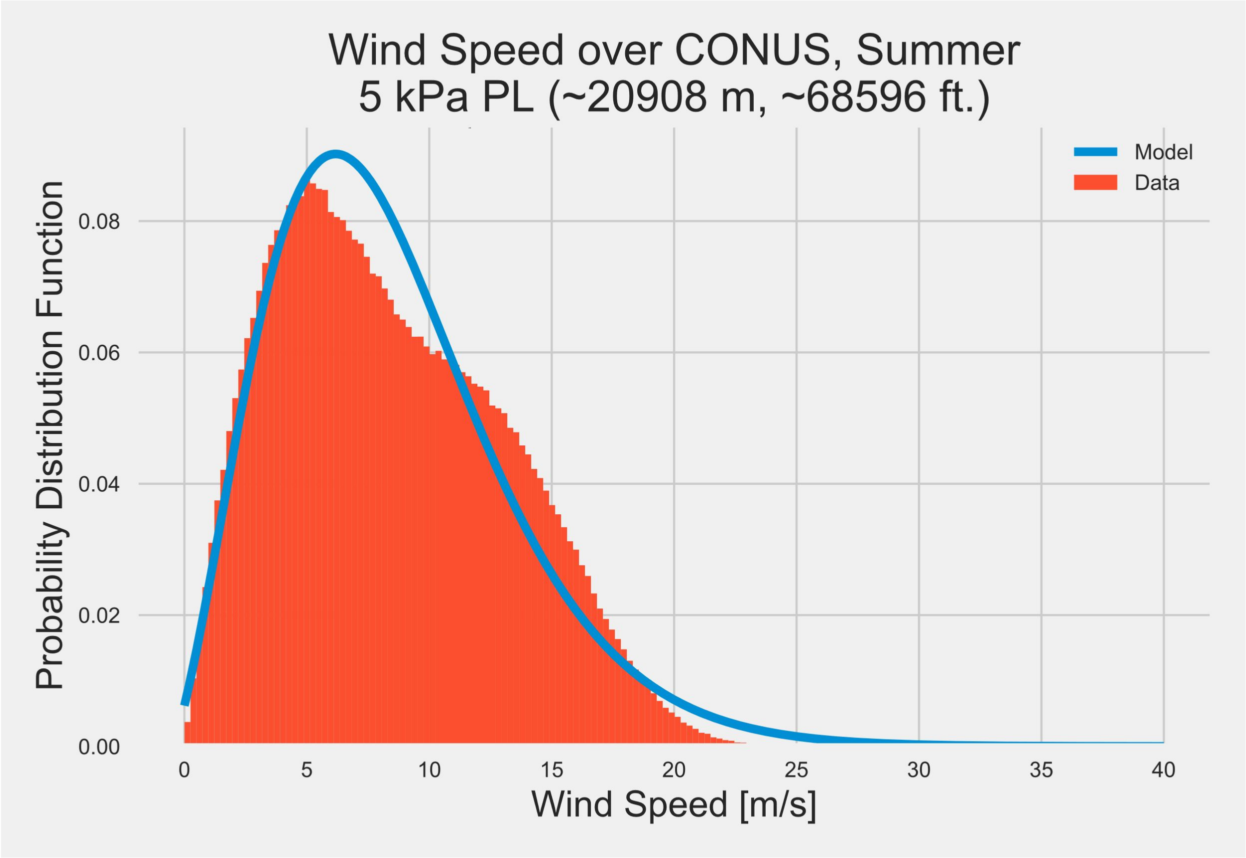
Ascent & Descent

- Ascend through to get to the altitude of interest and recover vehicle at end of study.
- Withstand vertical gusts

Transiting

- Move to a different storm at an expected speed of 2,000 km/day on a nominal wind day

Models: Atmosphere and Wind



Design Overview & Performance

Configuration & Structure

Aero Performance

Power

Propulsion

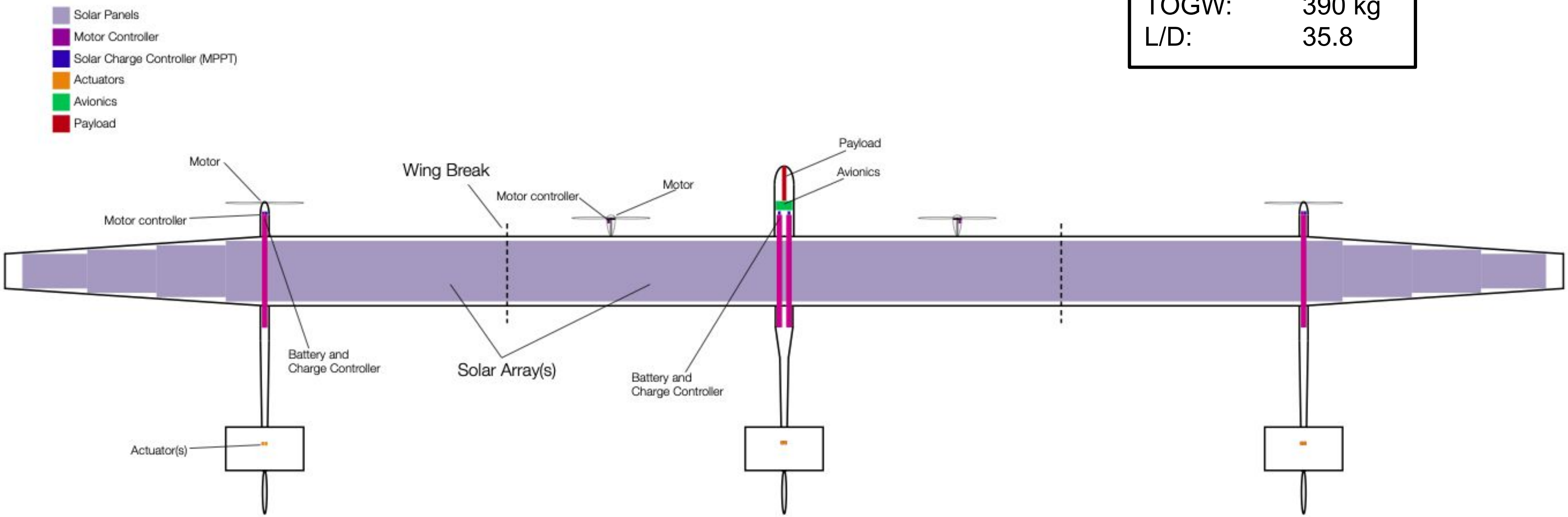
Avionics

Flight Operations

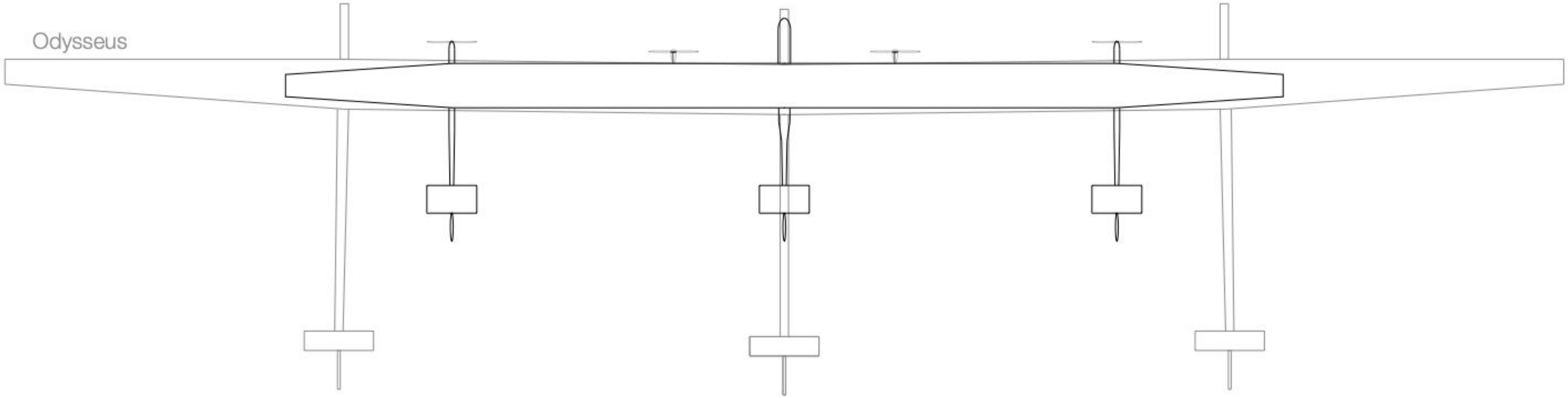
Future Development Plan

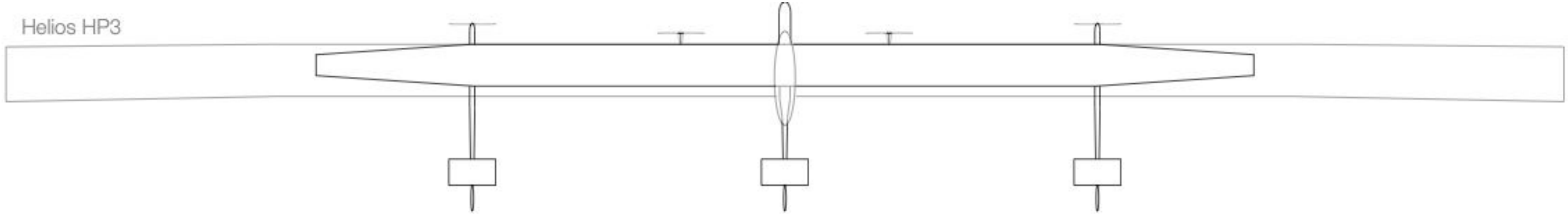
Design Overview

Span:	44.3 m
TOGW:	390 kg
L/D:	35.8



Comparison to Similar Airplanes





MIT ICAT

Design: Key Specifications

Figure of Merit	Value at Optimum
TOGW	390.3 kg
Wingspan	44.3 m
Wing aspect ratio	26.2
Wing area	74.9 m^2
Wing loading	All-up: 51.1 Pa (1.07 psf) Airframe only: 12.0 Pa (0.25 psf)
Mean airspeed	Day: 33.0 m/s Night: 31.9 m/s
Altitude	Nominal** range: 65.0 - 68.6 kft (19.8 - 20.9 km) Peak on solstice: 80.5 kft (24.5 km)

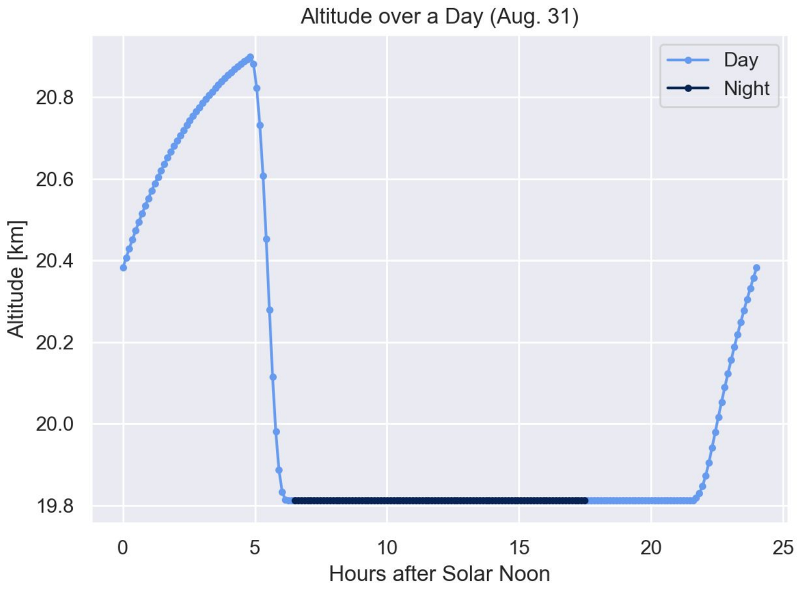
Figure of Merit	Value at Optimum
Total power output	Mean: 4.9 kW Peak: 5.4 kW
Battery capacity	68.3 kWh (@ 450 Wh/kg)
Wing Reynolds number*	Mean: 336,000 Min: 312,000
Wing lift coefficient	Nominal** range: 1.07 - 1.13
L/D Ratio	Nominal**: 35.8
Wing solar area fraction	80% (tight constraint)
Propeller arrangement	4x 2.16m dia., 2-blade propellers

* referenced to geometric chord

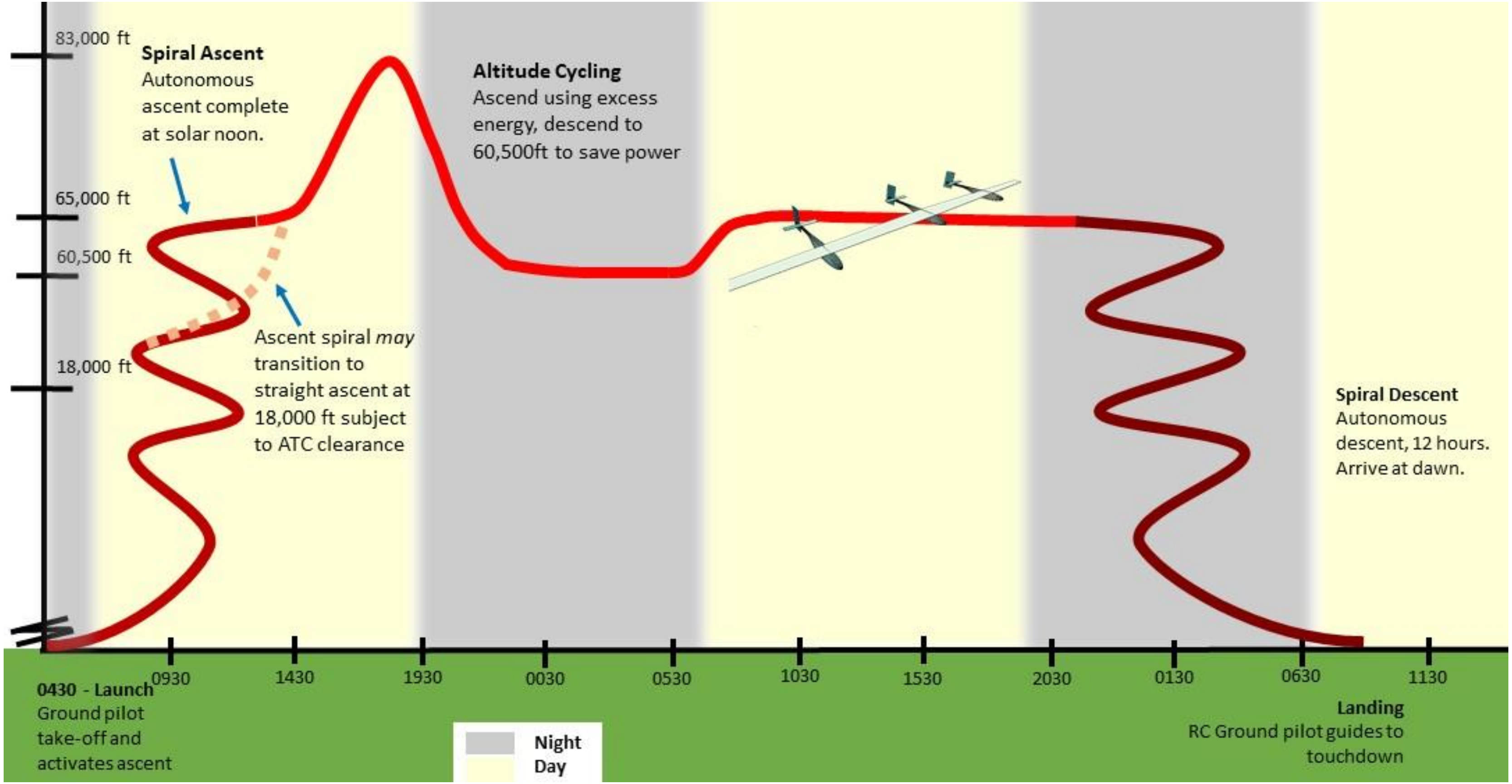
** all nominal values and statistical measures taken over a 24-hour cycle on worst day (design day)

Altitude Cycling

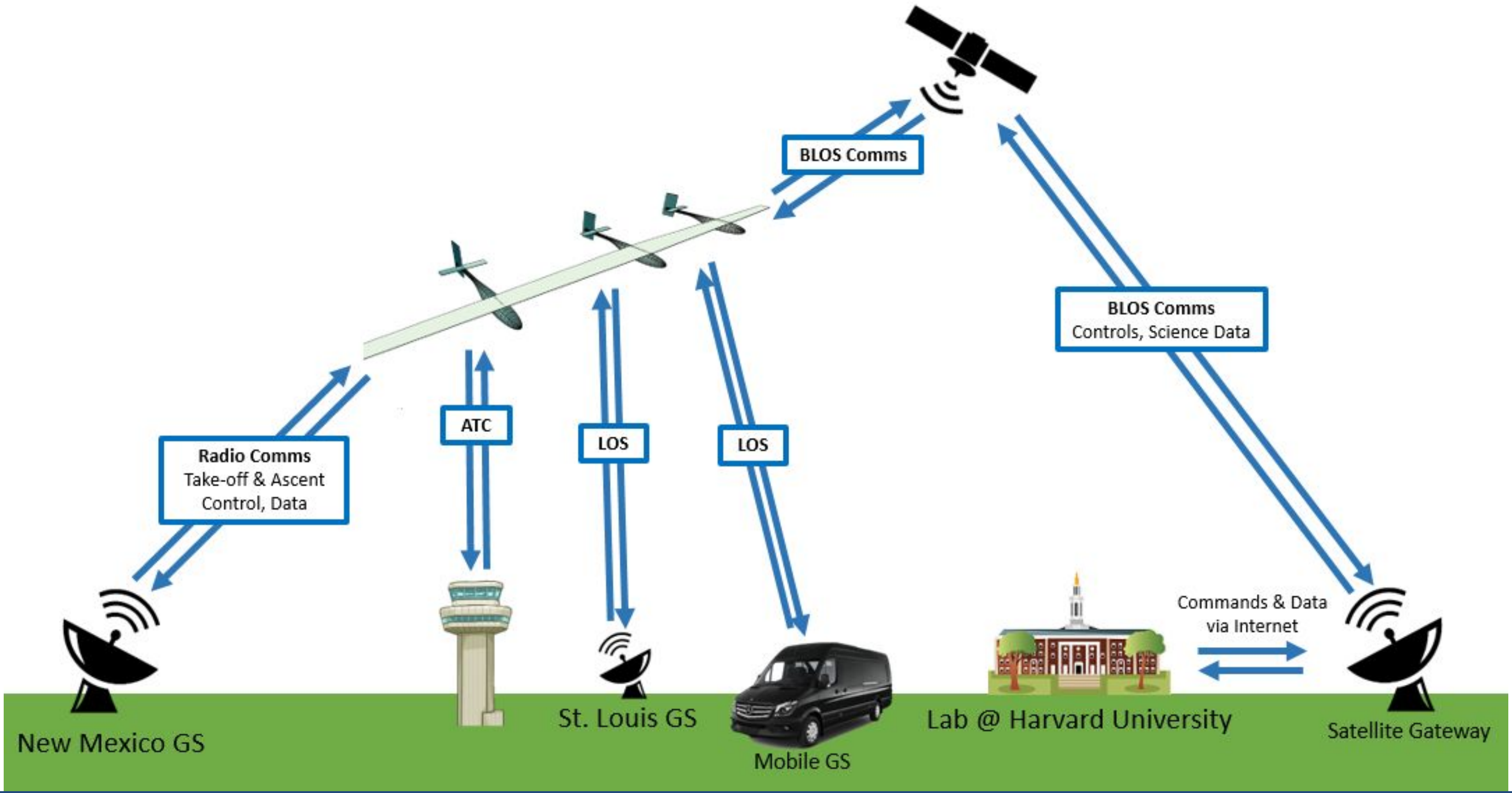
- In addition to battery power, we can use aircraft's gravitational potential energy as a form of energy storage.
- Ascend during day with excess energy from solar panels.
- Descend into the night with a low-power glide for several hours before consuming battery power.



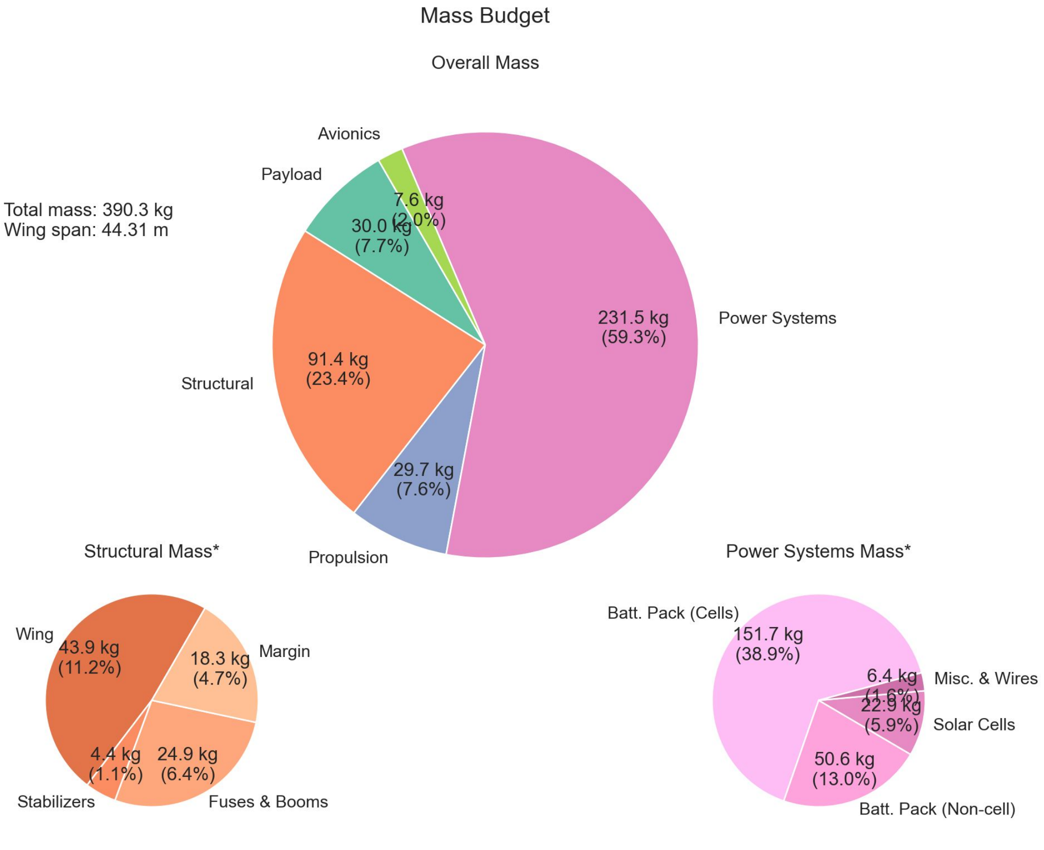
High-Level CONOPS



Mission OV-1


BLOS Comms
BLOS Comms
Controls, Science Data
Radio Comms
Take-off & Ascent
Control, Data
ATC
LOS
LOS
Commands & Data
via Internet
New Mexico GS
St. Louis GS
Mobile GS
Lab @ Harvard University
Satellite Gateway

Design: Mass Budget & Margins



* percentages referenced to total aircraft mass

- Margin:
  - 25% structural mass margin
  - 5% power margin to energy closure on worst day
- Margin reflects:
  - Model uncertainty
  - Manufacturing uncertainty

Problem Formulation

- Aircraft design is fundamentally an optimization problem: → $Objectives$, $Variables$, and $Constraints$

Typical Aircraft

Minimize: $Cost$
With respect to: $CONOPS, trajectory, vehicle\ geometry, other\ design\ variables$
Subject to: $Mission\ feasibility\ (risk \leq risk_{acceptable}), physics$

Solar Aircraft

Minimize: $TOGW$
With respect to: $Trajectory, vehicle\ geometry, power\ systems, CONOPS, etc.$
Subject to: $Mission\ feasibility\ on\ worst\ day, physics$

- Coupled Design and Trajectory Optimization Problem:
  - Highly multidisciplinary:
    - Aerodynamics
    - Structures
    - Propulsion
    - Stability & Control
    - **Trajectory/Dynamics (2D)**
    - Weights
    - Power Systems

  At hundreds of collocation points over a 24-hour modeling window

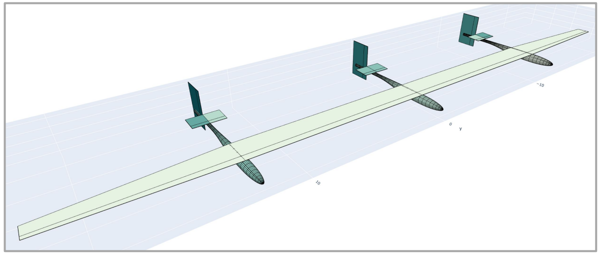
  - Problem size (tens of thousands of nonlinear, nonconvex variables and constraints)
  - The circle-closing problem!

Automatic-differentiable framework!

Optimization Overview

Simultaneously optimizing...

Aircraft Design



Variables
Hundreds, including:
- *wing geom. (two-sect.),*
- *tail geom. (one-sect.),*
- *boom length,*
- *propeller diam.,*
- *battery cap.,*
- *solar panel area,*
- *motor rated power,*
- *wing internal struct.*

Parameters
- *payload mass*
- *# of booms*
- *battery spec. energy*
- *margins*

Mission Profile

Variables
Thousands, including:
- *altitude*
- *airspeed*
- *throttle, ctrl. surf. inputs*

Parameters
- *min. altitude*
- *wind speed dist.*
- *latitude*
- *day of year*

Objective Function
Minimize wingspan (not TOGW!)

Constraints
Physics models
- *150 models, 4,000 constraints*

Optimization Methods

- 2,500 variables, 4,000 constraints
  - Nonlinear, nonconvex
- Automatic differentiation makes this problem tractable
  - Cost of derivative computations is independent of problem size
  - All models written in differentiable framework
- Problem + derivatives passed to IPOPT (open-source interior-point solver)
  - Solves in seconds instead of hours

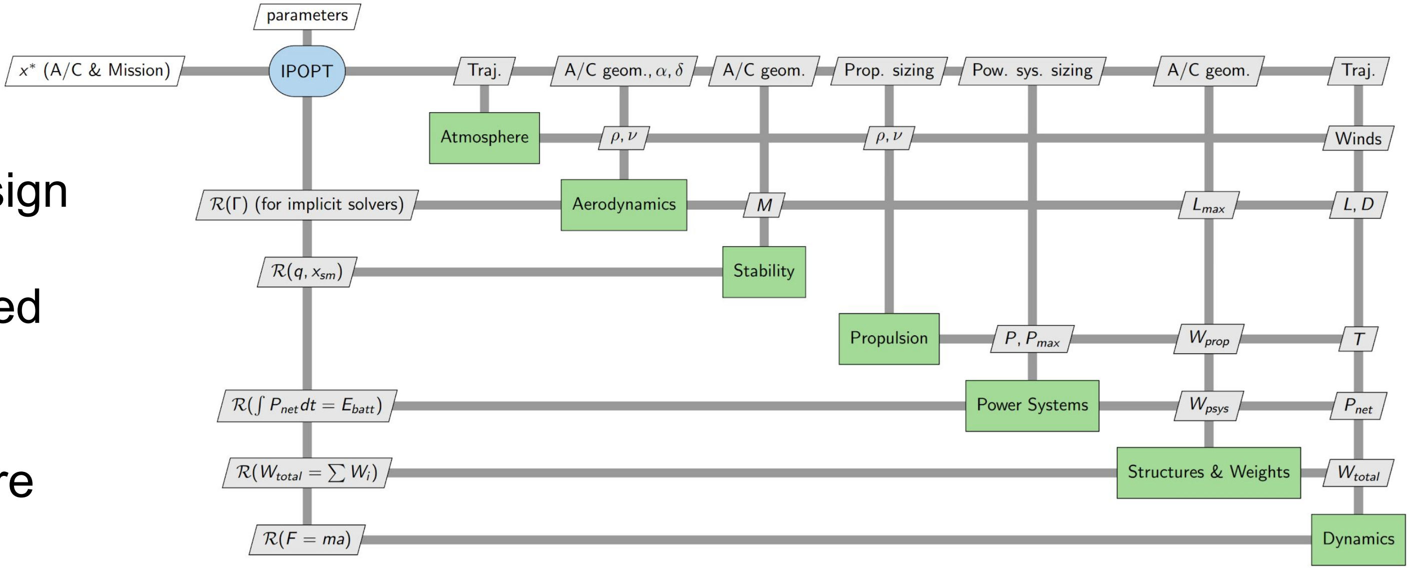
Disciplines

- Atmosphere
- Aerodynamics
- Stability
- Propulsion
- Power Systems
- Weights & Structures
- Dynamics

Optimization Disciplines

Key Takeaways:

- Considering all major aircraft design disciplines
    - Physics-based
    - Empirical
- No internal closure loops
- Models to be discussed throughout



<u>XDSM</u> <u>of MDO Architecture</u>**<u>:</u>**

- *Optimizer* and *Disciplines*
- Data flows **clockwise**, just like a matrix: $Ax = b$
- Same sparsity as Jacobian of constraints (residuals)

Wingspan as an Objective

- Typical surrogate for **<u>risk</u>**: TOGW
- Historically: most common failure modes have been aerostructural
  - Wingspan is a better surrogate for aerostructural risk than TOGW
- Explicitly drives towards lower-AR, less-flexible configurations
  - Higher wing loading
  - Faster speed

NASA Helios (2003). In-flight structural failure during ascent due to wind shear, deformation, and subsequent flutter

Google/Titan Solara 50 (2016). NTSB: “Significant thermal air mass activity” leading to “wing deformation” and subsequent crash

Facebook Aquila (2016). NTSB: “inflight structural failure on final approach”

Airbus Zephyr (2019). Loss of control due to turbulence.

Optimization Key Assumptions

- Designing to close specified mission with margins on worst day
  - Aug 31. solar conditions
  - 99% wind conditions (constraint not tight)
  - Airplane must ascend

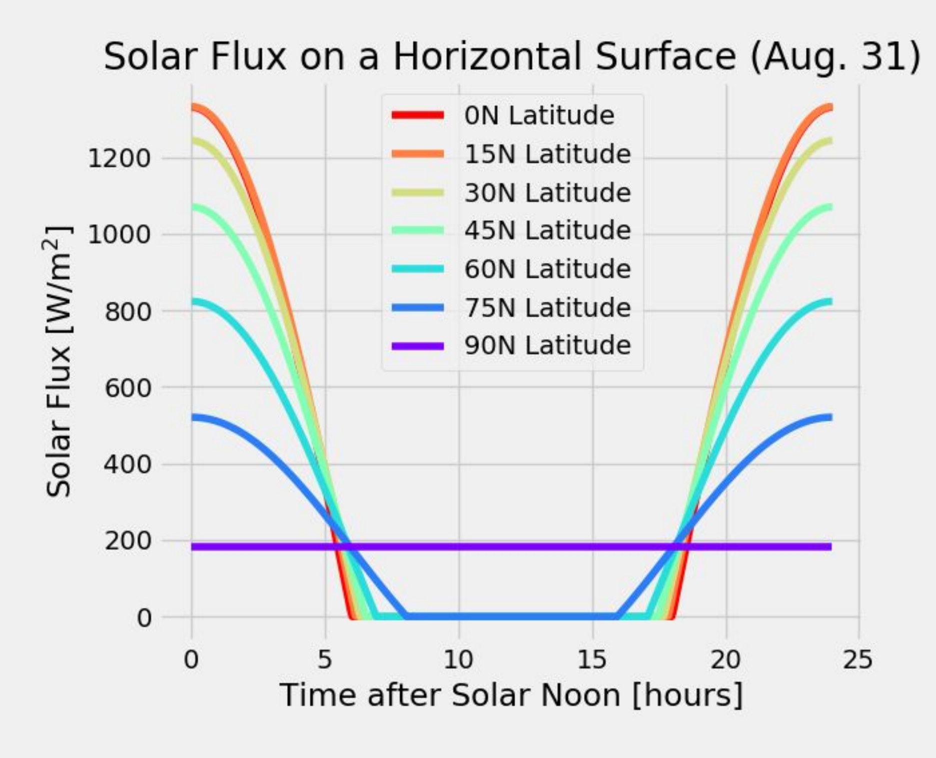
- **“What can we do with a rubber airplane?”**

- An optimizer is only as good as its assumptions and models!

<u>Reminder:</u>
- Margin:
  - 25% structural mass margin
  - 5% power margin to energy closure on worst day

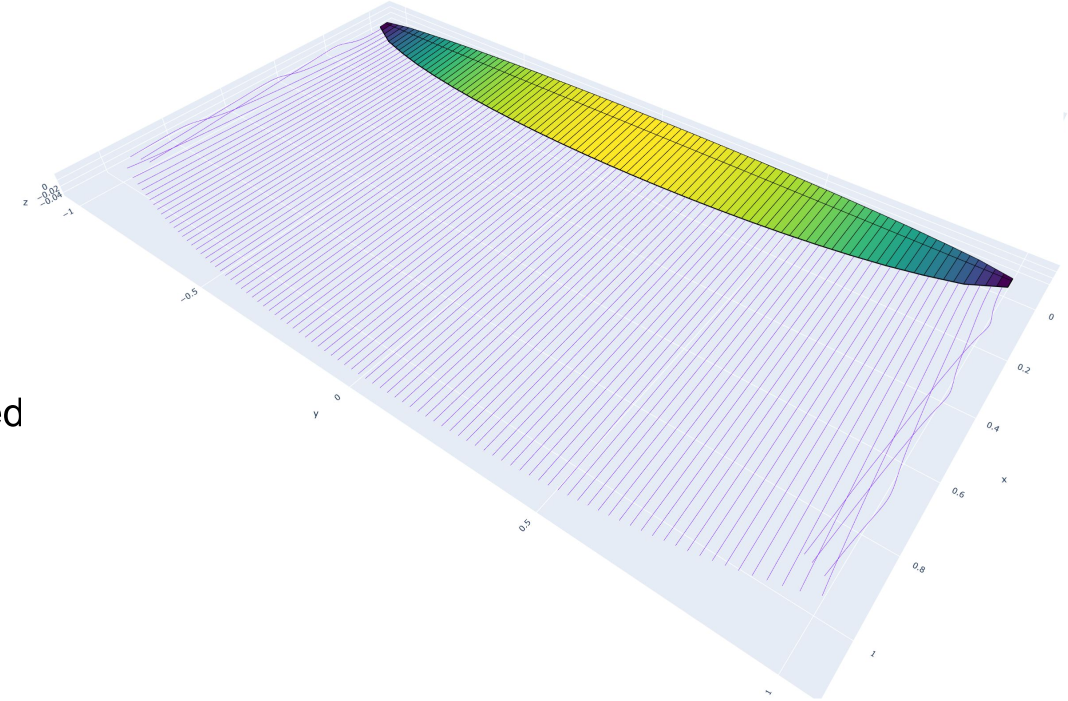
Models: Propulsion & Power Sys.

- Battery (*Sion Power*)
  - **450 Wh/kg** at cell
  - 85% depth of discharge
  - 75% cell packing factor
  - 97.5% charge/discharge eff.
- Solar Cells (*MicroLink*)
  - **25.0% realizable eff.**
  - 0.35 kg/m^2
- Propeller
  - Dynamic disc actuator; calibrated to QProp
- Detailed efficiency stackup from propulsion subteam



Models: 3D Aerodynamics

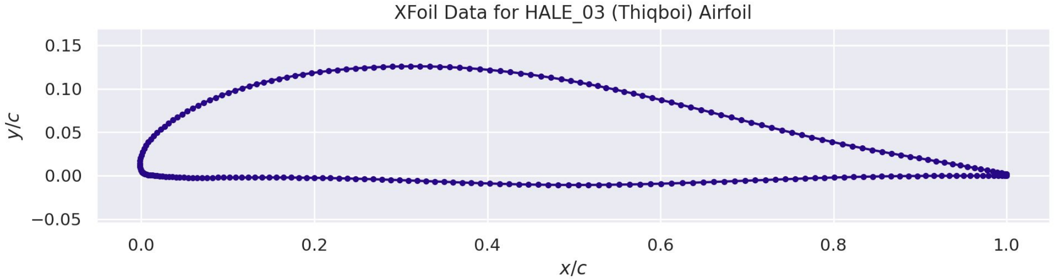
- Aerodynamics solved simultaneously at every point along trajectory
- Three models created:
  - **<u>Traditional lift/drag/moment accounting</u>**
  - Fully nonlinear lifting-line model (coupled viscous effects, local stall, etc.)
  - Vortex-lattice model
- All models differentiable*:
  - Fast optimization
  - Stability derivatives, eigenmode analysis

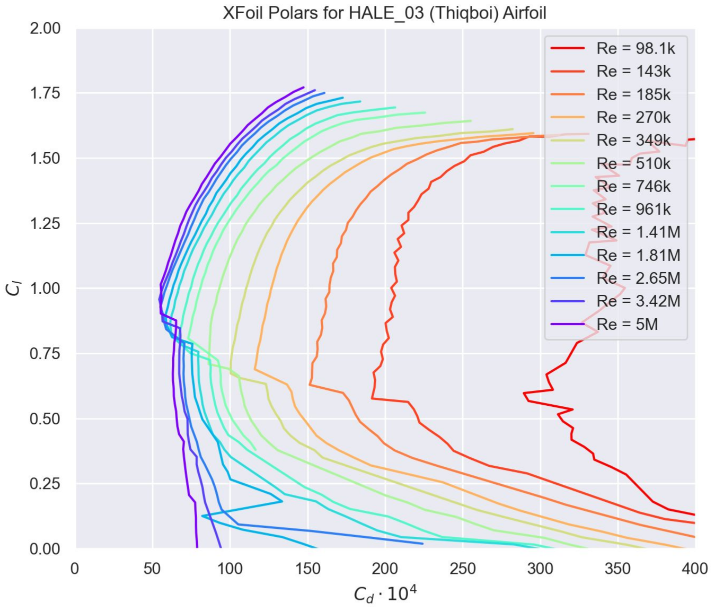


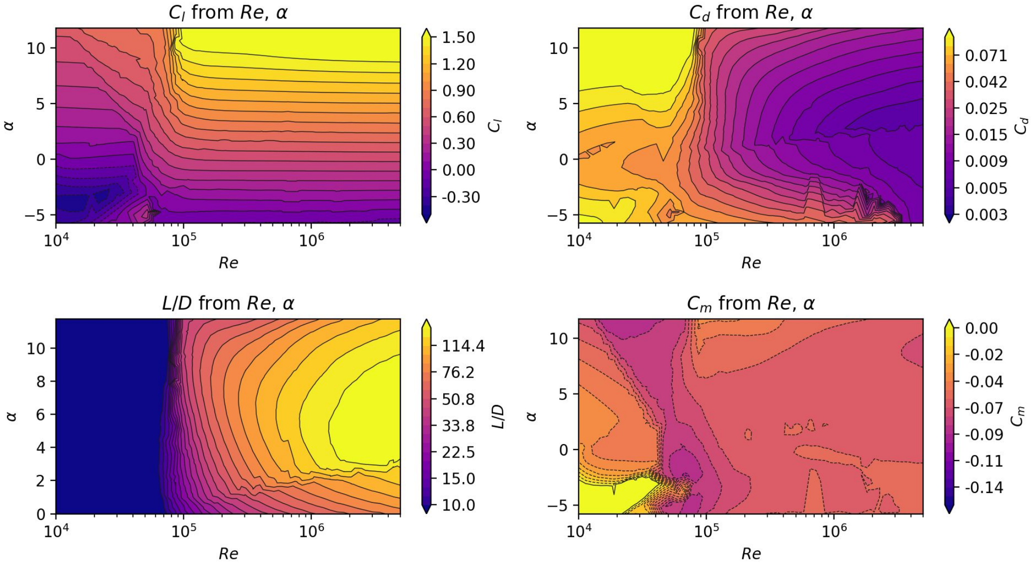
* and operator space is closed under differentiation

Models: 2D Aerodynamics

- Custom low-Reynolds airfoil
  - Fixed a priori
- Fitted model for optimization
  - Captures viscous effects

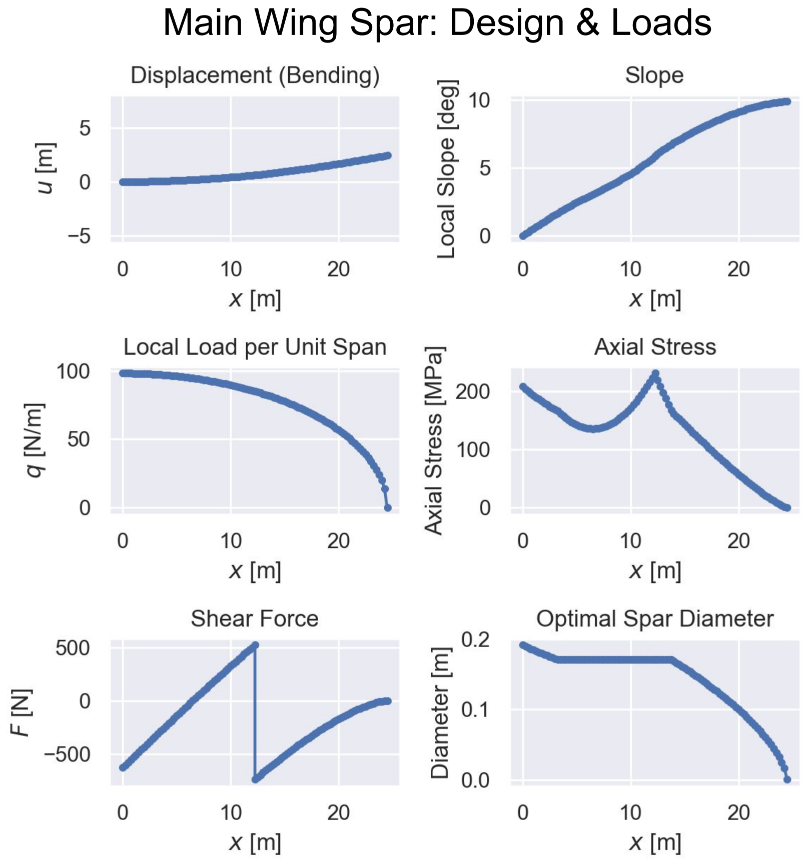






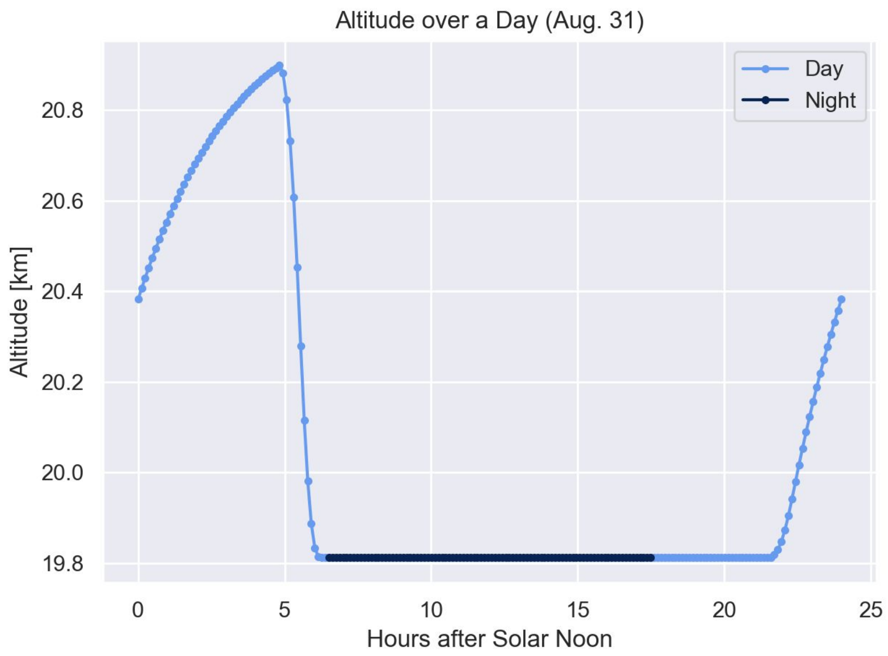
Models: Structures & Weights

- Collection of dozens of empirical and physics-based models
  - Validated against data from existing solar- and human-powered aircraft
- Optimizing internal structure
- 3G static load case as surrogate for dynamic loads; verified *a posteriori* with ASWing



Models: Dynamics

- Power input to the system cycles diurnally
  - Performance gains can be seen by exploiting this
- Types of cycling
  - Altitude cycling
  - Airspeed cycling
- Ascent modeling
- Cycling matters little on worst-day, but can add massive science value on certain days
- Ground track distance over a 50% wind day: ~2,000 km



Optimization Sensitivities

- Primal-dual formulation gives sensitivity information “for free”
- First-order derivatives:

$$\frac{\partial(wingspan)}{\partial(variable)}$$

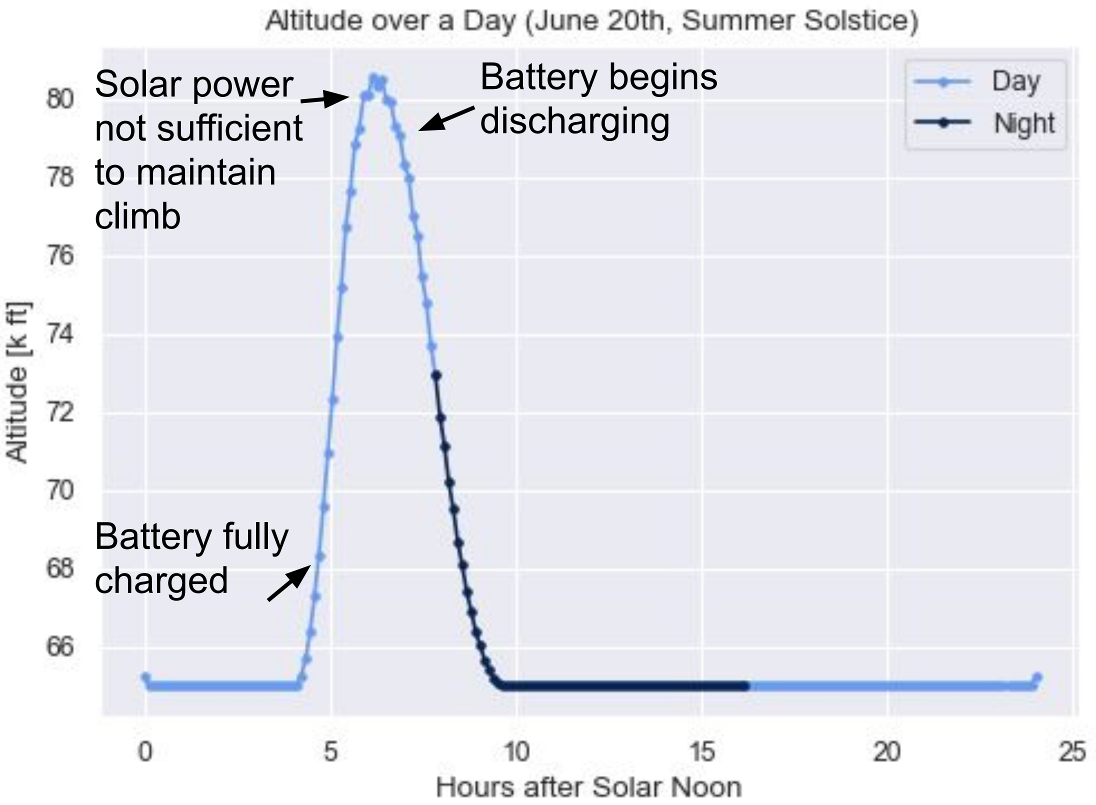
Figure of Merit	Sensitivity of Wingspan*
Any added mass	**0.231 m / kg**
Any added power outputs**	**0.0159 m / W**
Any added drag	**0.667 m / N**
Battery spec. energy	-0.0959 m / (Wh/kg)
Battery pack cell percentage*	-0.603 m / (%)
Solar cell efficiency*	-0.768 m / (%)
Solar cell area density	15.2 m / (kg/m^2)
Propeller COP*	-0.674 m / (%)
Motor efficiency*	-0.620 m / (%)

* Derivatives w.r.t. percentages are in terms of absolute percentage points (i.e. 25% -> 26%), not multiplied percentages
** assumed constant over 24 hours

Peak Altitude (Off-Design)

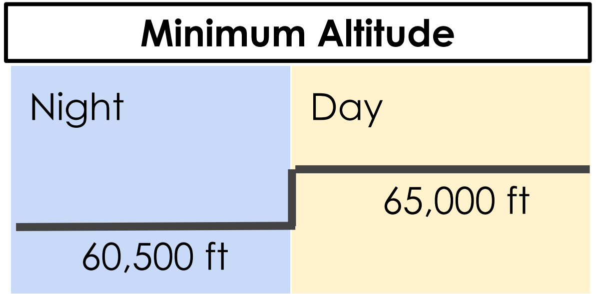
- Assuming June 20th
  - Summer Solstice
  - Excess power for extended science mission
  - Peak Altitude: 80.5 kft

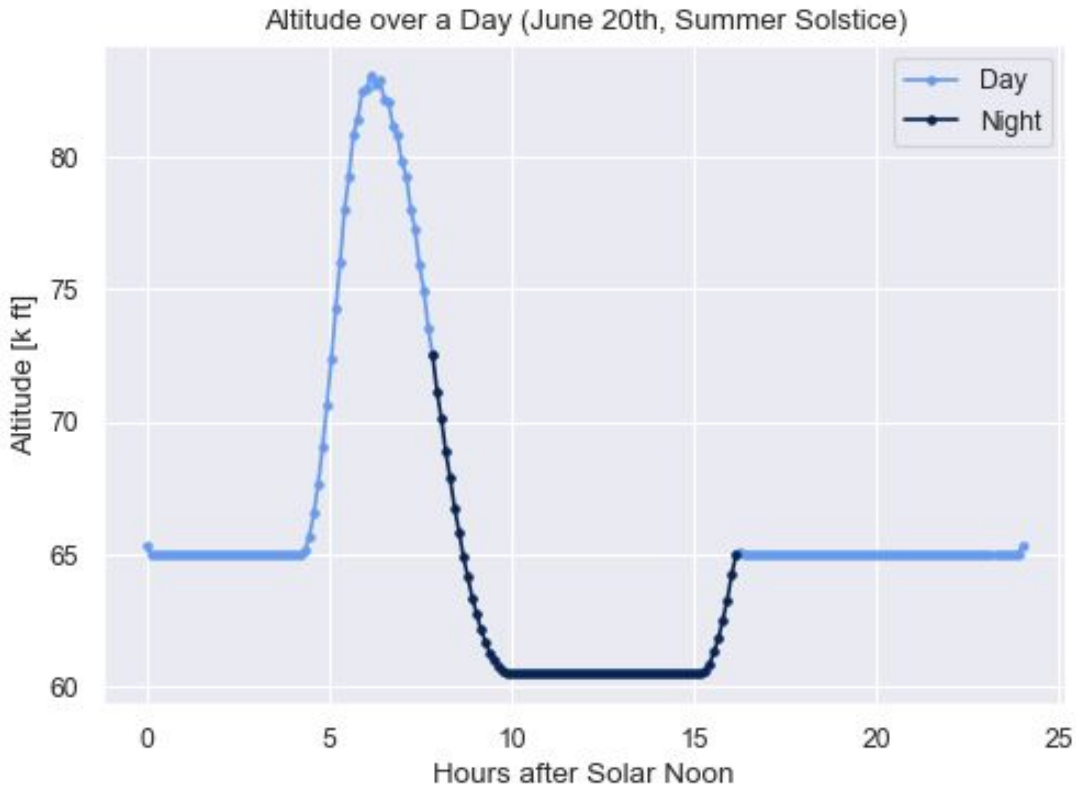
- Can we climb/aspire higher?



Peak Altitude (Updated Req)

- Set nighttime min altitude set at 60.5 kft
- Peak altitude:
  80.5 kft → 83.0 kft
- Weather permitting min altitude change:





Design Overview & Performance

<u>Aero & Structures</u>

Power

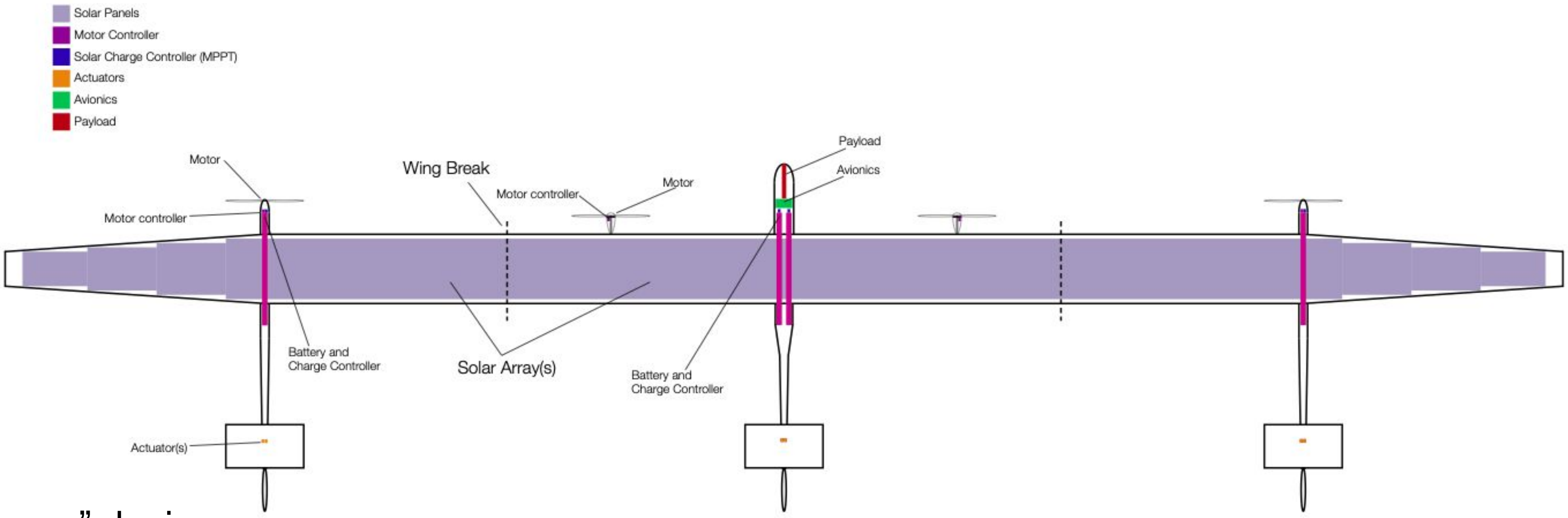
Propulsion

Avionics

Flight Operations

Future Development Plan

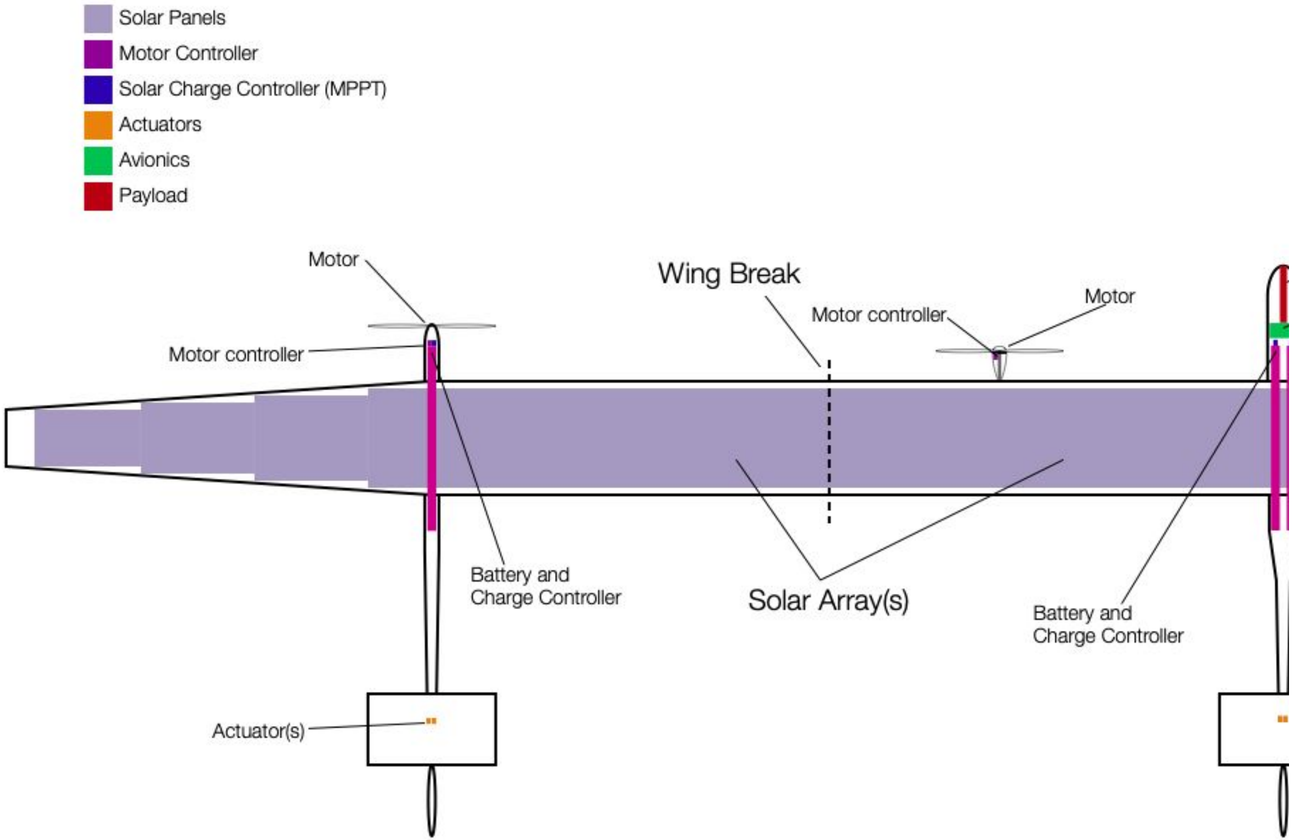
Structure Overview



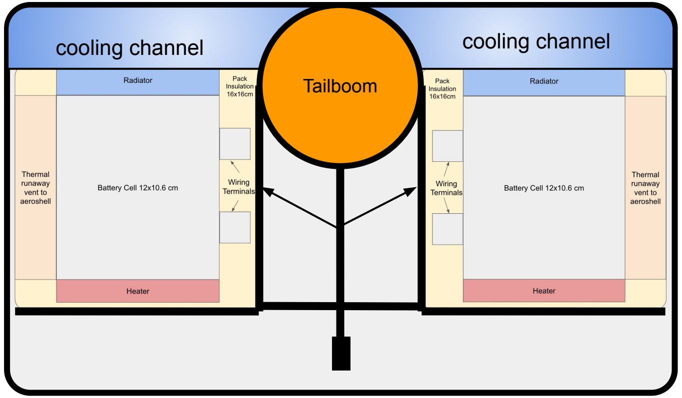
"3 boom" design
- primary center tailboom
- 50% outer tailboom by mass
- 4 motors

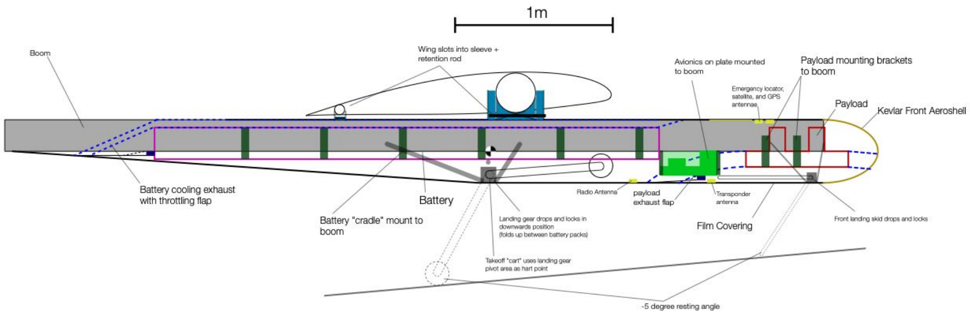
Sizing Cases
- Worst gust condition
- Divergence speed
- Maximum tail input

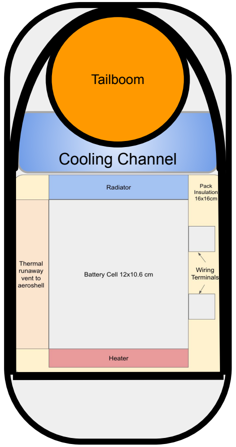
Structure Overview

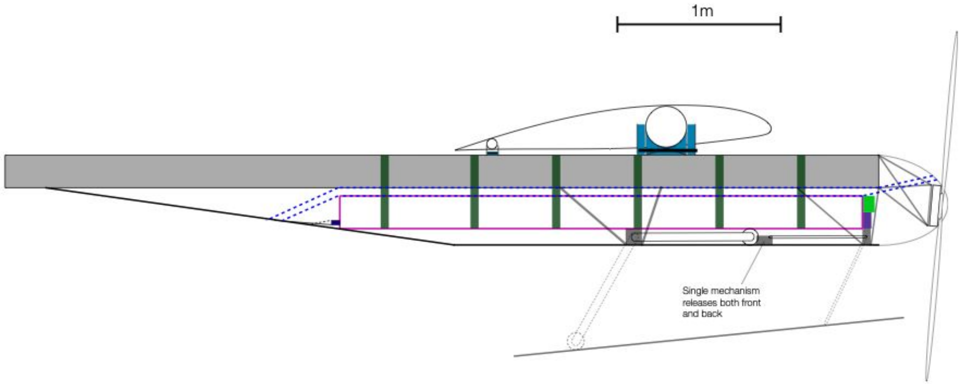


Structure Overview

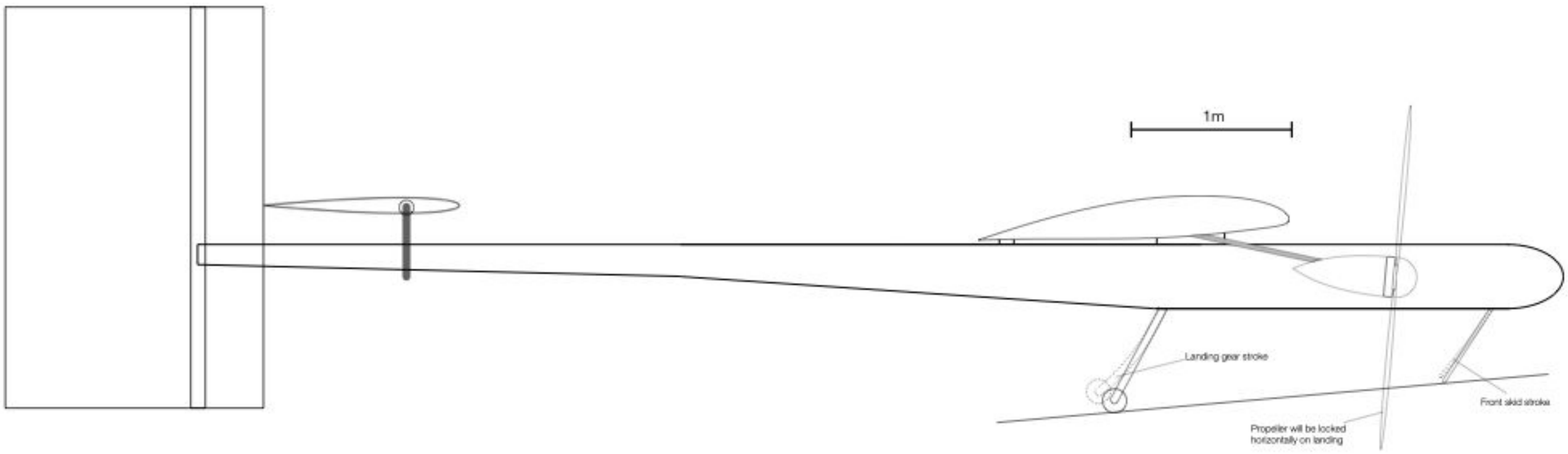








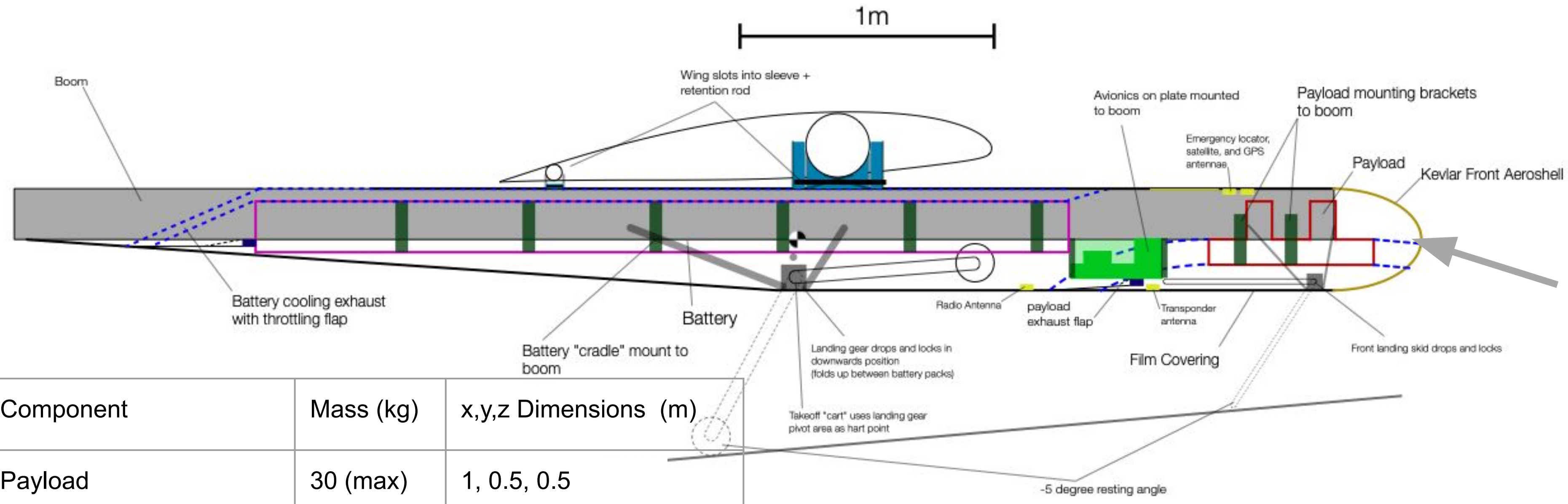
Main Tailboom



Sizing Case

- Worst gust condition
- Maximum tail input

Main Tailboom

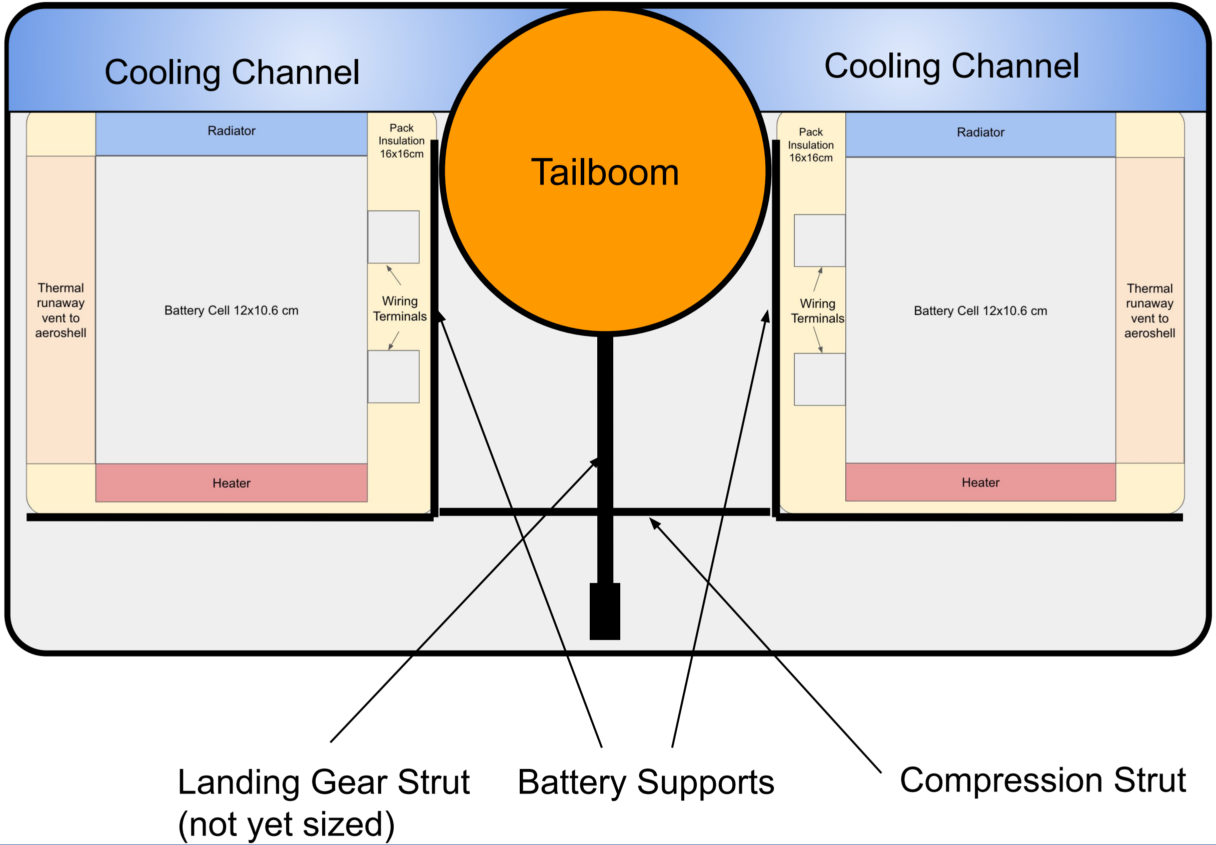


Component	Mass (kg)	x,y,z Dimensions (m)
Payload	30 (max)	1, 0.5, 0.5
Avionics bay	12**	0.5, 0.5, 0.5
Battery Pack	100 kg	0.66, 0.16, 0.16 (single pod)
tailboom	6	9.77, 0.13, 0.13

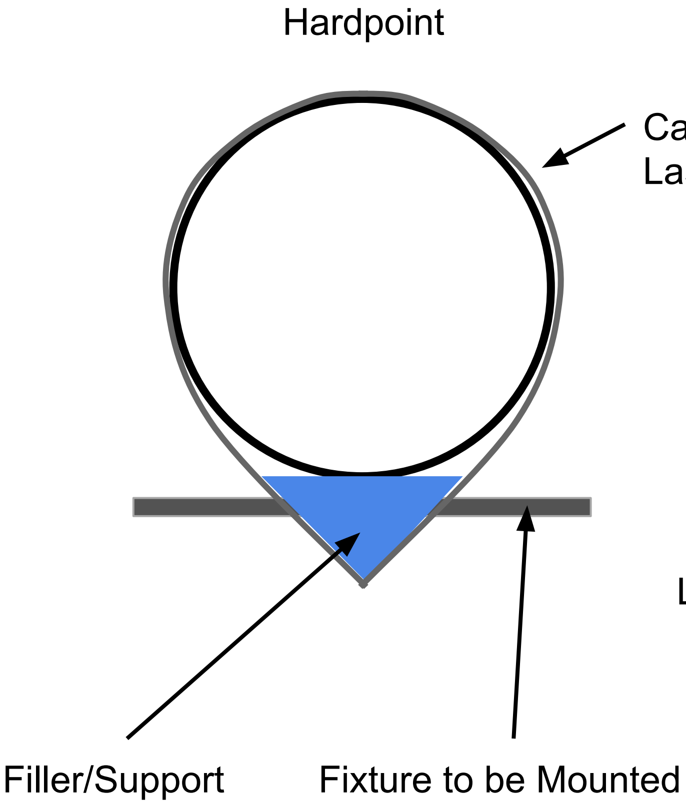
- All hardware is “hung”
- Skin is thin mylar* sheeting
- Single deploy landing gear
- Wing offset 8˚

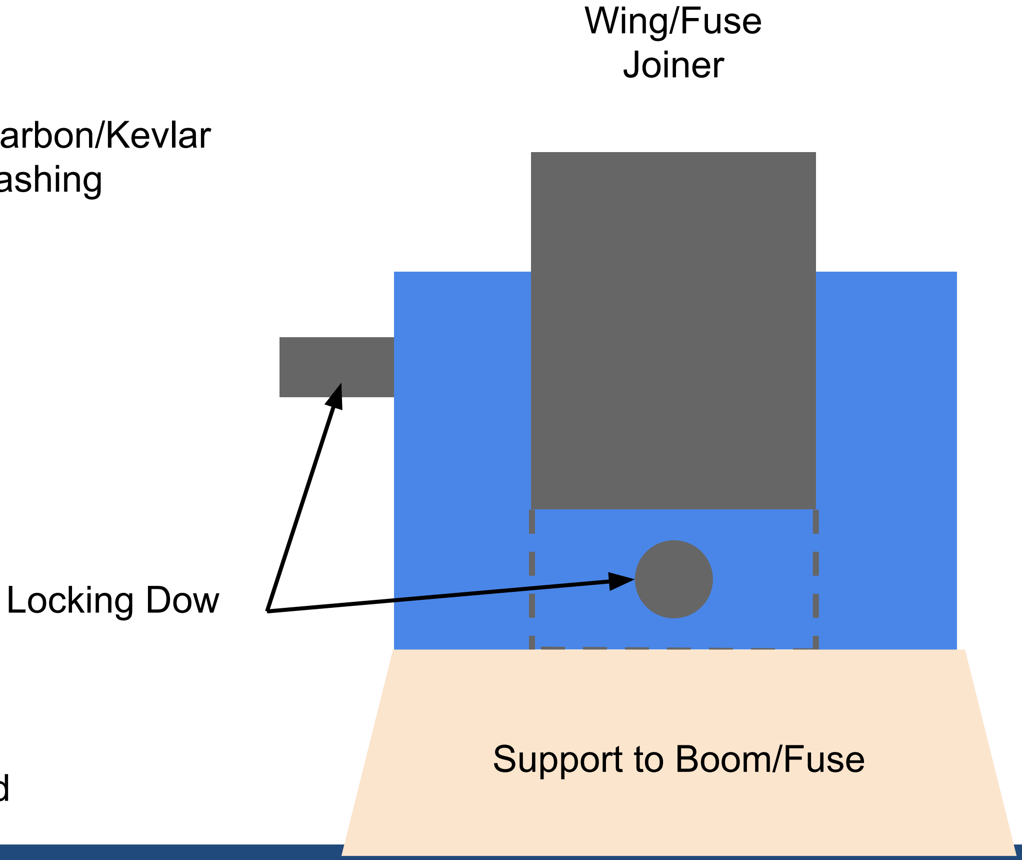
Main Tailboom

Boom Dimensions	
Diameter	13 cm
Wall thickness	1.5 mm
Length	9.7 m
Deflection at max control input	
	20 cm



Hardpoints


Hardpoint
Carbon/Kevlar Lashing
Filler/Support
Fixture to be Mounted

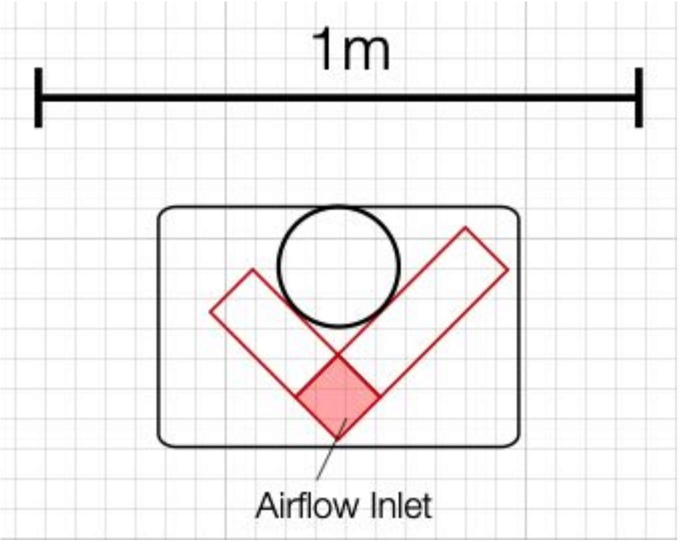

Wing/Fuse Joiner
Locking Dow
Support to Boom/Fuse

Payload Mounting (Front)

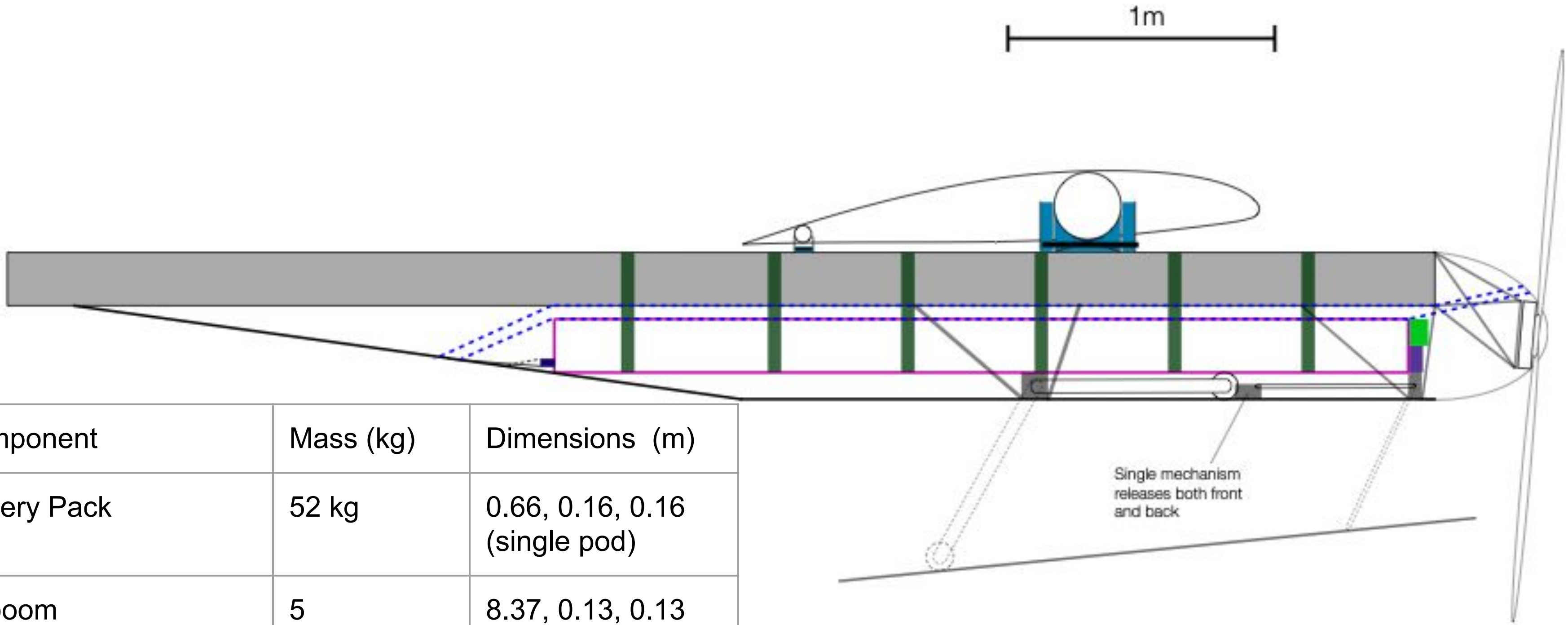
2 mounting options:

- Mounted at 45 degrees, centered inlet
- Mounted orthogonally, offset inlet

Front aeroshell will need to be designed to properly direct airflow into payload



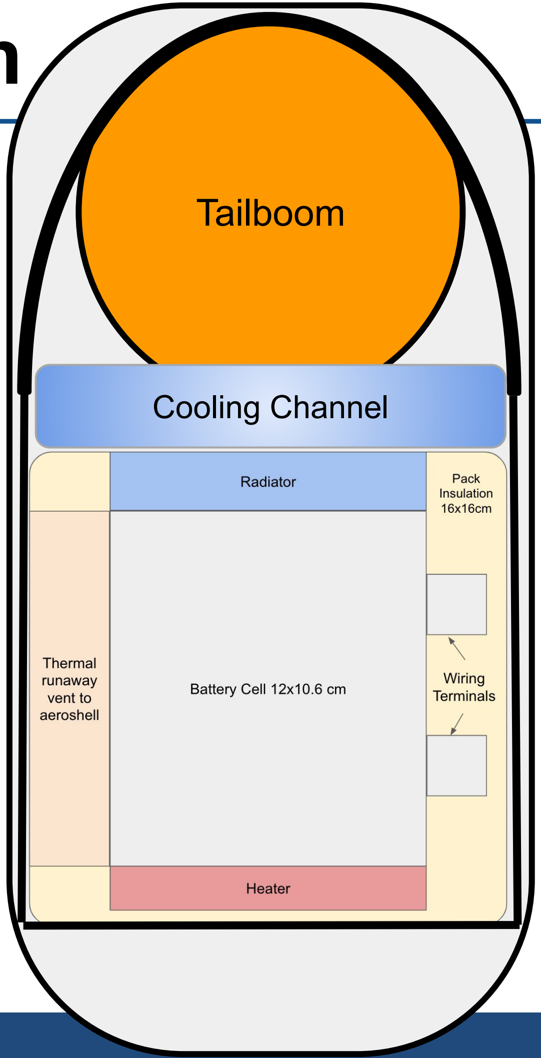
Outer Tailbooms



Component	Mass (kg)	Dimensions (m)
Battery Pack	52 kg	0.66, 0.16, 0.16 (single pod)
tailboom	5	8.37, 0.13, 0.13
MPPT, motor controller		Negligible

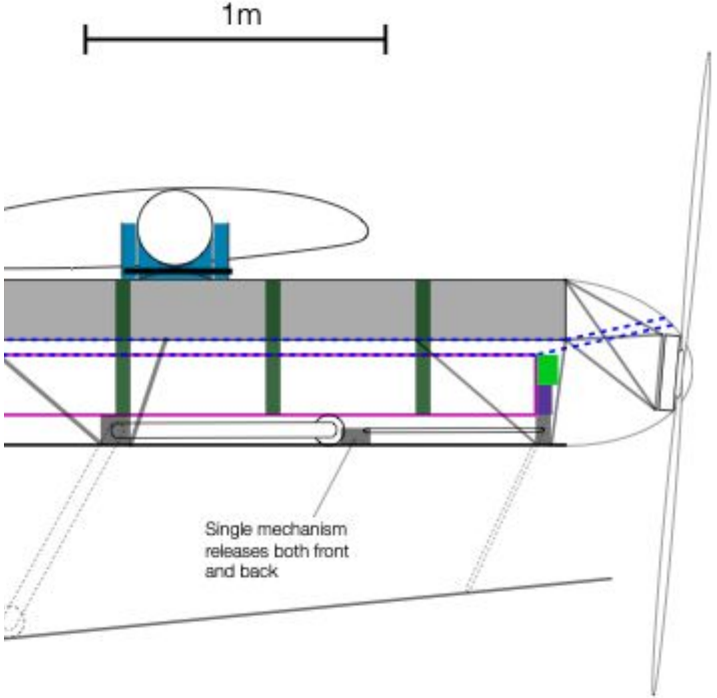
Outer Tailboom

Boom Dimensions	
Diameter	13 cm
Wall thickness	1.5 mm
Length	9.7 m
Deflection at max control input	
20 cm	

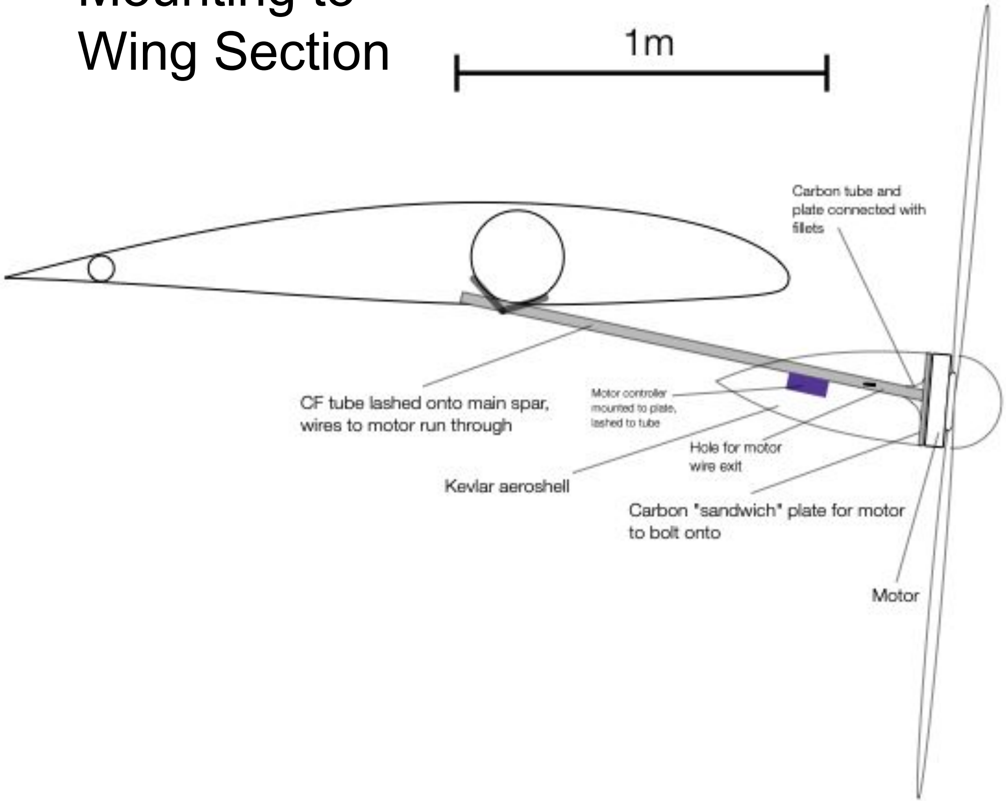


Motor Attachment

Outside Boom Mounting

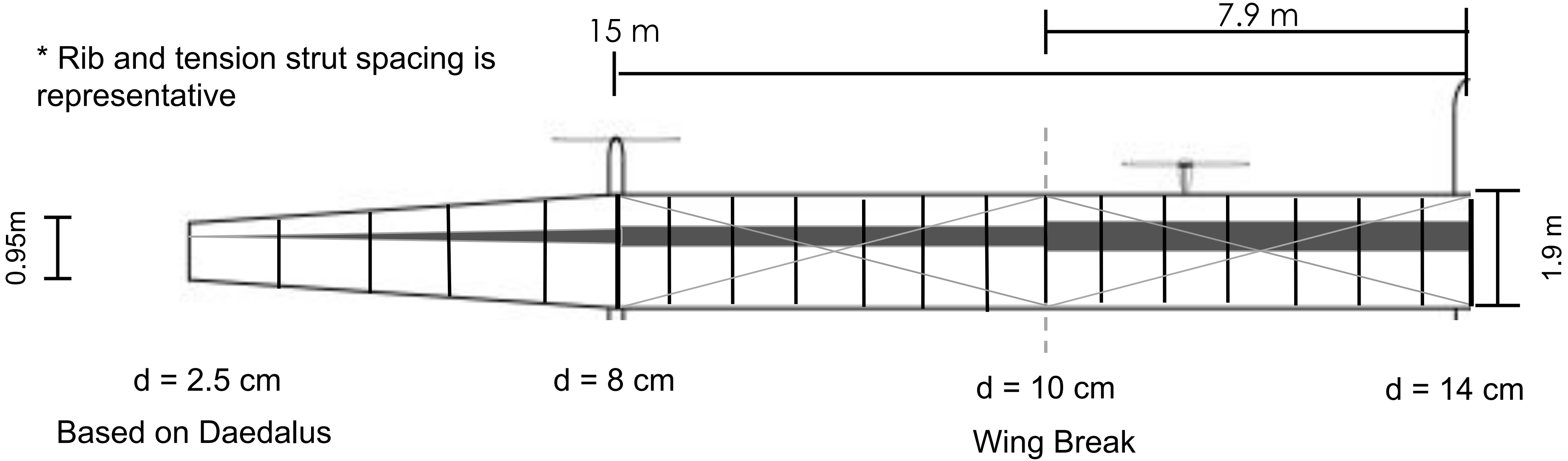


Mounting to Wing Section



Wing

* Rib and tension strut spacing is representative

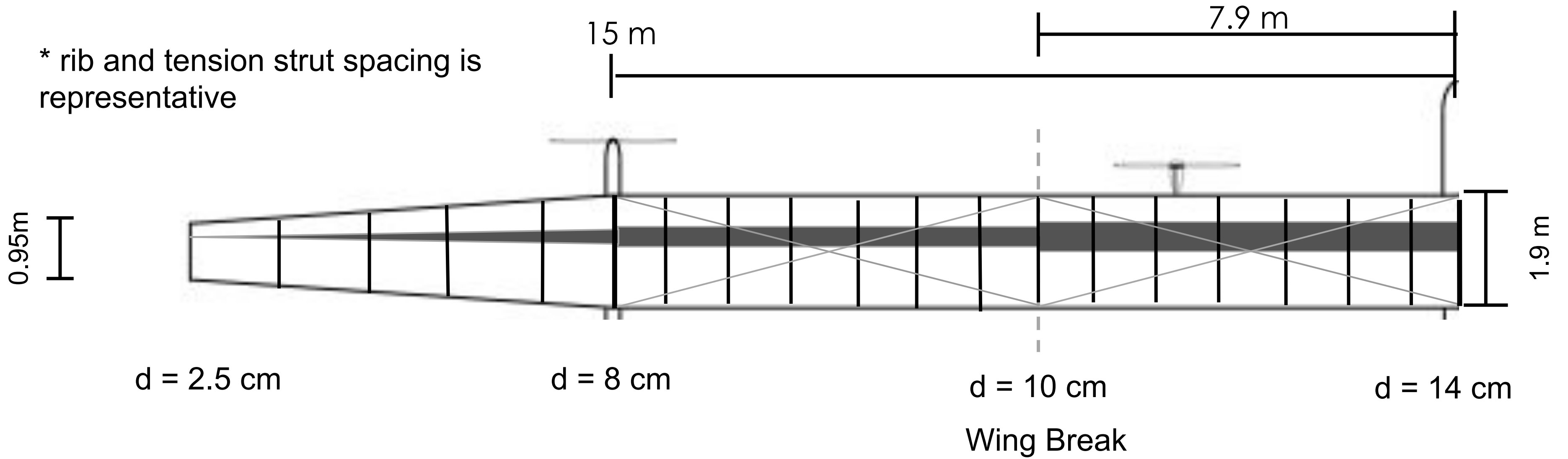


Primary:
- Tiered main spar
- Ribs to provide shape
- Compression struts

Secondary:
- LE sheeting
- Rear spar and TE
- Polymer skin

Non Structural:
- Solar Panels
- Wiring
- Misc.

Wing



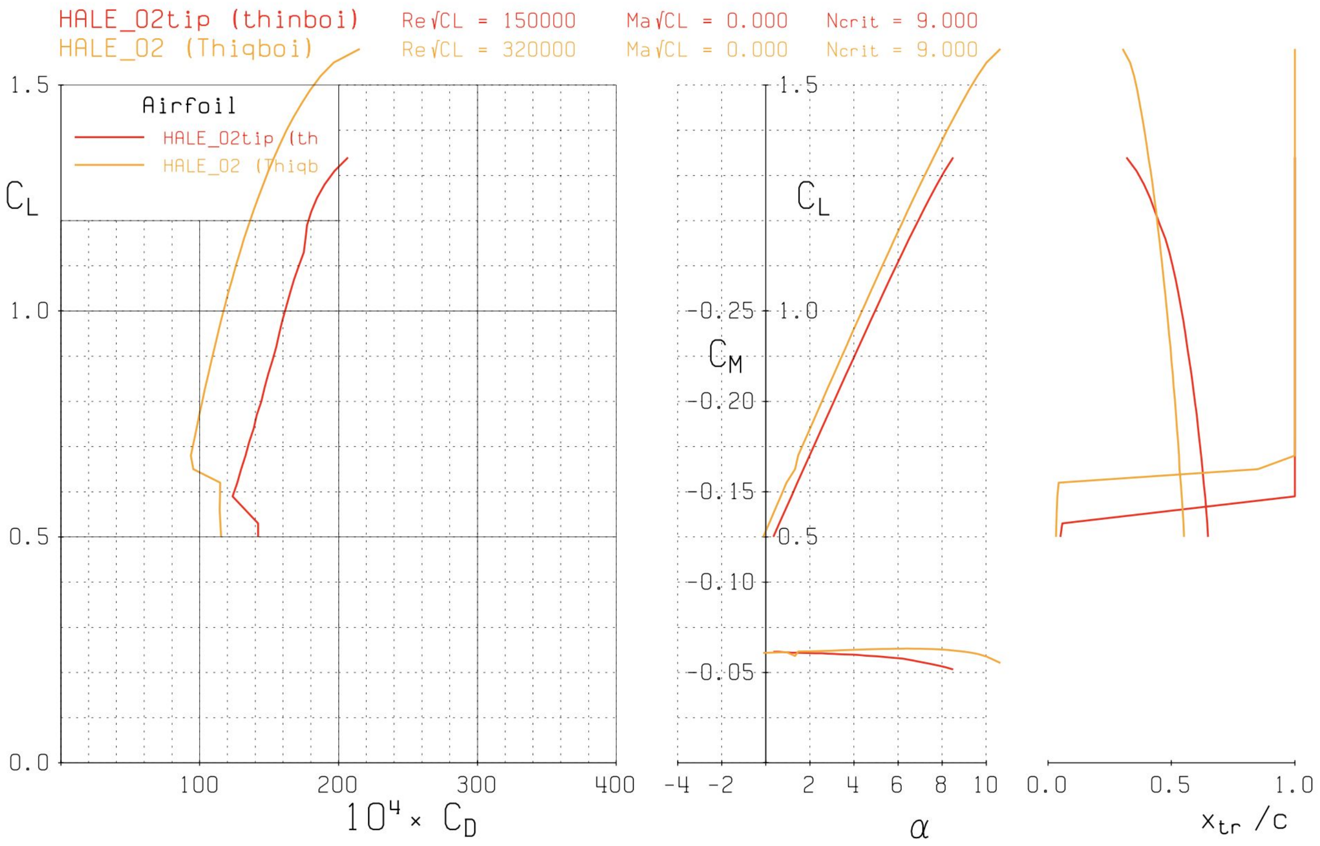
Spar designed and accounted for as physics-based model

Non-spar weights based on scaled Daedalus with 1.3 multiplier

Airfoils

HALE_02 (main foil)	
t/c max	%13.5
t/c max x	0.31
z/c max	%5
z/c max x	0.33
HALE_02tip (tip)	
t/c max	%8
t/c max x	0.32
z/c max	%4.8
z/c max x	0.33

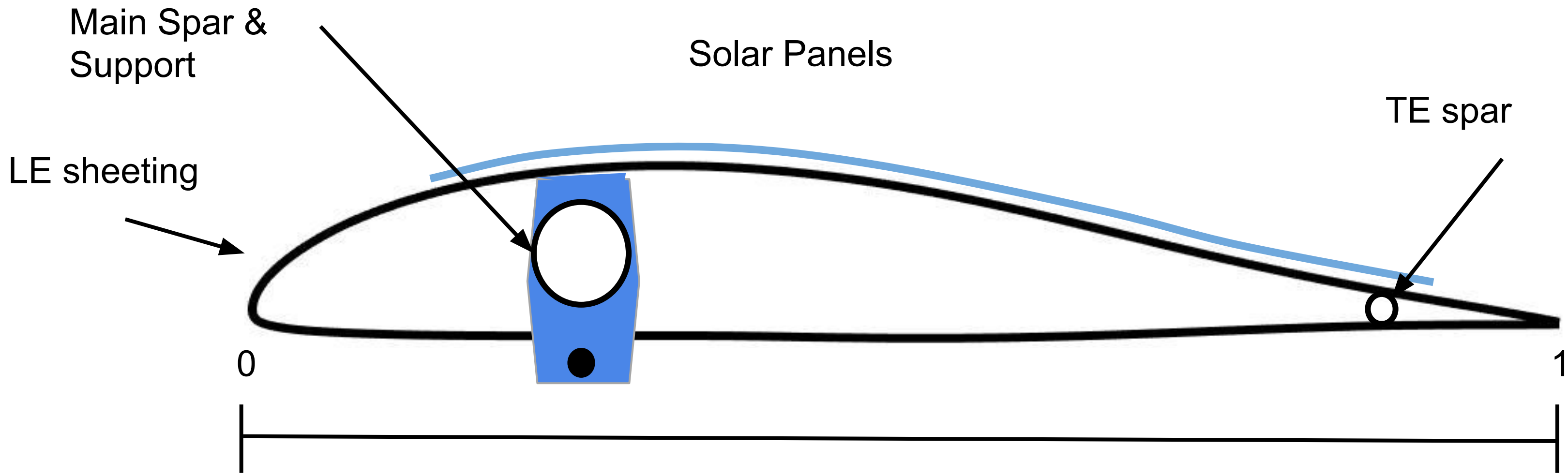
Airfoil Performance



Rib/Airfoil

Open Questions:

- What is skin material?
- Do Solar panels need cover?
- How to attach panels?



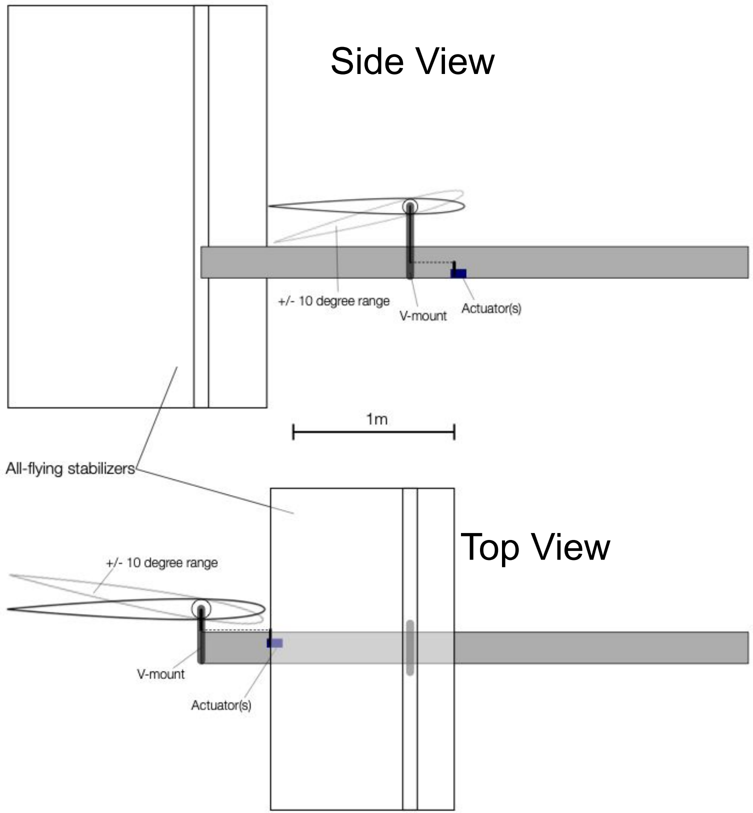
Tail

Construction:

- Same tube & skin as wing
- Weights from scaled Daedalus model

Airfoil

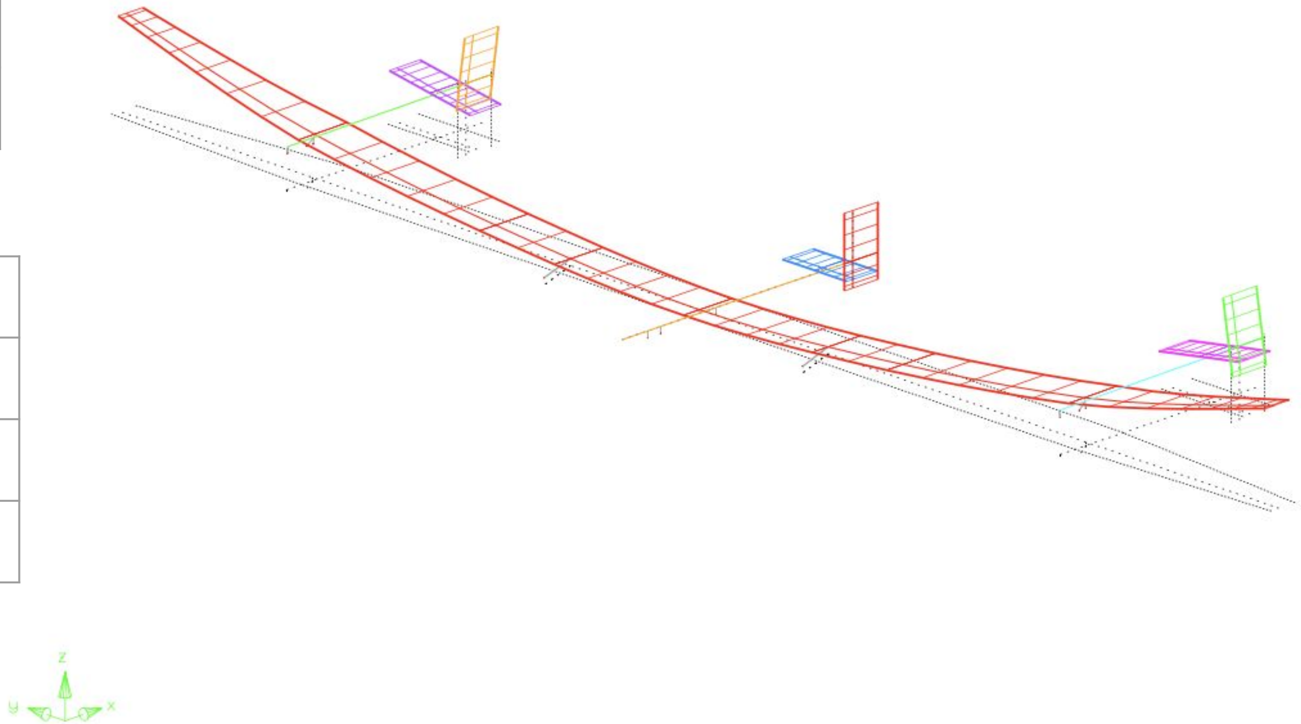
- NACA 0008
- - 10˚ max control authority*



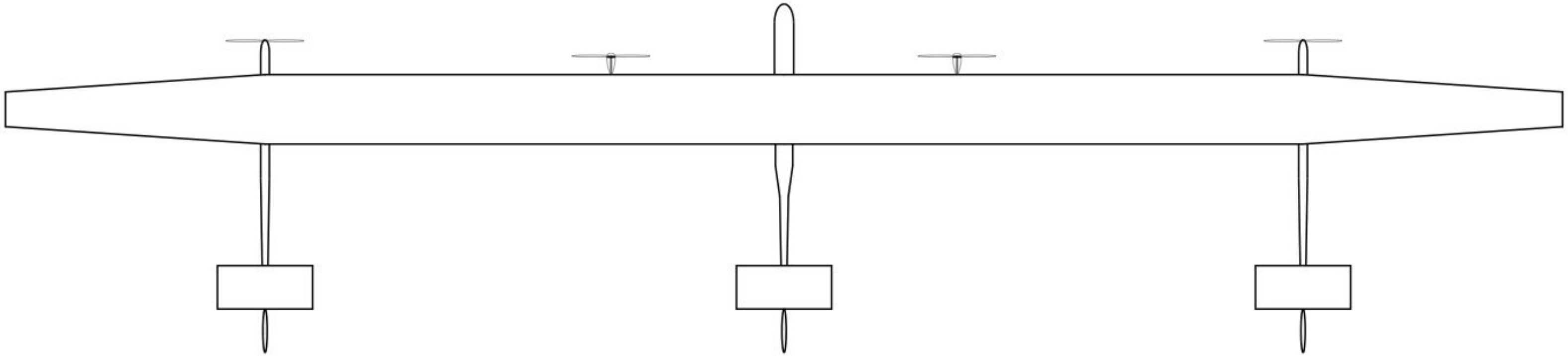
Dynamic Analysis

Operating Conditions	
Altitude	0 km (sea level)
Airspeed	8.8 m/s

Summary of Results	
q_{ne}	103.5 Pa
Max bank	3 deg
Max vertical gust	2 m/s



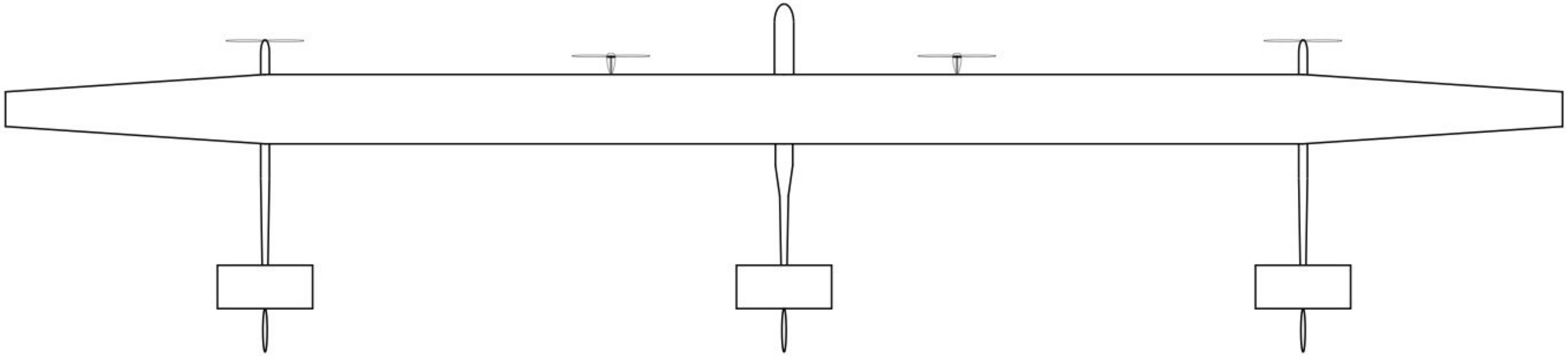
Control Scheme



Use only tail inputs for all controls

- differential control to deform wing → turn
- unison control to pitch up/down as unit
- other schemes for structure control

Control Scheme



Action
Pitch up
Steady R bank
C-boom down

Tail	Stab.
-	up
left	down
-	up

Tail	Stab.
up	-
left	-
-	down

Tail	Stab.
up	-
left	up
-	up

Divergence

Short description: Find speed where aerostructural modes are damped or tuck occurs

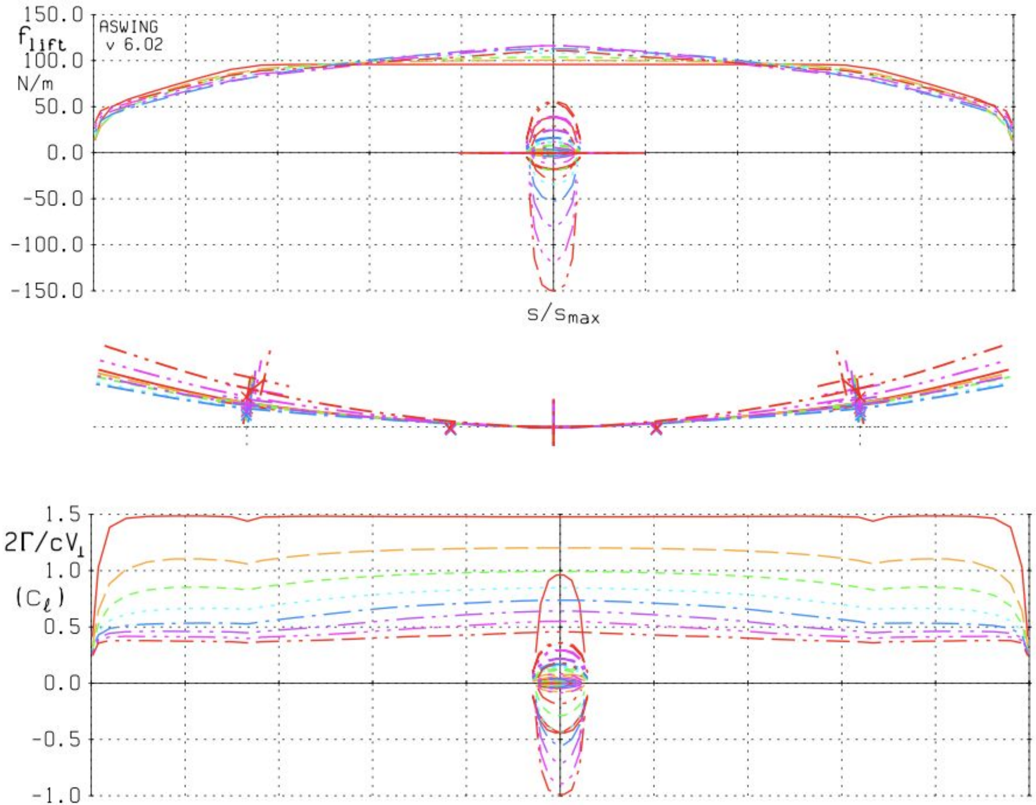
Qne or Vne

Our operating range:

$35 \leq q \leq 129$ (Pa)

$7.5 \leq V_{sea} \leq 13.5$ (m/s)

$28.0 \leq V_{op} \leq 54.0$ (m/s)



Divergence

Short description: Find speed where aerostructural modes are damped or tuck occurs

Qne or Vne

Our operating range:

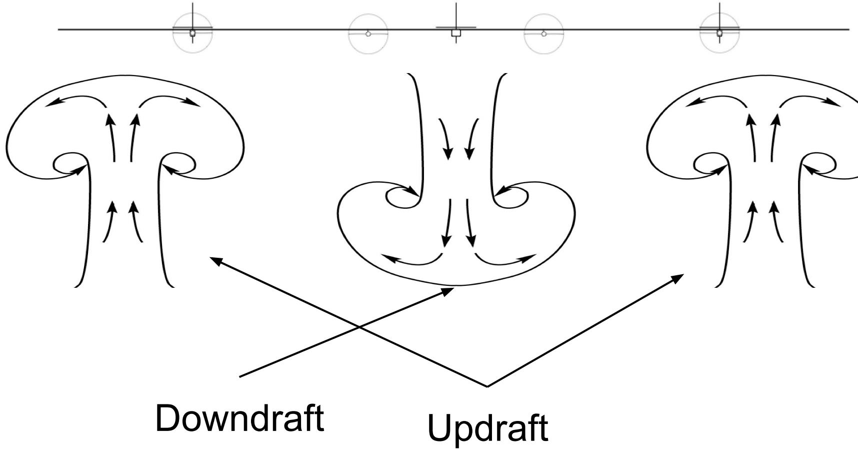
$$35 \leq q \leq 129 \text{ (Pa)}$$

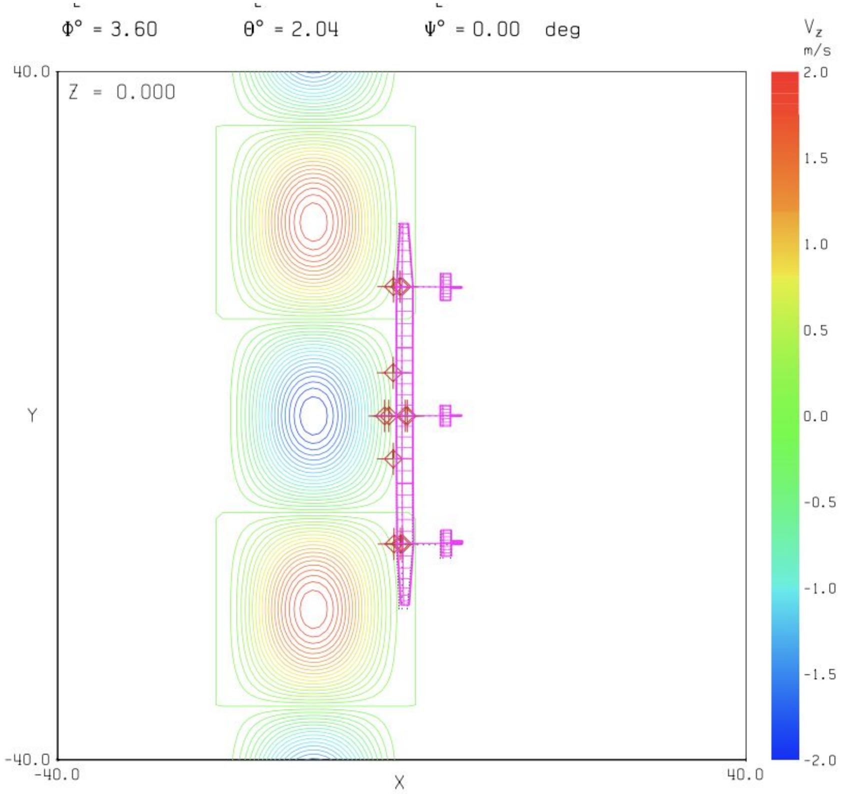
$$7.5 \leq V\_sea \leq 13.5 \text{ (m/s)}$$

$$28.0 \leq V\_op \leq 54.0 \text{ (m/s)}$$

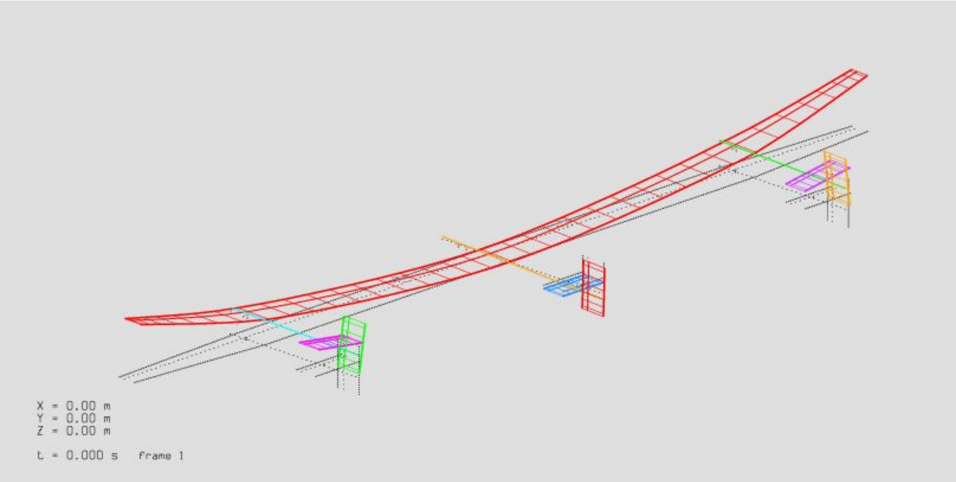
Gust Case: Cosine

- "Cosine" gust
- 2 m/s updraft*
- Considered worst case

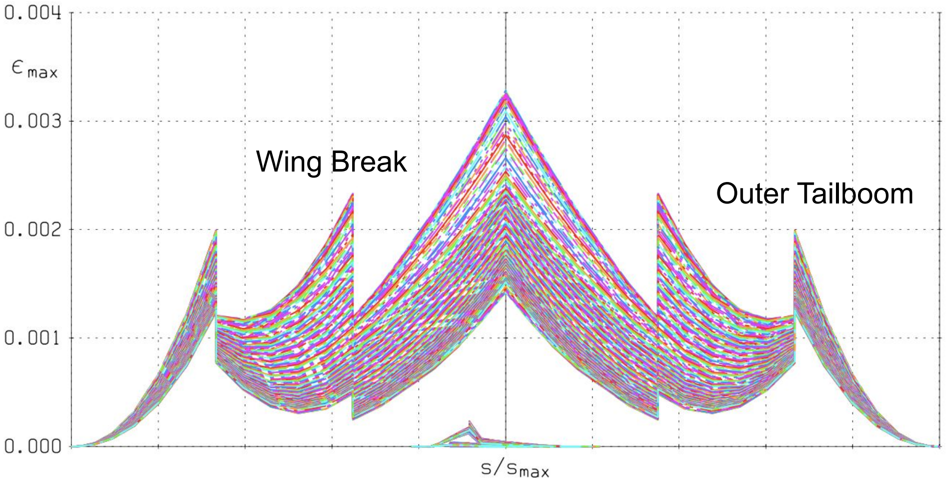




Gust Results



Encounter Results	
Max velocity	9.3 m/s
Max strain	0.032 at root
Control input	none



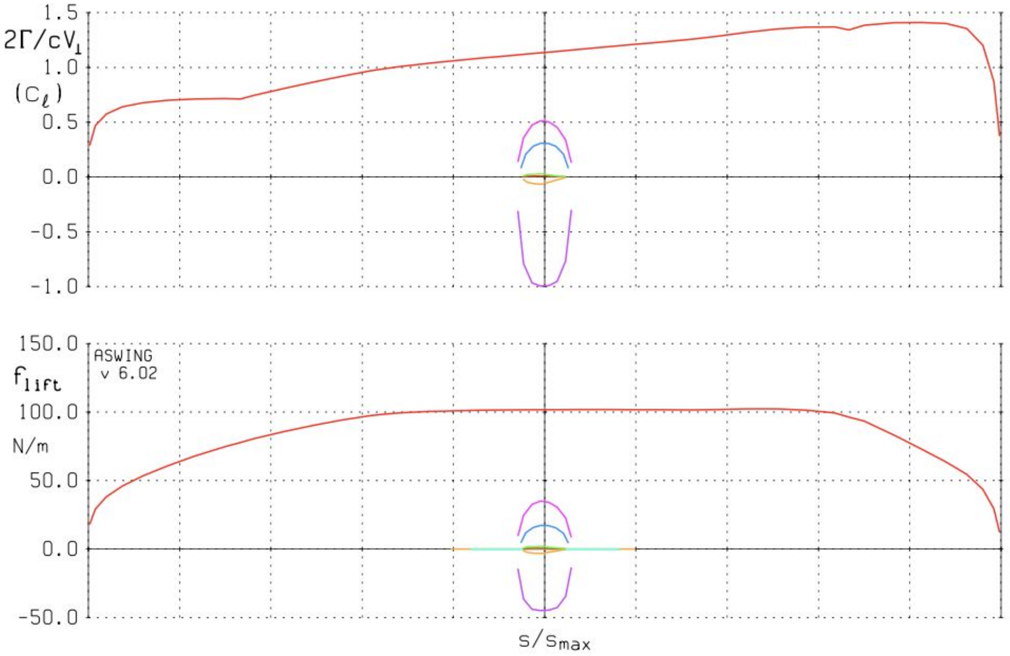
Considerations:

- Gust tolerance likely higher
- Could drive main spar lighter/smaller
- How much margin are we willing to tolerate?

Maximum Bank

Nominal Operating Cond.	
Max Bank	3.3˚
Limit	tip lift coeff = 1.5

Nominal Operating Cond.	
Sea Level 180 diam	.136 km
Nom. Op. 180 diam	3.8 km



Maximum Bank

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Max Bank	3.3˚
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Sea Level 180 diam	.136 km
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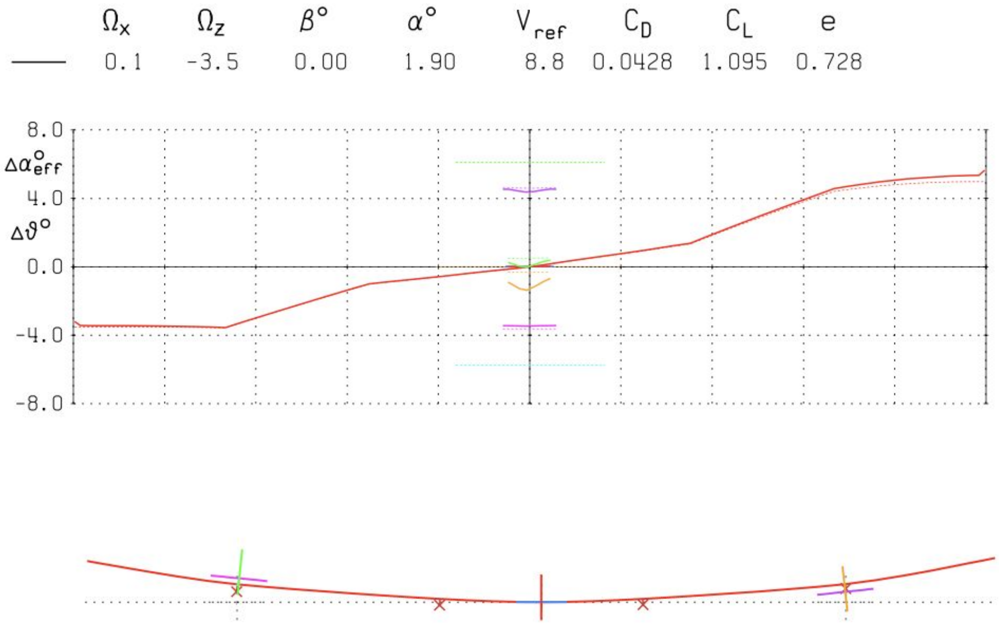


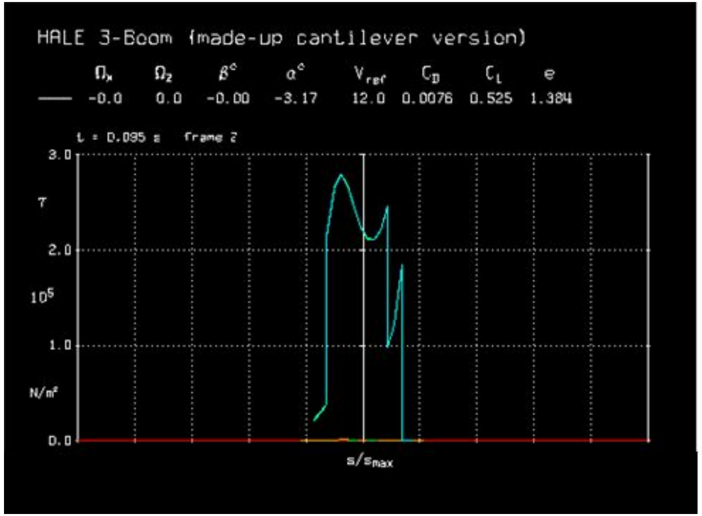
Landing Case

- Ensure structural integrity while landing

- Simulation process
  – Set Initial V
  – Get Initial U_z
  – Set a_z = 2g, dt = U_z/a_z
  – Simulate descent
  – Set a_z = 0
  – Simulate landing

Landing Results

```
grnd Fx :   0.000     N
grnd Fy :   0.000     N
grnd Fz : -5684.      N
```



Side landing gears land about 3 seconds after main landing gear

Looking Ahead:

- Good check for smooth landing case
- Want to design for higher than 1.4g
- Particular concern comes from sudden downgusts

Open Questions

Skin Polymer material

- Cover solar panels Y/N
- UV transparency vs. stability

Dynamic loads

- Tailboom lengths
- Differential tail sizing
- Clever control schemes

Wing, Structure Mass

- Main boom, what tolerate
- secondary structure mass
    - prototyping
- Landing gear sizing

Design Overview & Performance

Aero & Structures

<u>Power</u>

Propulsion

Avionics

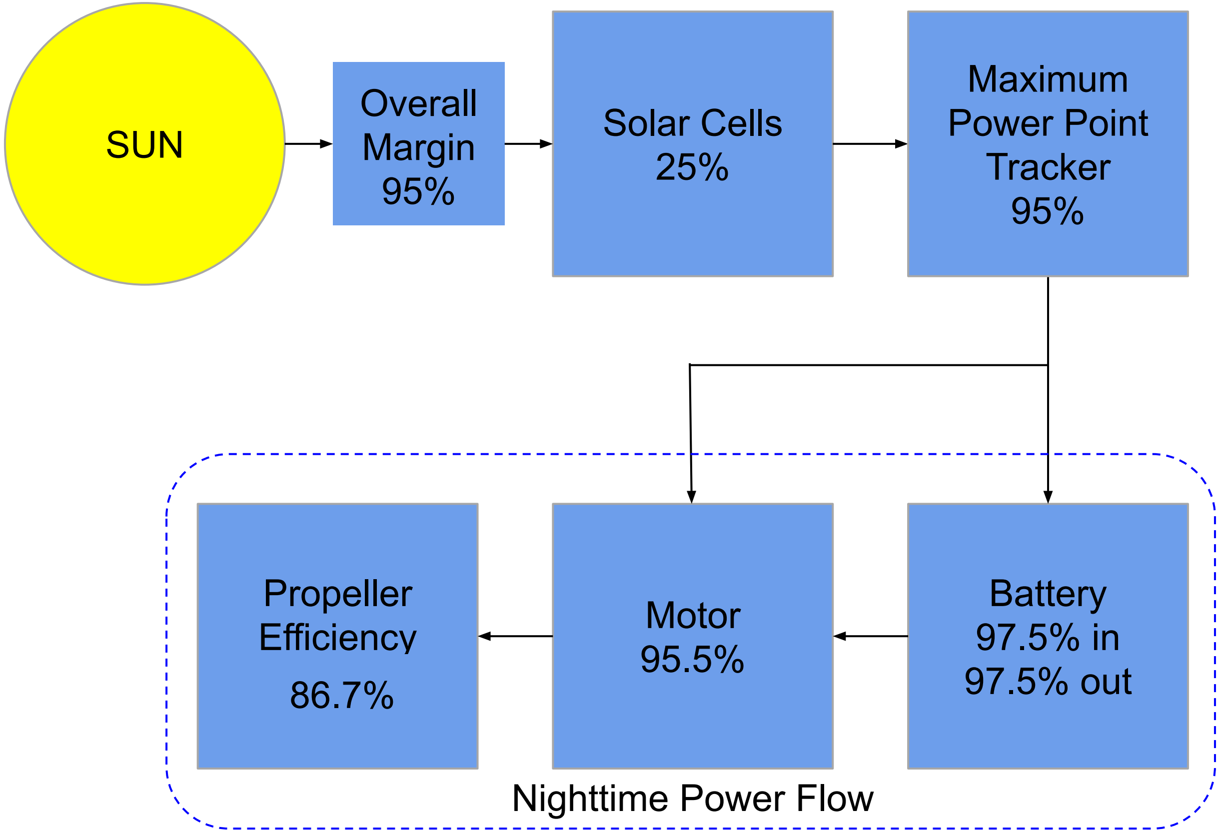
Flight Operations

Future Development Plan

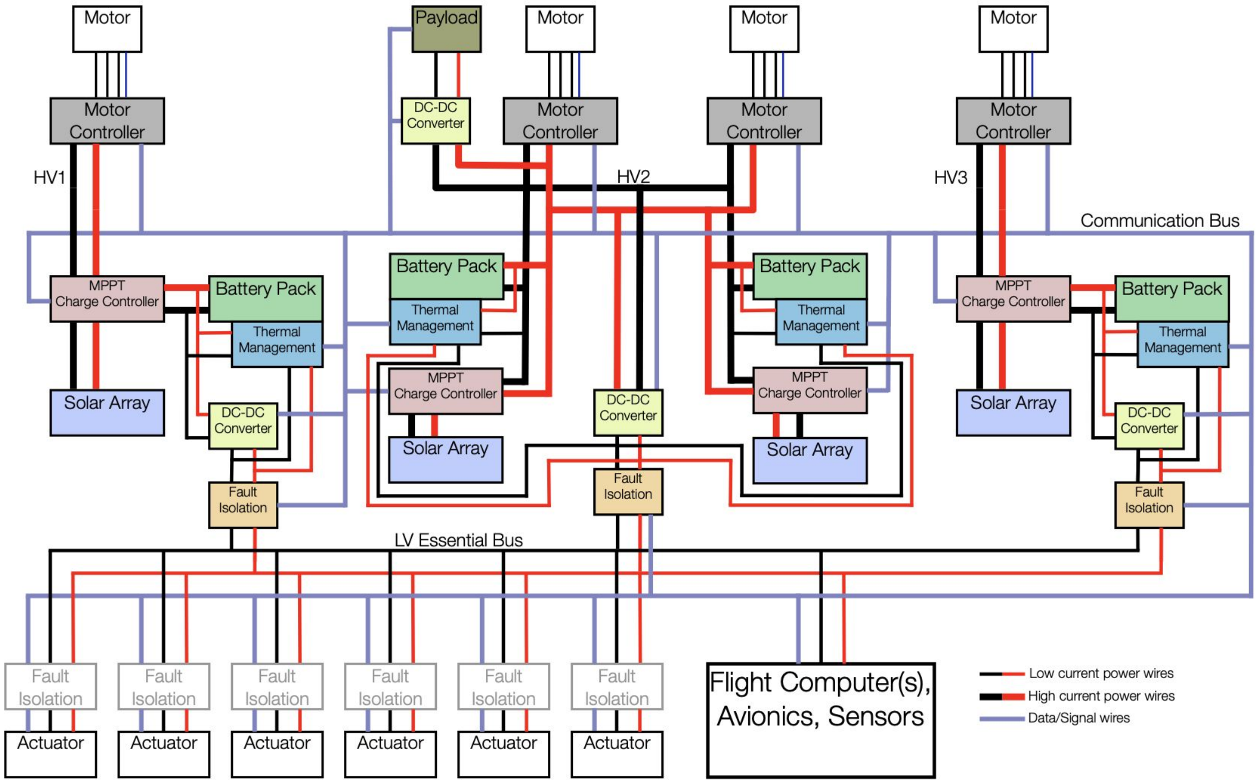
Power System Efficiencies

- Overall system efficiency is 18.6%

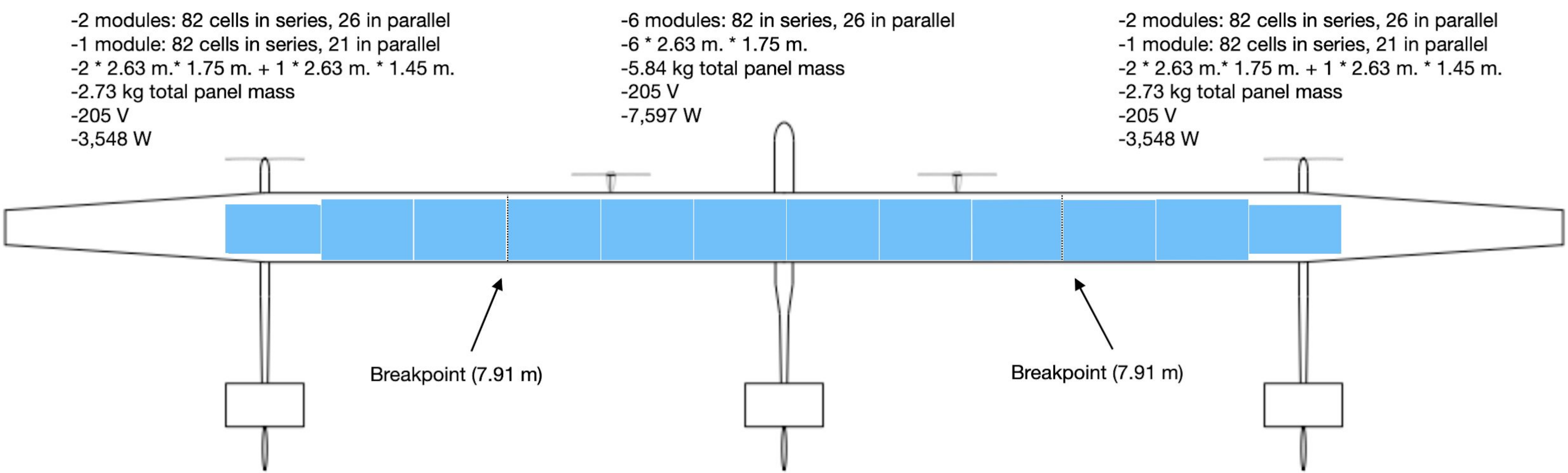
- 5 % overall power excess applied to retain margin in the propulsion system



Electrical System Schematic

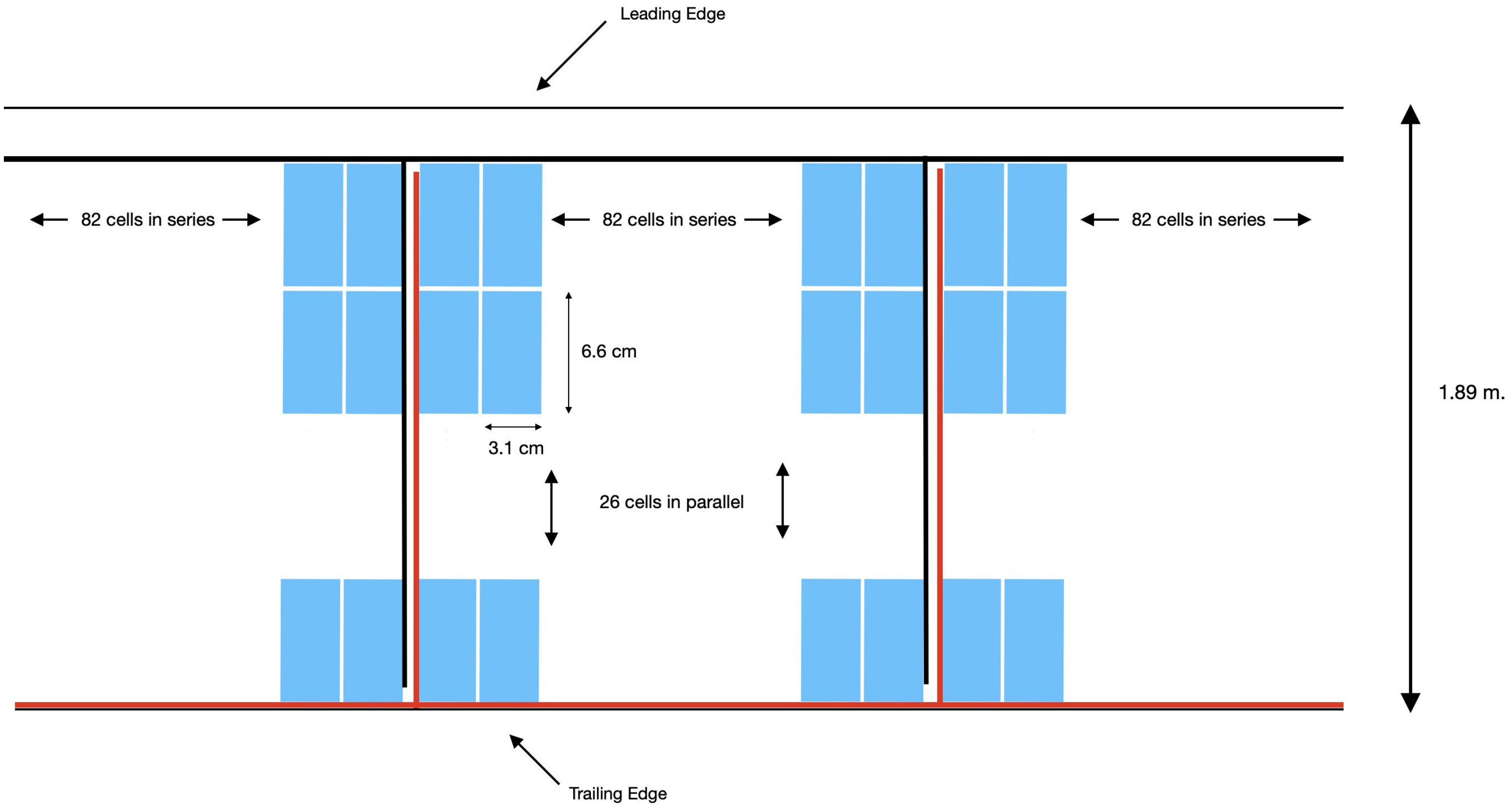


Microlink Cell Layout



- 14.7 kW on Aug 31, 49N with 30 kg payload
- 11.3 kg system mass
- $3.7 mil total cost of solar panels (major identified risk)

Microlink Cell Layout

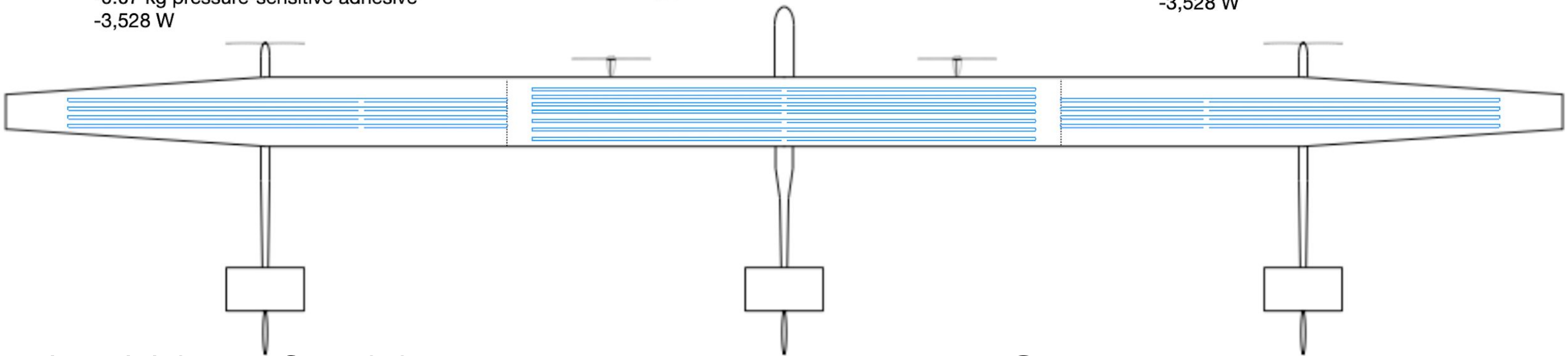


Sunpower Cell Layout (Demonstrator)

-194 cells in a loop, 4 loops (124.1 V)
-12.6 meters * 1.04 meters
-5.12 kg cell mass
-0.75 kg at 30um EVA encapsulant
-0.05 kg bus bars
-0.07 kg pressure-sensitive adhesive
-3,528 W

-222 cells in a loop, 7 loops (142.1 V)
-14.4 meters * 1.75 meters
-10.2 kg cell mass
-1.45 kg at 30um EVA encapsulant
-0.11 kg bus bars
-0.15 kg pressure-sensitive adhesive
-7,057 W

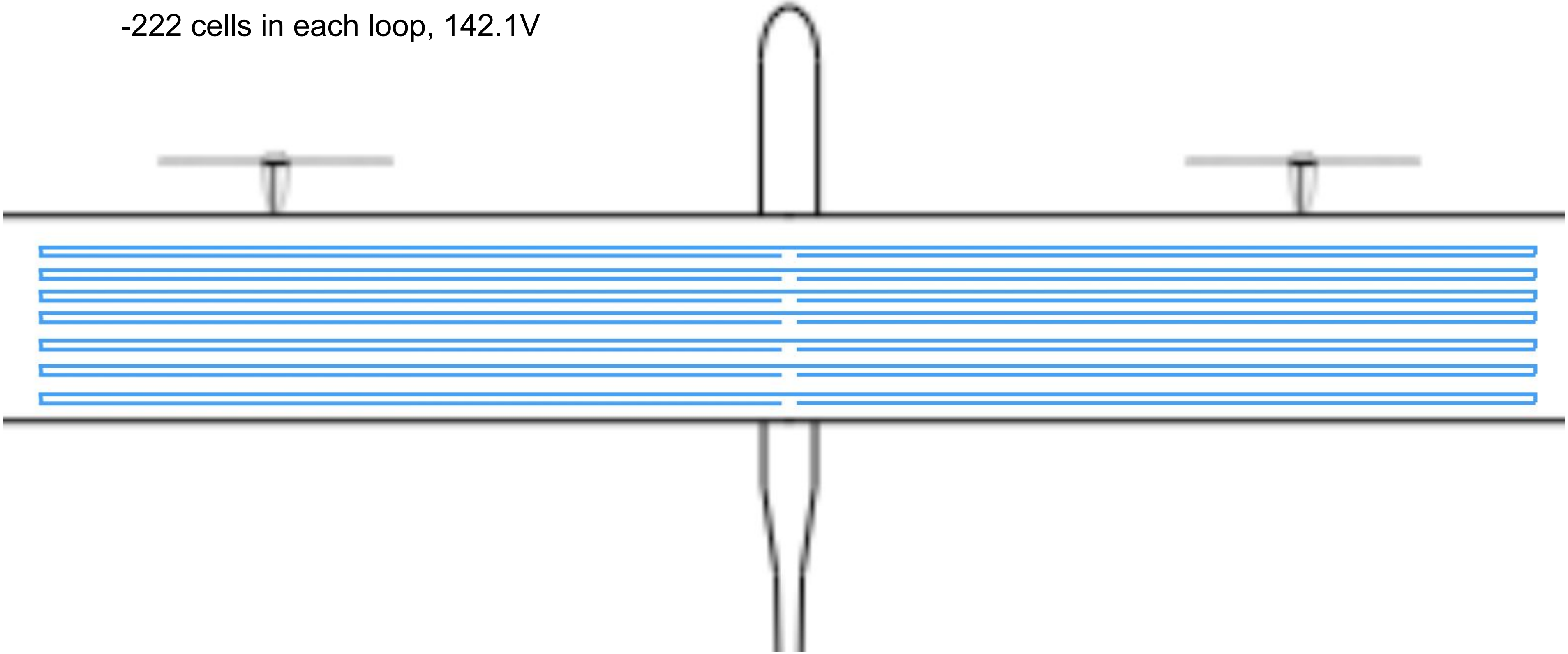
-194 cells in a loop, 4 loops (124.1 V)
-12.6 meters * 1.04 meters
-5.12 kg cell mass
-0.75 kg at 30um EVA encapsulant
-0.05 kg bus bars
-0.07 kg pressure-sensitive adhesive
-3,528 W



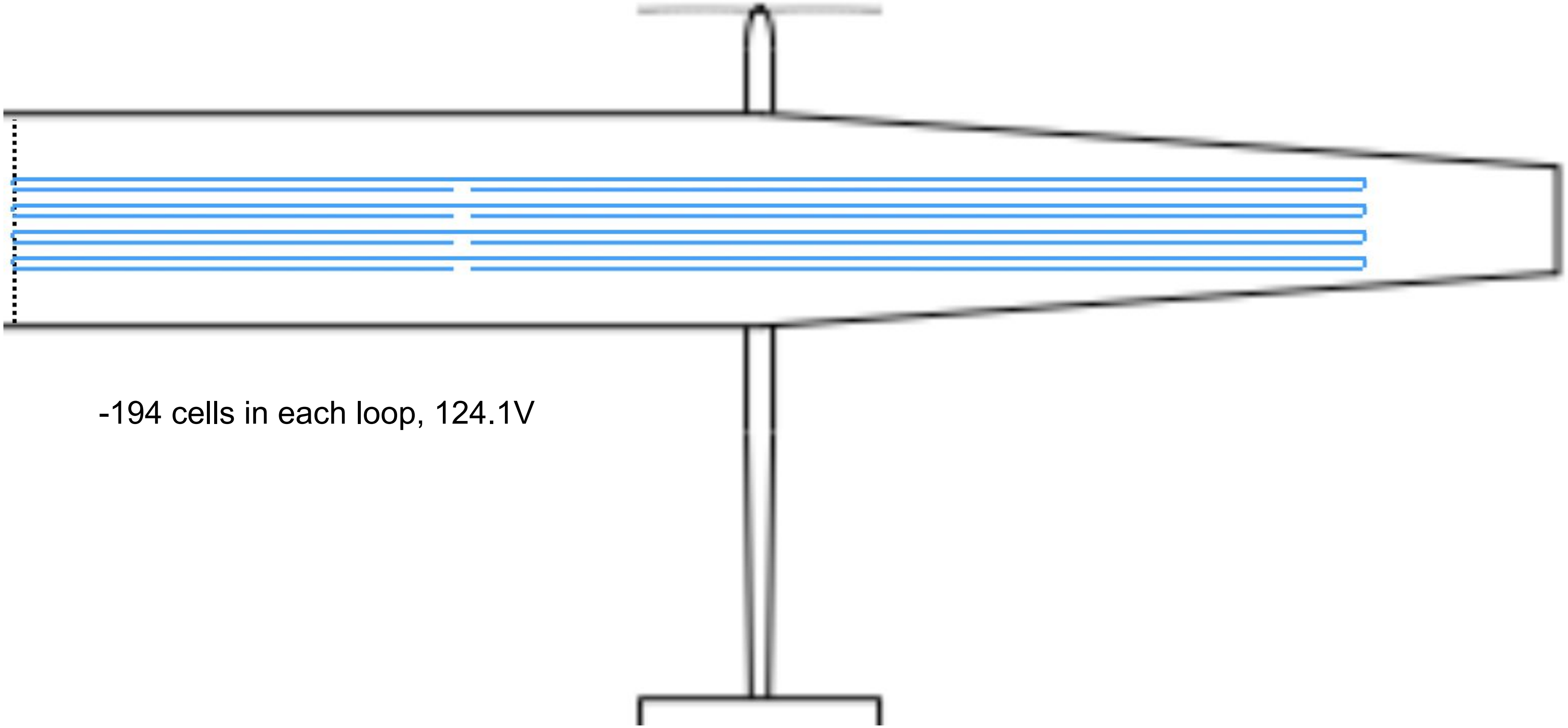
- 14,113 W for 30 days around solstice at Spaceport America
- 23.89 kg system mass (compensated by removing payload)
- $48k total cost of solar cells

Sunpower - Center Loops

-222 cells in each loop, 142.1V



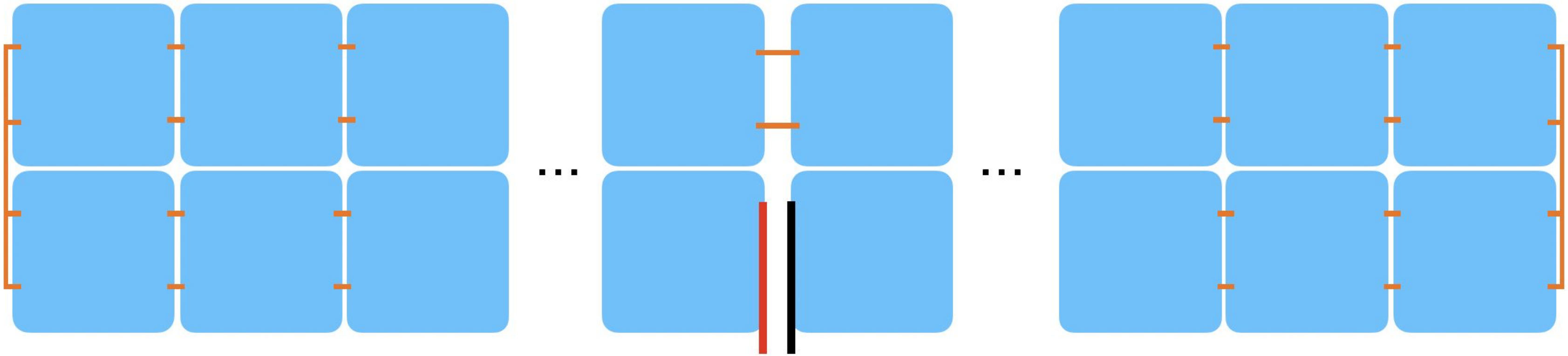
Sunpower - Outer Loops

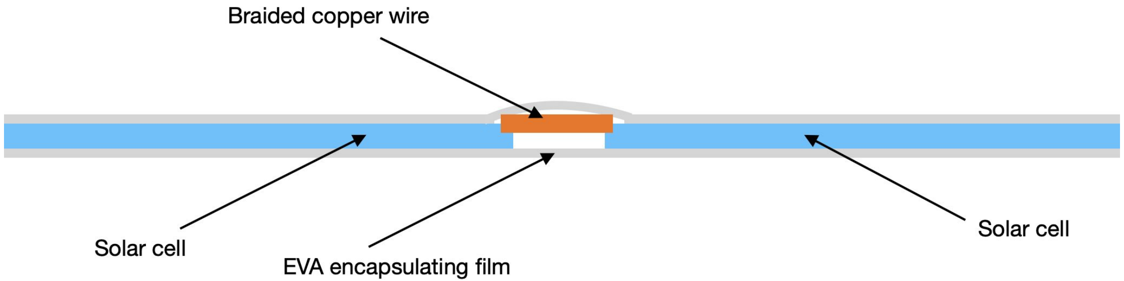


-194 cells in each loop, 124.1V

Sunpower Cell Layout (Demonstrator)

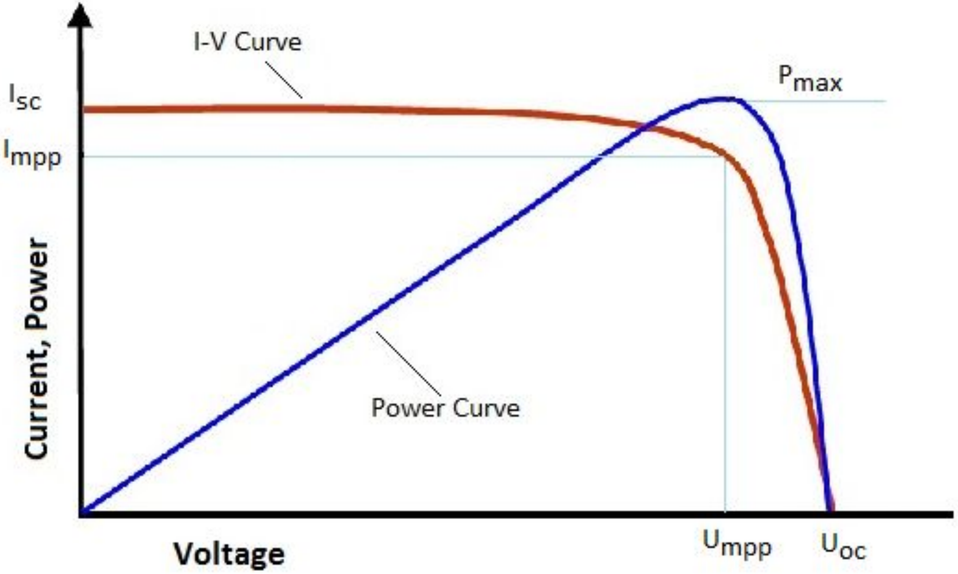
Cell Loop:



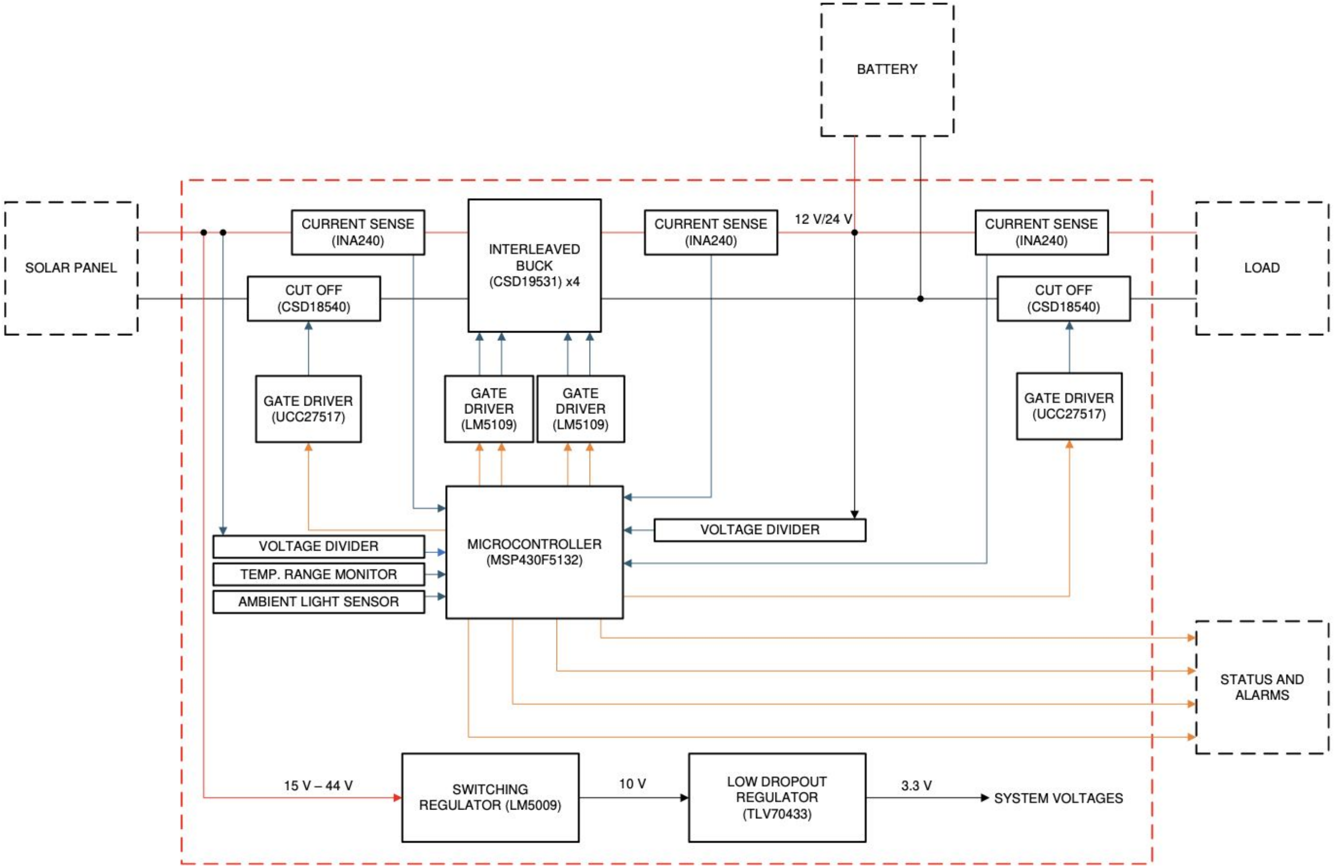


Maximum Power Point Tracking

Controller maintains operation at maximum power point → varies the output voltage



Maximum Power Point Tracker



-Weight-optimized MPPT’s should be 2.3 kW/kg at 95% efficiency

-But: doesn’t exist in off-the-shelf package at voltage and max power we need

-Should integrate our own MPPT: high voltage/high power buck converter + standard MPPT logic controller

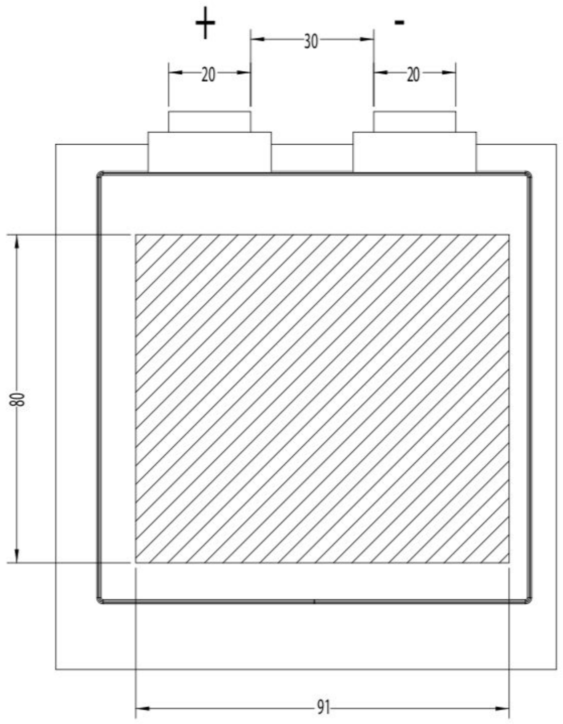
Battery Cell Details

Several potential battery suppliers have been identified with similar energy densities:

Amprius:	500 Wh/kg (lithium-ion)
Ion Storage Systems:	550 Wh/kg (solid-state)
Sion Power:	486 Wh/kg (lithium-metal)

Technical specifications used for designing the battery system

- Energy Density: 450 Wh/kg
- Nominal Cell Voltage: 3.82 V
- Cell Dimensions: 120 x 106 x 10 mm
- Cell Volume: 1.27x10^-4 m^3
- Temperature Range: -10 to 45 °C
- Ideal Temp Range: 20 to 30 °C
- Weight: 158 g

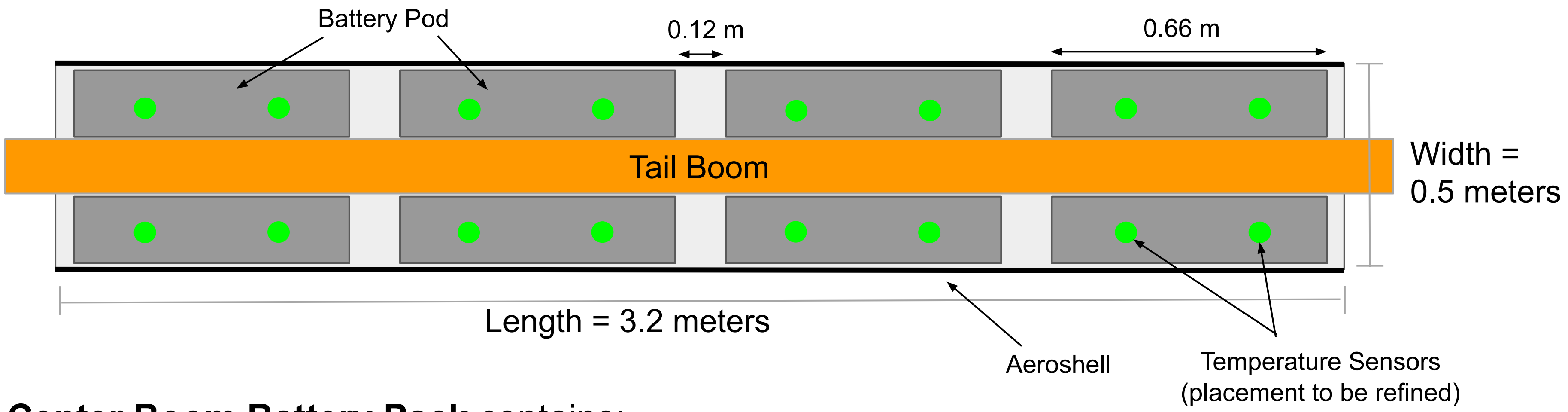


Source: Licerion-1 Cell Technical Specifications

Voltage Bus Change from 270V to 230V

- Now that the config is down from 6 motors to 4
  - The center boom battery pack provides power for 2 motors
  - The outside boom battery packs each provide power for 1 motor
- Therefore the ideal battery configuration is
  - 25 % of batteries in each outside boom
  - 50 % of batteries in the center boom
- However given our 10 battery strings from the previous design, this doesn’t divide evenly
- Move to 230V bus voltage corresponds to 16 strings which will be divided
  - 4 strings per outer boom
  - 8 strings in the inner boom

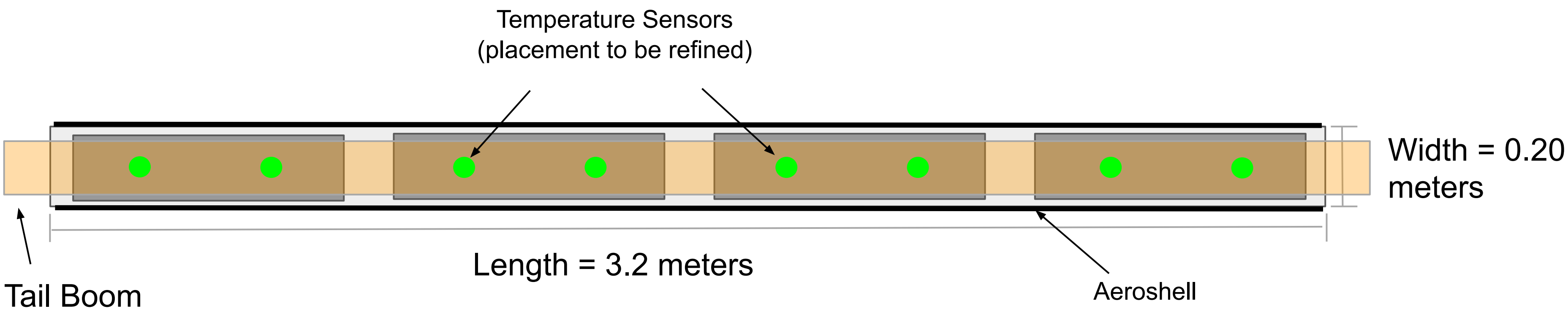
Battery System Layout - Center Boom



Center Boom Battery Pack contains:

- 8 **battery pods**, each corresponding to one **string** of 60 cells
- Powers the 2 inboard motors, mounted to the wing between the center boom and the outside boom
- Pod dimensions are 16x16x66 cm
- Each pod has 2 temperature sensors
- Total battery weight in center boom is 101.12 kg

Battery System Layout - Outside Boom



Outside Boom Battery Pack contains:

- 4 **battery pods**, each corresponding to one **string** of 60 cells
- Each powers corresponding outboard motor, mounted to the boom
- Pod dimensions are 16x16x66 cm
- Each pod has 2 temperature sensors
- Total battery weight in each outside boom is 50.56 kg

Thermal Runaway Considerations

Risk Source:

- *Thermal runaway can result in loss of vehicle*

Mitigation Strategies:

Operational Procedures:

- Vetted (dis)charging operational procedures

Quality Control:

- Perform quality control of each battery cell to identify any internal inconsistencies that may cause shorts
- Sort cells into strings by their (dis)charging characteristics

Design:

- Opening on battery pods for thermal runaway vent

Monitoring:

- Anomalous voltage and current reading at the pack level
- Active thermal control of battery pods (heat and cool)

Current Battery: Licerion-1 Cell
Source: Sion Power Spec Sheet

Further design dependent on battery selection

Thermal Management of Battery Packs

Operational temperature range of Sion Power’s Licerion batteries: **263-318 K**

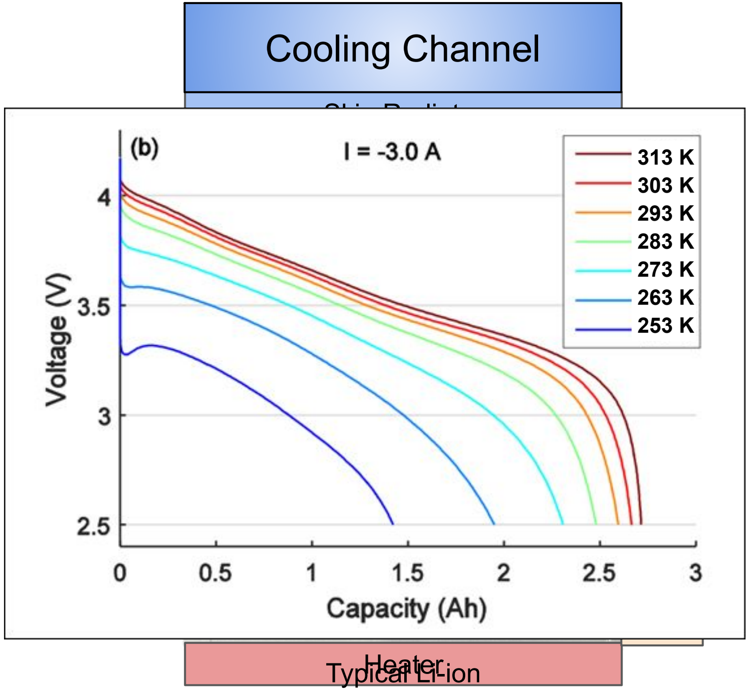
Ambient temperature at altitude: ~**220 K**

➔ **Design battery pods for cold environments:**
  - **Provide insulation + cooling**

Thermal Management Control Knobs:

➔ **Skin radiators** in a ducted cooling channel with a variable exhaust nozzle for heat dissipation

➔ *Open trade*: Resistive heaters to supply heat



Typical Li-ion
Source: Battery University
Current Battery: Licerion-1 Cell
Source: Sion Power Spec Sheet

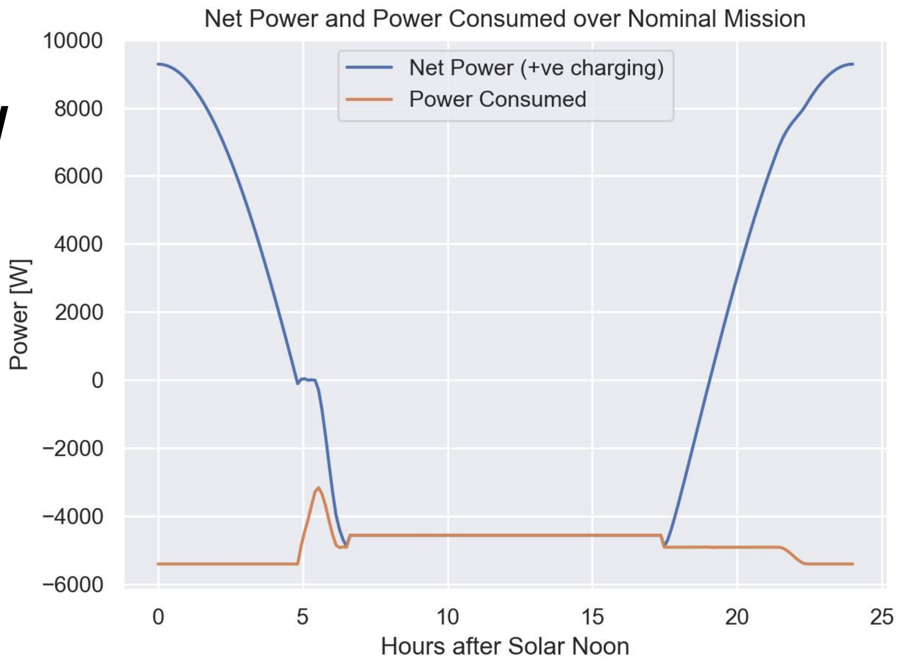
Thermal Demands of Battery Pods

Heat Generation:

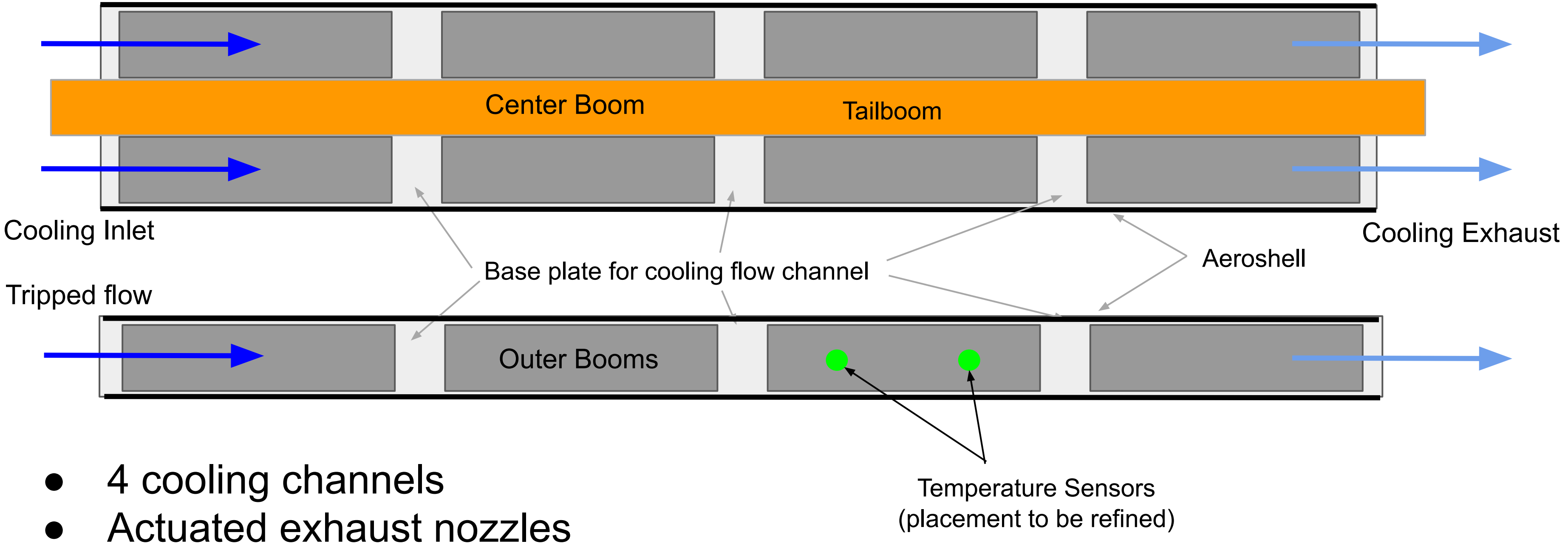
- Joule heating from (dis)charging
- Typical losses of **2.5%** with **~ C/8**
- Maximum battery power throughput **9 kW**
- Minimum battery power demand **0 kW**
  - Min aircraft demand 3.2 kW
- Joule heating per pod **5-14 W**

Thermal Needs:

- Steady state heat dissipation **≤ 14 W** per pod
  - 60 cm x 10 cm skin radiator
- Open trade: Resistive heating **0-9 W** per pod
  - 60 cm x 10 cm heater

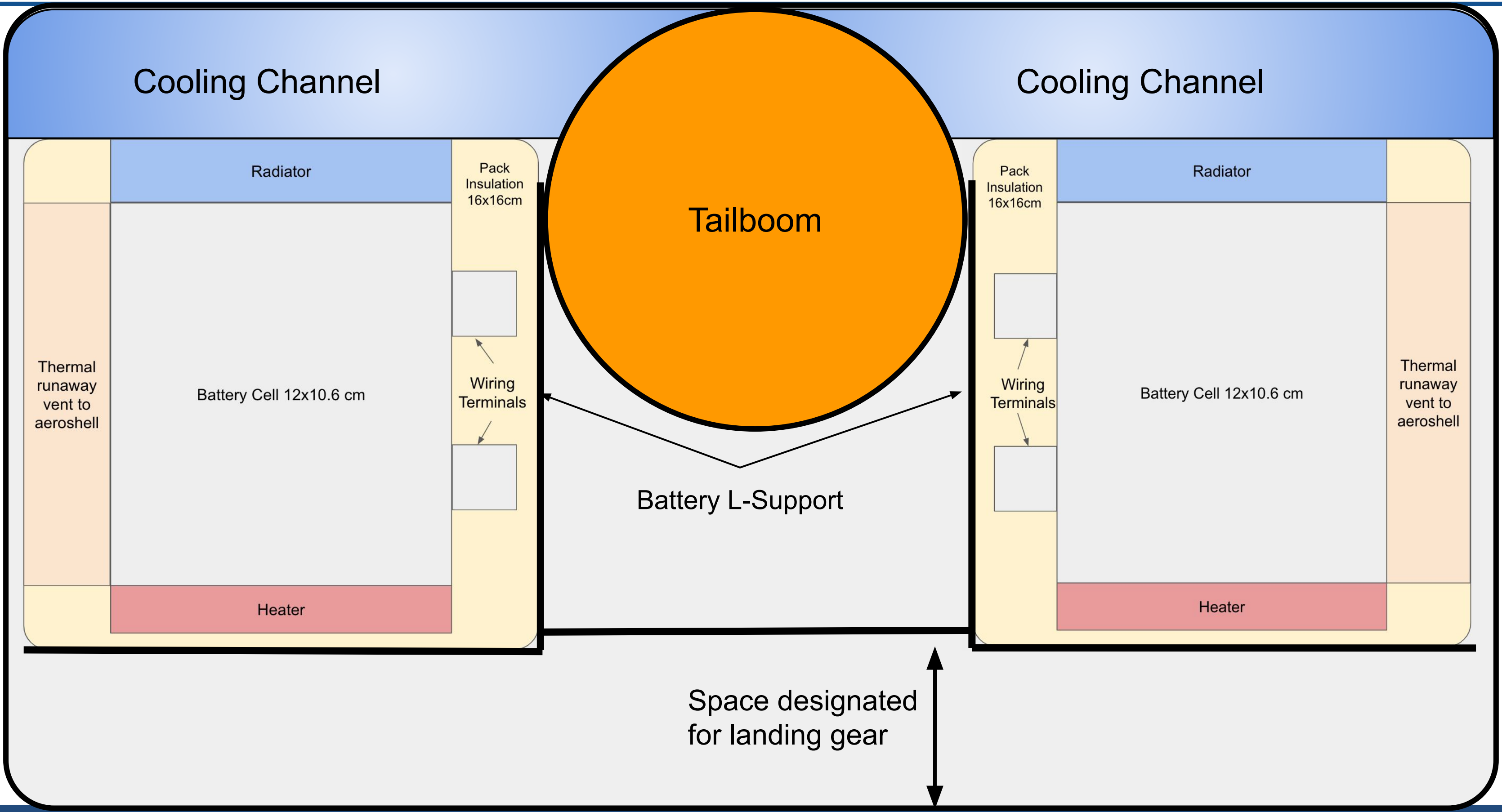


Thermal View of Battery Pods

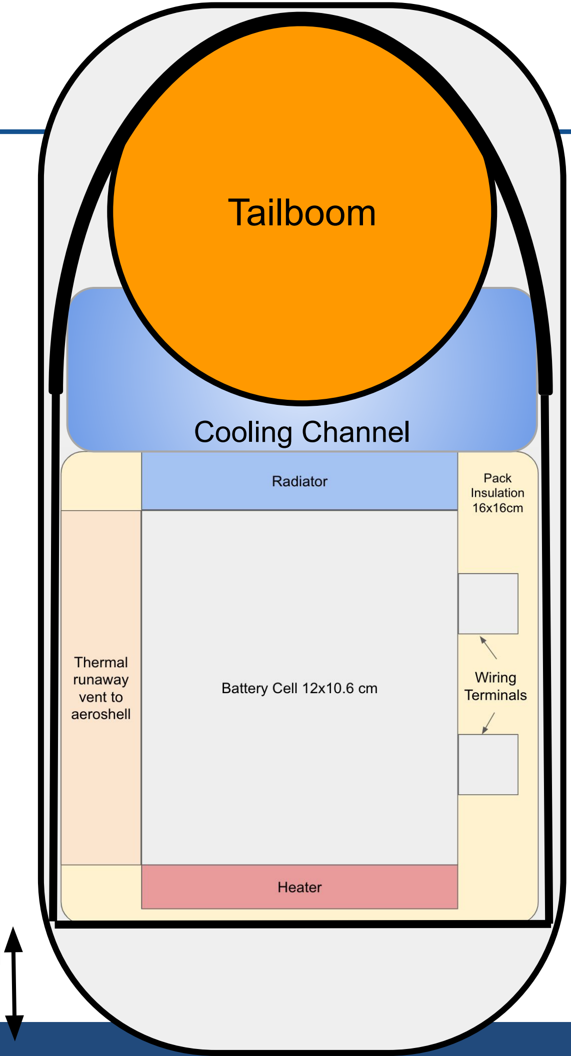


- 4 cooling channels
- Actuated exhaust nozzles
- Lower heat dissipation capability at exhaust

Center Boom Cross Section



Outer Boom Cross Section



Total drag of cooling system: ~0.07%*

**Total drag w/o cooling: 100 N*

* $V_{cooling} \sim V_{\infty}/3$

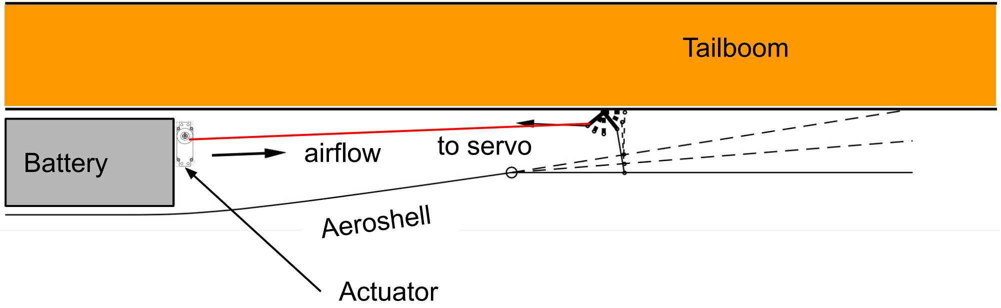
Space designated for landing gear

Cooling Channel Exhaust Nozzle

- Pegasus PA-R-135-4 Servo Actuator
  - Torque capability: 30 Ncm
  - Partial opening capability
  - **65 gr**/each

- Push arm, ‘L’ bracket, hinges, mounting structure and thermal insulation: ~**65 gr**

- Four cooling channels:
  - Total mass: ~**520 gr**



Weight Breakdown of Battery Pack

	Per pod (x60 cells)	Total (x16 pods)
Battery Cells	9.5 kg	152 kg
Wiring	0.01 kg	0.16 kg
Insulation	1.2 kg	19.2 kg
Structural Casing	0.72 kg	11.5 kg
Skin Radiator	0.11 kg	1.8 kg
(Open trade: Heaters)*	(0.08 kg)	(1.3 kg)
Thermal Paste	0.05 kg	0.8 kg
Thermistor	0.002 kg	0.032 kg
V and I Sensors	-	0.1 kg
Microprocessor/FPGA	-	0.1 kg
Cooling Duct	-	0.2 kg
Exhaust Nozzle	-	0.52 kg

Per pod: **11.6 kg**
Total: **186.4 kg**
Modeled mass: **202.3 kg**
Delta: **15.9 kg (8%)**

*Weight not included

Mass Budget of Power System

Component	Actual Component Mass	Modeled Mass	Max Power/Energy Rating
Solar Arrays & MPPT	20.5 kg	22.9 kg	6 x 2.5 kW = 15 kW
Battery Packs, incl. Thermal	187.3 kg	202.3 kg	60 x 16 x 71.1Wh = 68.3 kWh
Thermal Management	-	-	144 W
Wiring & DC-DC Converters	6.4 kg	6.4 kg	Converters: 700 W (each, triple red.)
Total Weight	**214.2 kg**	**231.6 kg**	**-**

Delta: 18.3 kg (8%)

Power System Risks

Risks	Strategy
A. Thermal runaway of a battery cell/pack	Prevention, active thermal control and monitoring of string voltages and amperage. Develop vetted (dis)charging operational procedures of batteries. Mitigation, ensure off-gasses from thermal runaway are routed out of the aeroshell. Remaining battery strings sized to ensure vehicle can safely return to base.
B. Thermal management of battery packs	Through further modeling, analysis and validation testing to size skin radiator and cooling channel for heat dissipation, and refine an active heating solution. Requires selecting battery supplier and understanding internal resistance and chemical heat generation.
C. Battery supplier can't supply promised technology	By designing system to energy density below promised value. By carrying forward several potential battery suppliers with similar energy densities.
D. Batteries drop below design pressure	Design battery pods to compress pods, ensuring sufficient pressure is applied at altitude.
E. Cost of solar cells	Carry a secondary supplier (SunPower) for the demonstrator mission as a low cost alternative. Continue researching various solar cell suppliers to find potential donors.

Power System Risks

Risks	Strategy
F. Electrical breakdown of atmosphere	Rigorous environmental testing of DC-DC converters, maximum power point tracker, motor controllers, motors, batteries and between solar cells and wing surface in relevant environment.
G. Battery depth of discharge exceeds 15% (TBR)	Through power generation and consumption modeling. Carry a power storage margin. Utilize Battery Management Unit to monitor state of charge.
H. Bus/battery voltage drops below 230 V (TBR)	Power regulation circuitry capable of operating over large range of voltage. Essential systems (avionics) can tap into power from three unique battery packs.
J. Solar Panel Mounting	Consult with experts in the industry. Acquire sample cells to start developing procedures and experience of mounting solar cells to a comparable structures.
K. Solar cell damage due to wing compliance	In parallel with testing of pressure sensitive adhesive evaluate the structural soundness of solar cells and their risk of damage due to wing compliance

Design Overview & Performance

Aero & Structures

Power

Propulsion

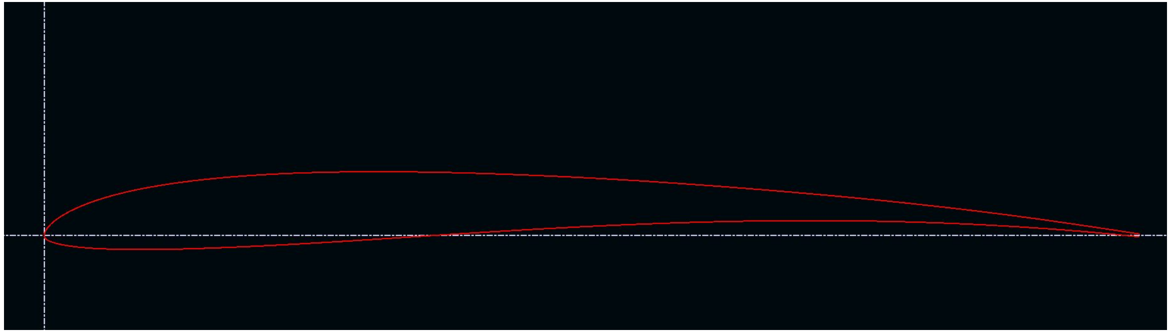
Avionics

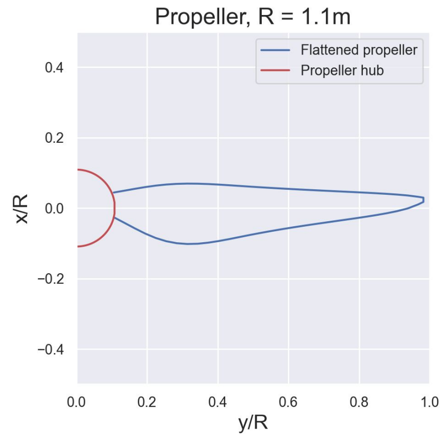
Flight Operations

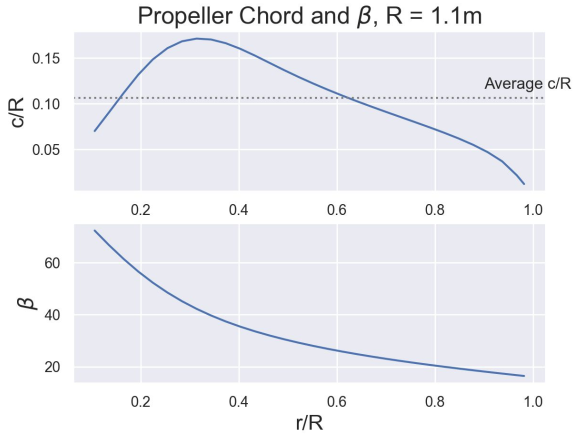
Future Development Plan

Propeller Design

- QMIL propeller design
  - 2 blade, low Reynolds Number airfoil (30,000 - 60,000)
  - High cd at negative cl for increased windmill descent drag
- Design considerations
  - Trade between propeller efficiency and motor weight
  - Maximize efficiency over 24 hour altitude cycling trajectory
  - Induced efficiency ~ 0.93

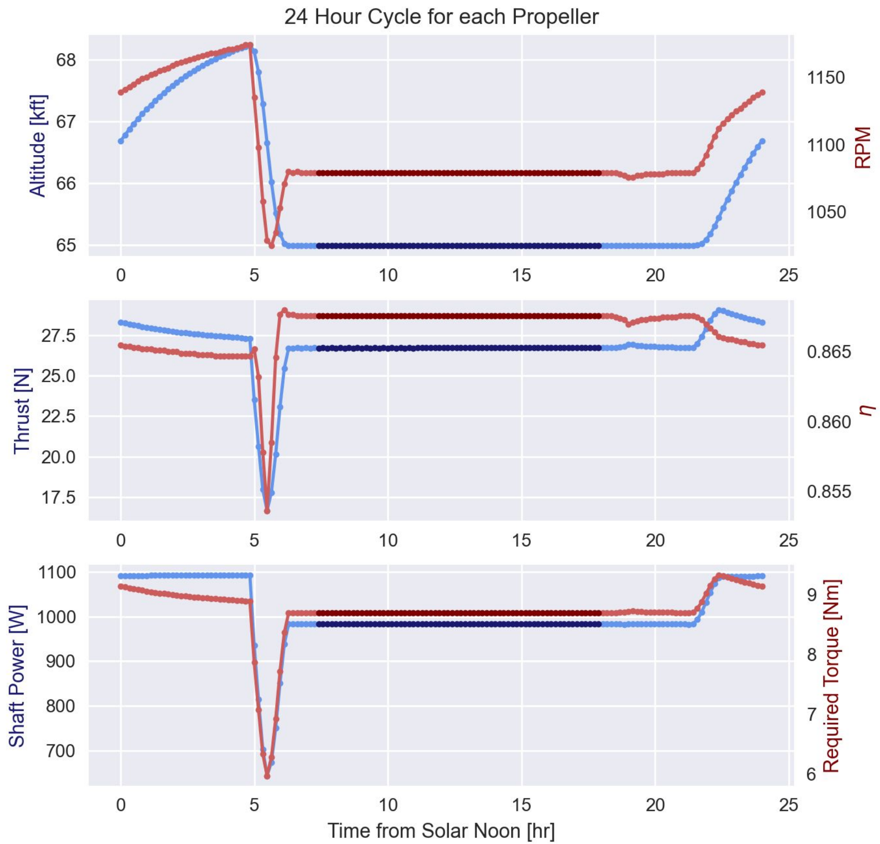






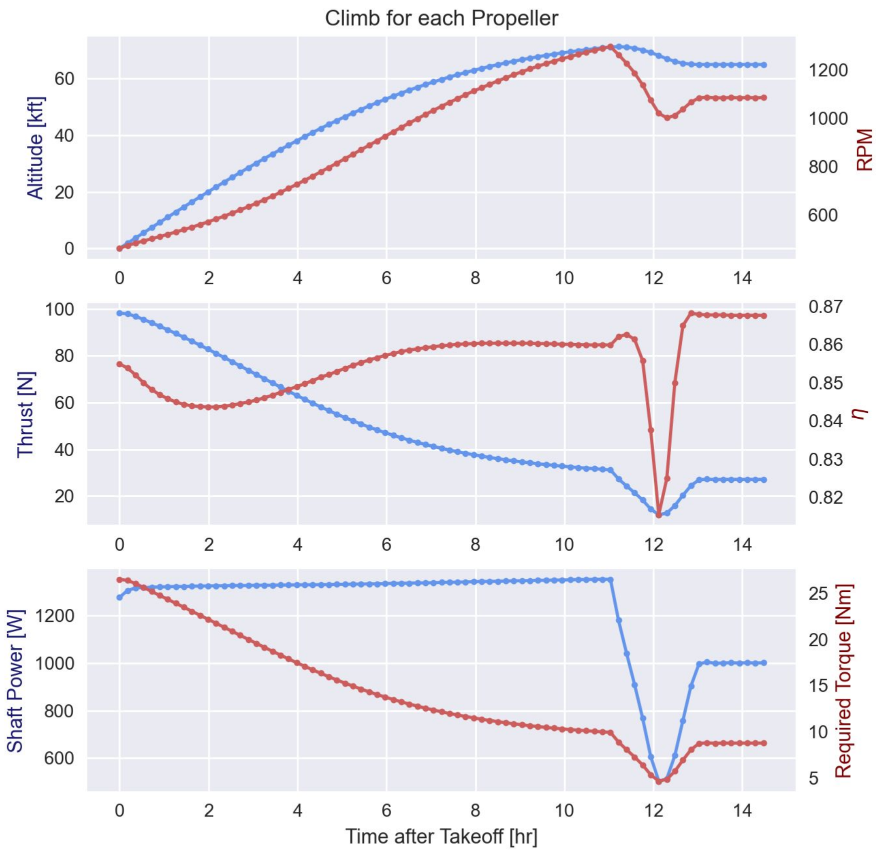
Propeller Cruise Performance

- Qprop analysis using altitude, airspeed, and thrust time data for 24 hour cycle
- Calculate efficiency, shaft power, rpm, torque, etc. over 24 hour cycle
- Feed efficiency back to Qmil design
- Average prop efficiency: 86.7%



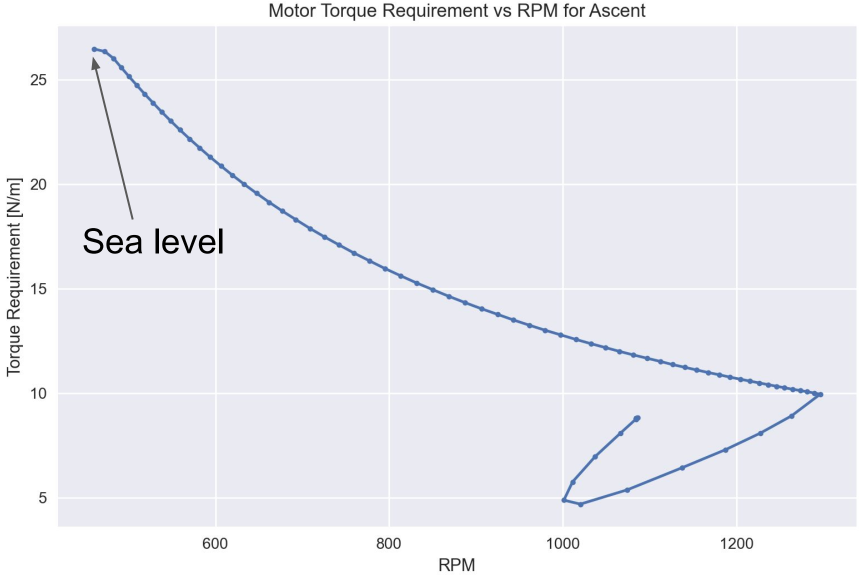
Propeller Initial Climb Performance

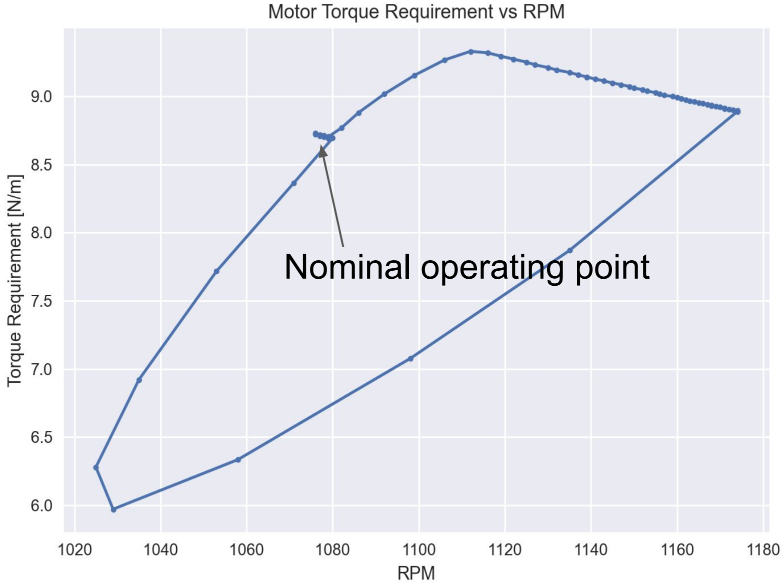
- Max RPM: 1300 RPM
- Max Shaft Power: 1.36 kW
- Max Torque: 26.5 Nm
- Average efficiency over climb: 85.5%



Prop Motor Matching

- Torque requirements at altitude: 6 - 10Nm
- Torque requirements for ascent: 5 - 26.5 Nm
- Nominal operation at ~ 1100 RPM
- Required Kv ~ 6 RPM/V





Motor Requirements

To meet the mission's needs, the following motor requirements were established:

- Lightweight construction - Carbon fiber and composites
- Efficient performance at low torques - 95% at 9 Nm
- Double the performance at sea-level - 30 Nm, 4.5 kW
- High bus voltage - 230V

Custom Motor Specifications

All specifications are per motor unit:

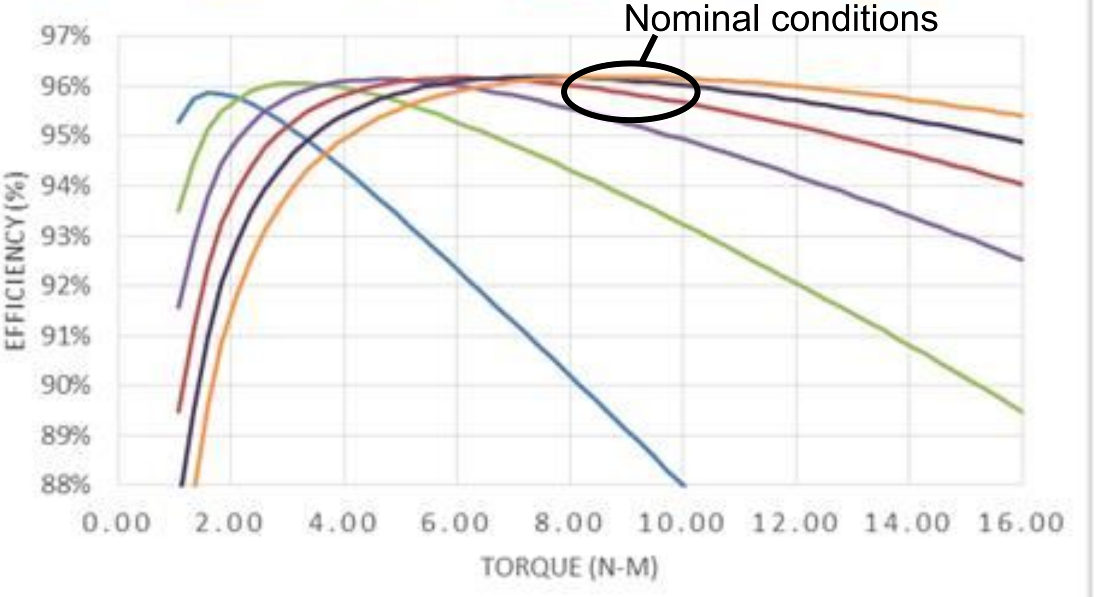
Altitude	Sea level	65,000 ft
Continuous Torque	30 Nm	15 Nm
Power	4.5 kW	2.25 kW
Speed	1500 rpm	1100 rpm
Kv	6 RPM/V	
Outer Diameter	0.25 m	
Rotor + Stator mass	2.4 ± 0.24 kg	

Source: ThinGap

Motor Performance

95.5% efficiency at altitude and nominal 1000 RPM

RPM	
250 RPM	
500 RPM	
750 RPM	
1000 RPM	
1250 RPM	
1500 RPM	



Source: ThinGap

Motor Mounting

Motor "Pod" Breakdown:

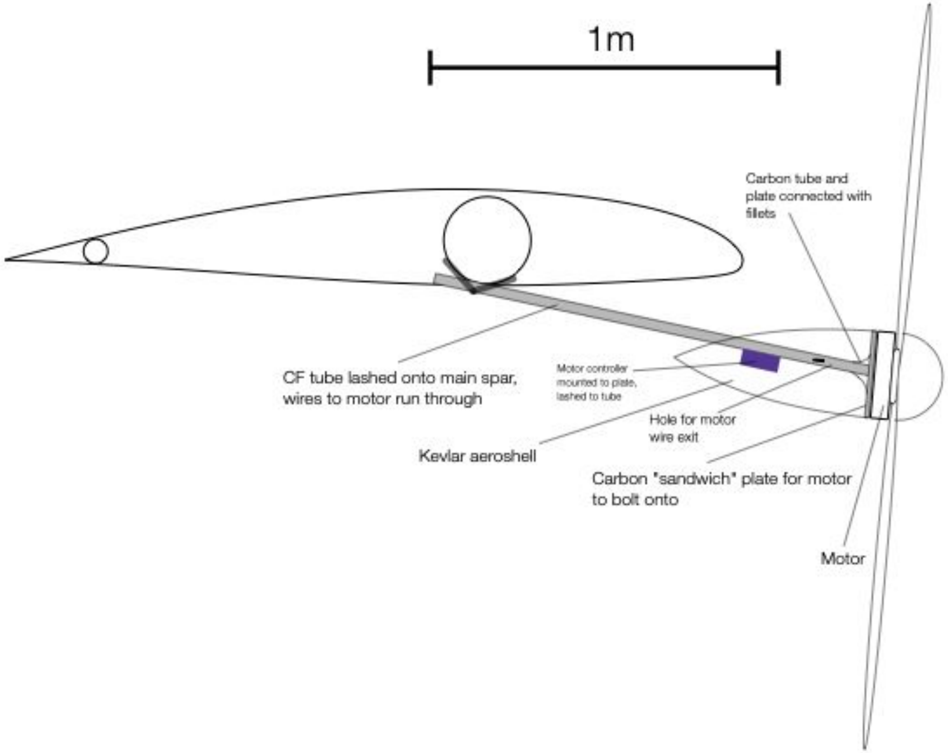
2.4 kg motor

2.4 kg mount

0.5 kg propeller

= 5.3 kg total

6.5 kg modelled weight →
1.2 kg remains for motor controller, faring, cooling flap, etc.



Design Overview & Performance

Aero & Structures

Power

Propulsion

Avionics

Flight Operations

Future Development Plan

Avionics Topics

System architecture/overview

Autopilot

Sensors, actuators, radiators, antennae, etc.

Elaborate on decision making/communication pathways, what is processed where

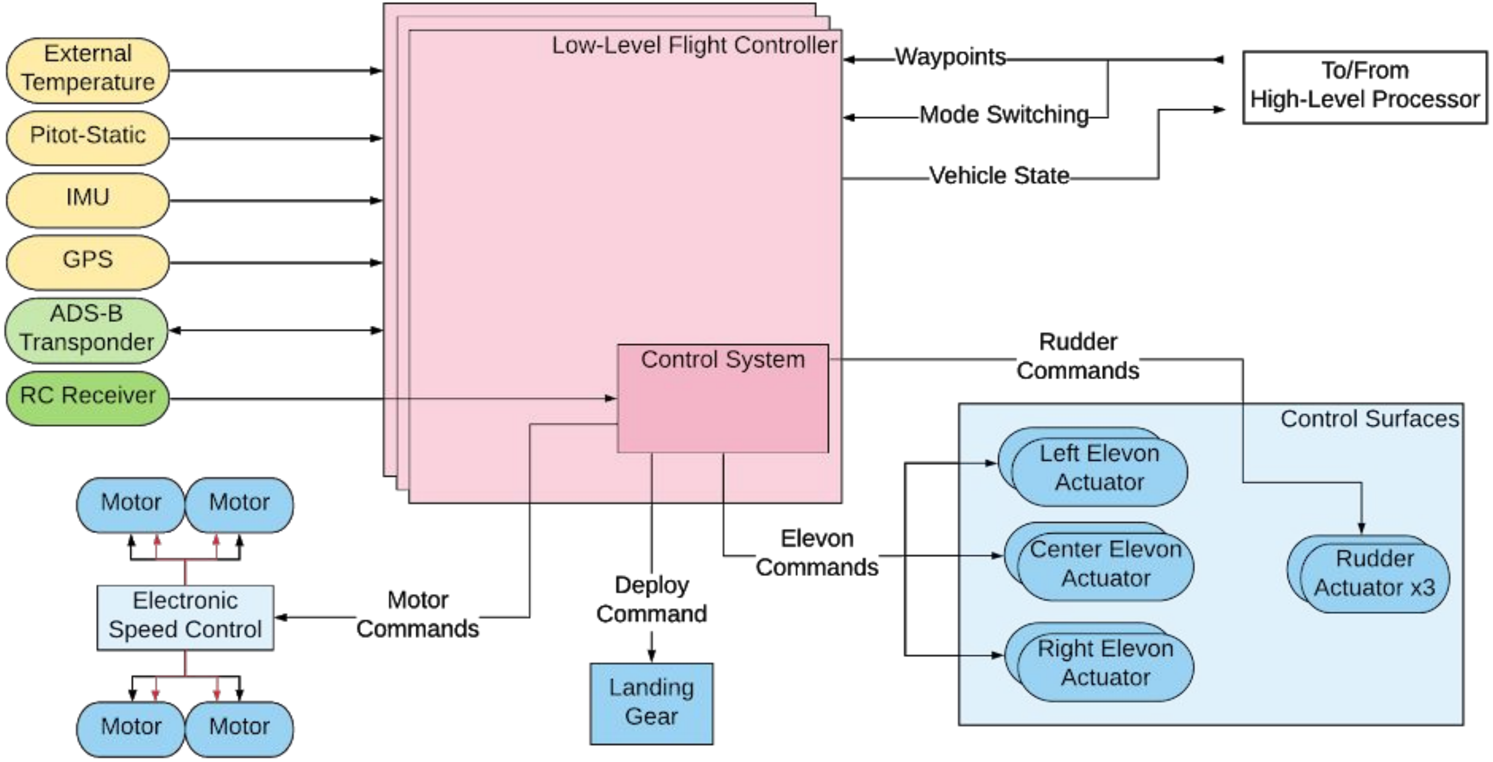
Ground Station

Weight breakdown

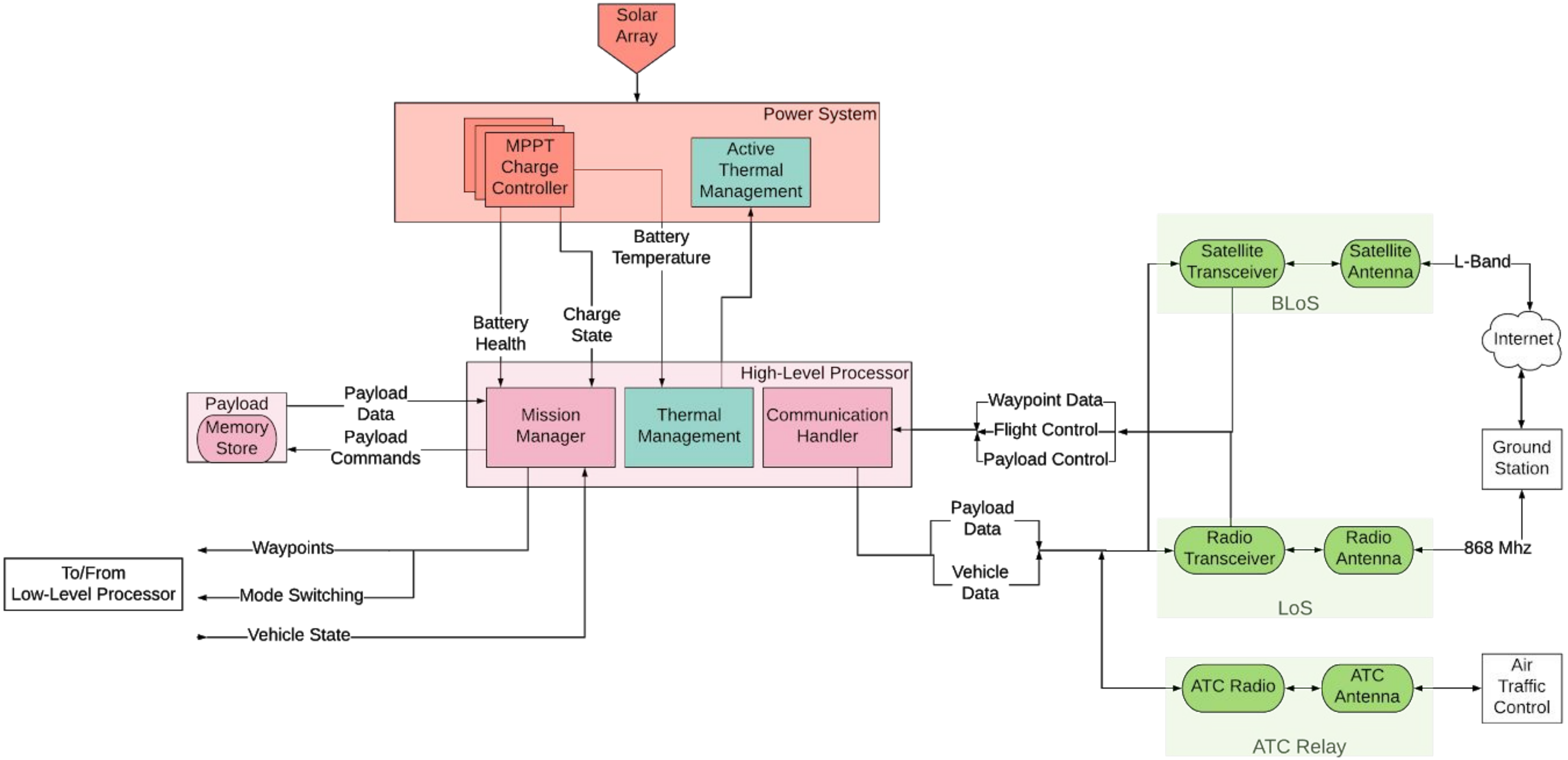
Power demands by components (min & max values)

Avionics System Risks

Avionics Architecture: Low-Level



Avionics Architecture: High-Level



Autopilot/Low-Level Processor

For the autopilot, we use Embention's Veronte 4x Redundant Autopilot.

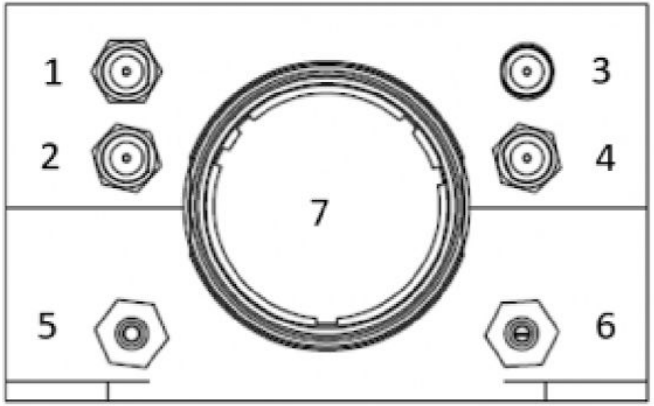
- Triple redundant sensing
- Double redundant processing

VERONTE AUTOPILOTS

Specifications

- Mass: 660g (including enclosure)
- Temperature range: - 40°C to + 65°C
- Voltage range: 6.5 - 36V
- Power: 17 W

Interfacing with Flight Controller



Veronte Connectors

Index	Connector
1	LOS SSMA connector
2	GNSS1 SSMA connector
3	M2M SSMA connector
4	GNSS2 SSMA connector
5	Static pressure port (Fitting 5/64in)
6	Dynamic pressure port (Fitting 5/64in)
7	68-pin connector

Beyond Line of Sight Communication

Air-side satellite communication module consists of:

Transceiver: Iridium Certus 9770

+

L-Band Blade Antenna: Verdant JL-50

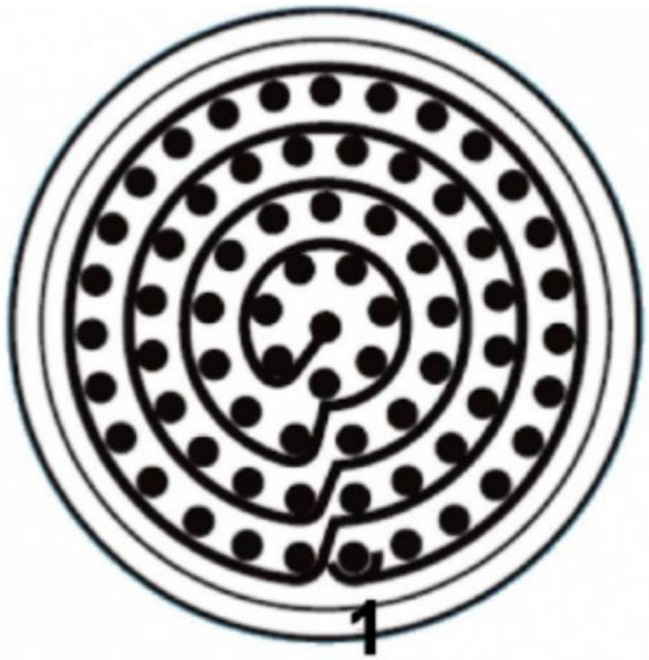
- L-Band speeds ranging from 22 Kbps transmit to 88 Kbps receive.
- Voice support for interfacing with the ATC relay

Local C2 (radio 868MHz)

Airborne ~5dBi blade antenna

Veronte PCS Pole

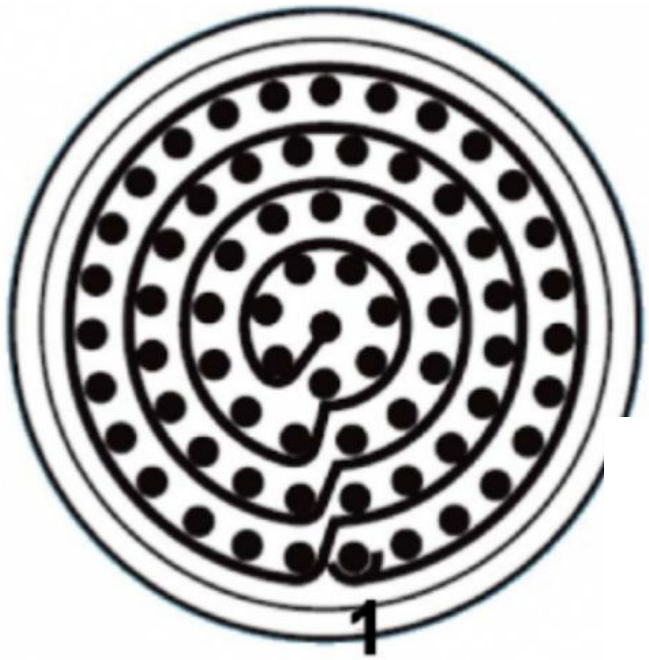
68 Pin Connector: System Status



Pin 42: Deadman Signal

Pin 43: !SystemOK (0 if OK and 1 if not)

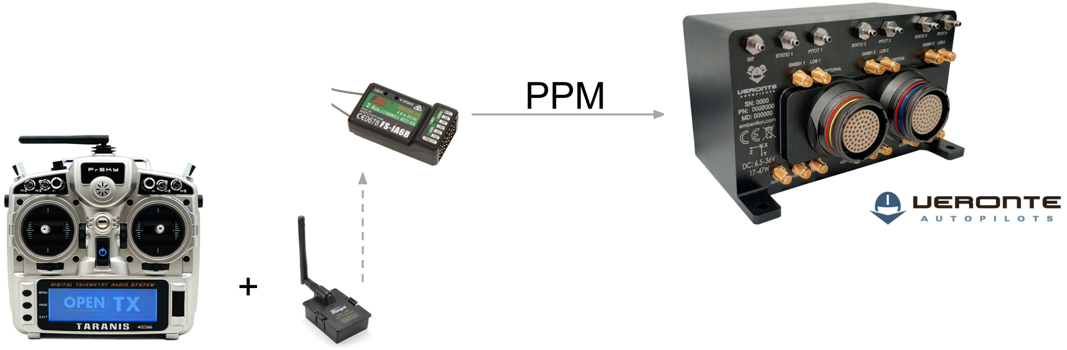
68 Pin Connector: RC Connection



Digital Input Pin (Pins 1-8, 10-17 and 55-58): PPM Input in

Pin 55: Ground

8-Channel RC with channel 8 reserved for auto/manual switch



Not to scale

B/LOS Switching

Inputs

- Data packet from ground station at specified rate

Medium

- Radio (LOS) link

Handler

- HLP Communication manager

Logic:

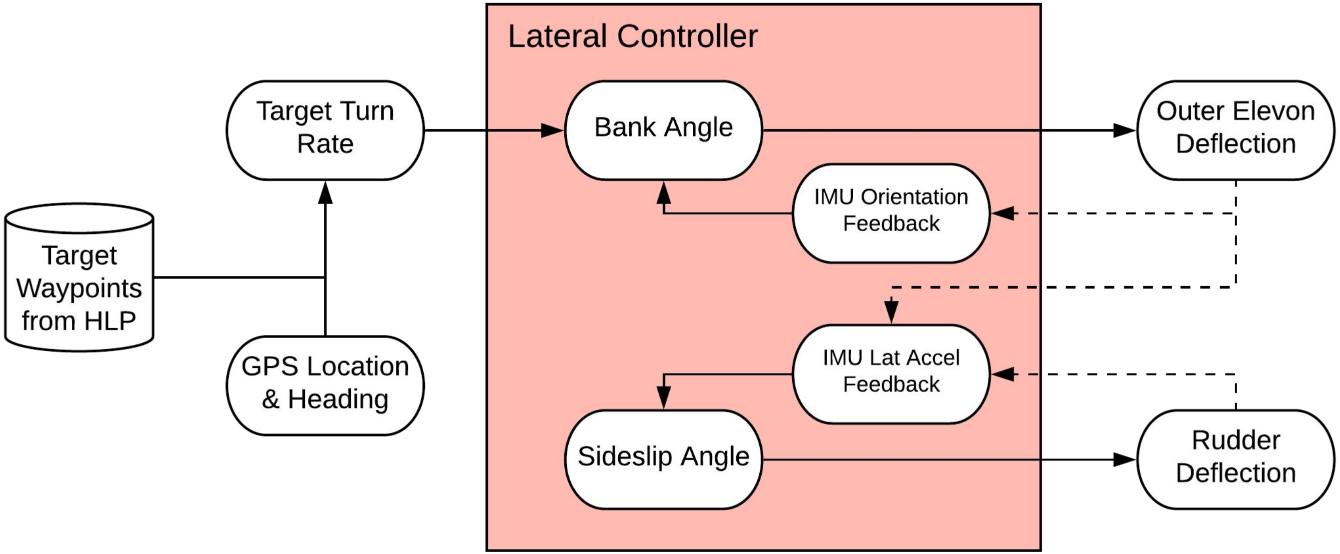
- If package is still being received, still within line of sight
- Data rate drops below some threshold → lost LOS
- Timeout on data reception → lost LOS
- Distance from start point exceeded → lost LOS

Output/Effect

- Switch to BLOS

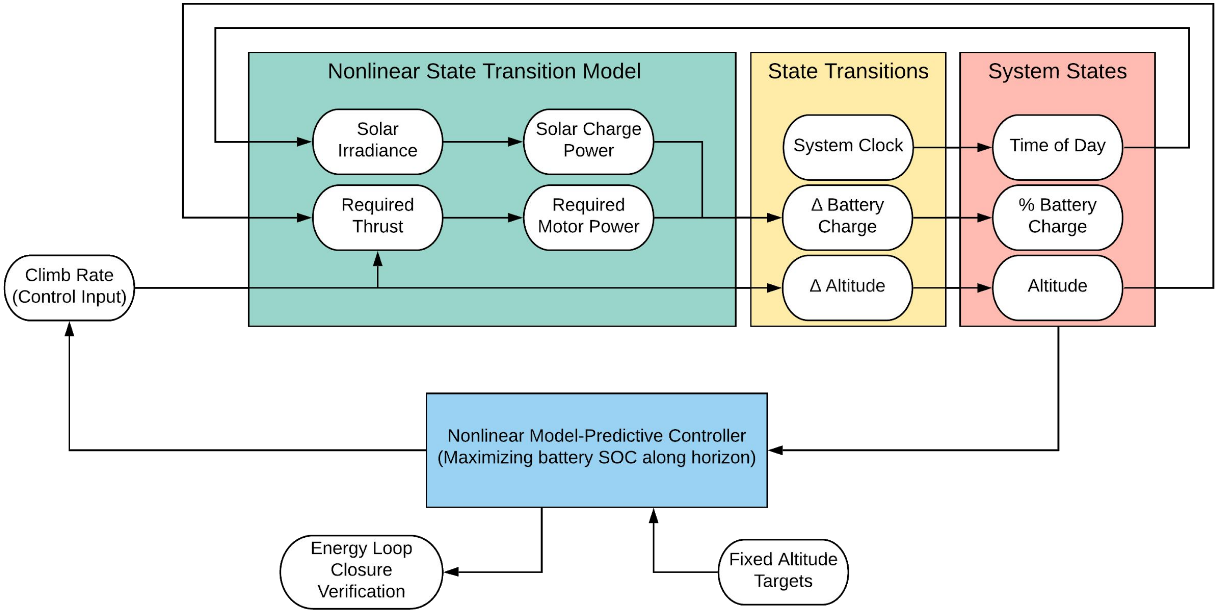
Control Scheme - Waypoint Following

Target waypoint from GCS commands a turn rate, which the Lateral Controller uses to actuate Elevons and Rudders.



Control Scheme - Altitude Control

A Model-Predictive Controller is used to control altitude over the 24 hour cycle and verify energy loop closure.



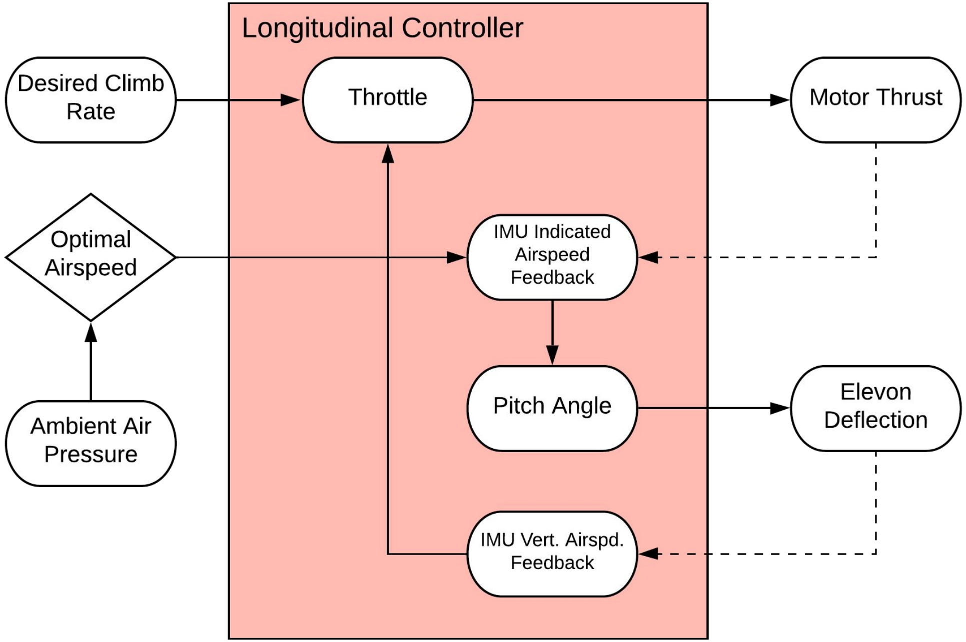
MPC Constraints:

- Altitude:
  - Min: 60,500 ft
- Climb rate:
  - Max: 0.58 m/s
  - Min: -0.9 m/s
- Battery SOC:
  - Max: 100%
  - Min: 15%
  - Critical: 10%

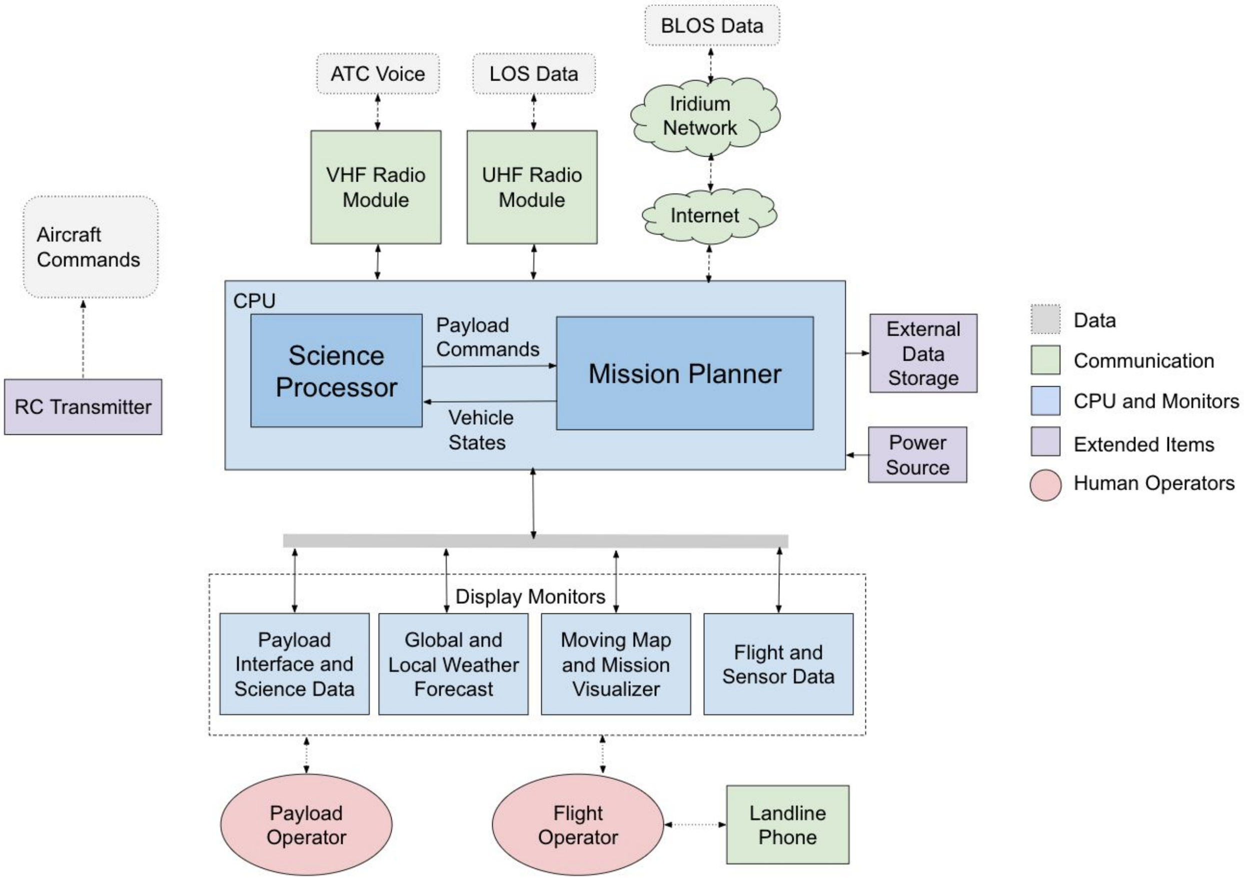
Control Scheme - Thrust & Airspeed

Climb rate commanded by the altitude MPC controls throttle output.

Pitch angle is regulated to maintain an optimal airspeed.



Ground Control Station (GCS)



GCS Control of Aircraft

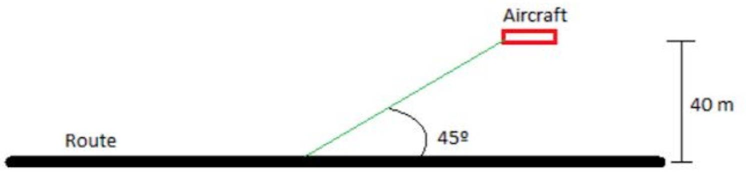
Veronte Pipe software

- Supports major OS including Linux
- Used as GCS software to communicate with Aircraft

Natively Supported Modes: Climb

Input Parameters:

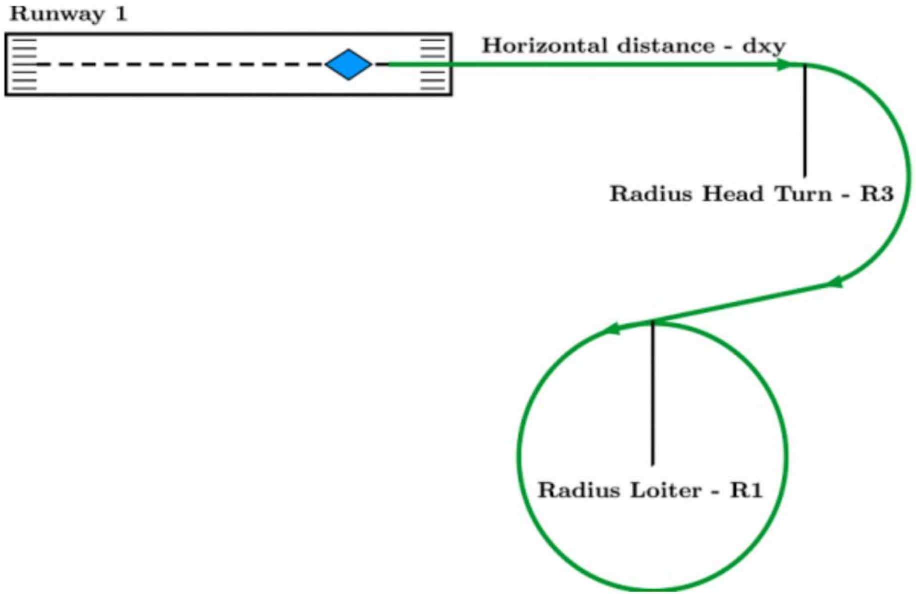
- Line Attraction
- Set height mode:
  - 2D (ignores altitude)
  - 2.5D (goes to target point in diagonal fashion)
  - 3D (not supported for fixed-wing)
- Set Limit Acceleration
  - Due to structural constraints
- Set speed
  - IAS at which aircraft climbs
  - Waypoint speed (optional)



- Height
- Route (next slide)

Climb Route Parameters

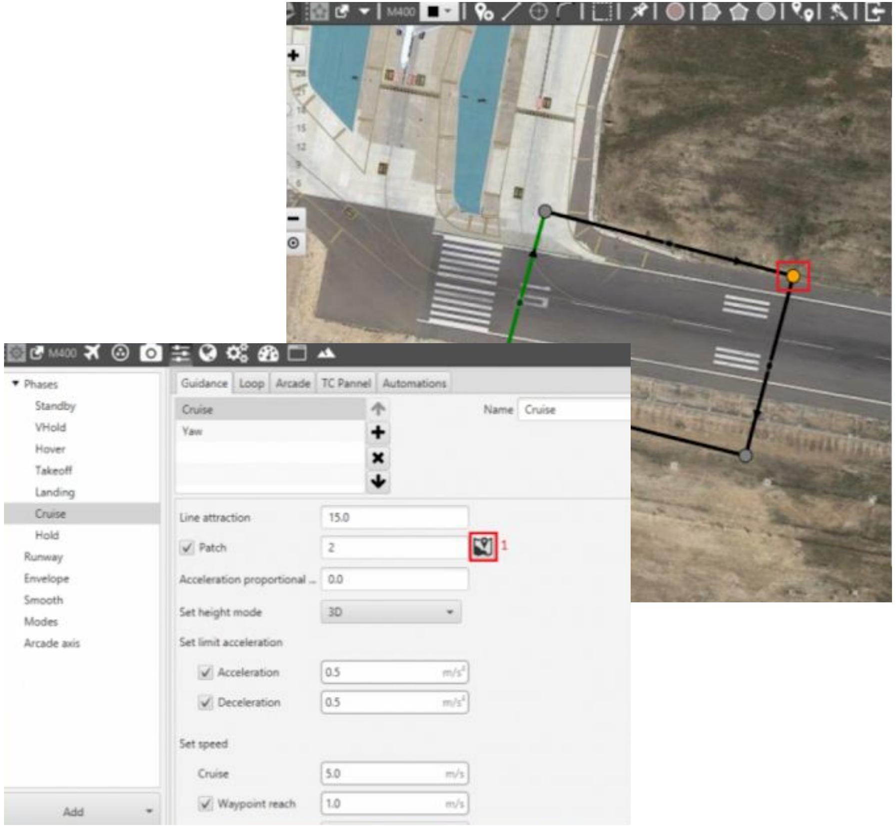
- Runway
- Flight Path Angle: angle at which the aircraft will climb.
- Horizontal Distance: distance to the start of the circular climbing path.
- Radius Head Turn R3: radius of turn made to head the airplane towards the loiter direction.
- Radius loiter



Natively Supported Modes: Cruise

Input Parameters

- Patch:
  - A defined region the aircraft is directed towards
- Same parameters as climb excluding climb route

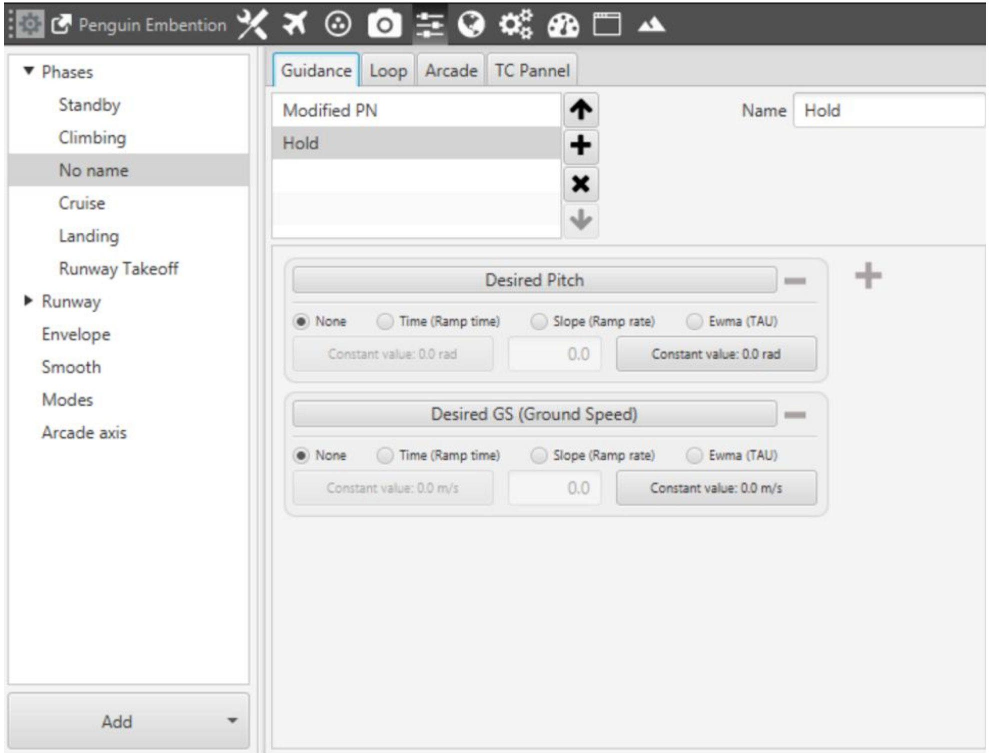


Natively Supported Modes: Hold

Hold any given control variable at the given value

Hold configuration:

- None: Simple hold
- Time: Changes after fixed time
- Slope: Changes with given slope
- EWMA: Exponential change



Natively Supported Modes: Landing

Input parameters:

- Height mode (2D, 2.5D, 3D)
- Set speed
  - With acceleration/deceleration limit
- Loiter and runway positions
- Trajectory distances
  - Similar to climb route parameters
- Trajectory flight path angles
- Trajectory velocities

Native Pipe Attribute: Events

Action triggered by:

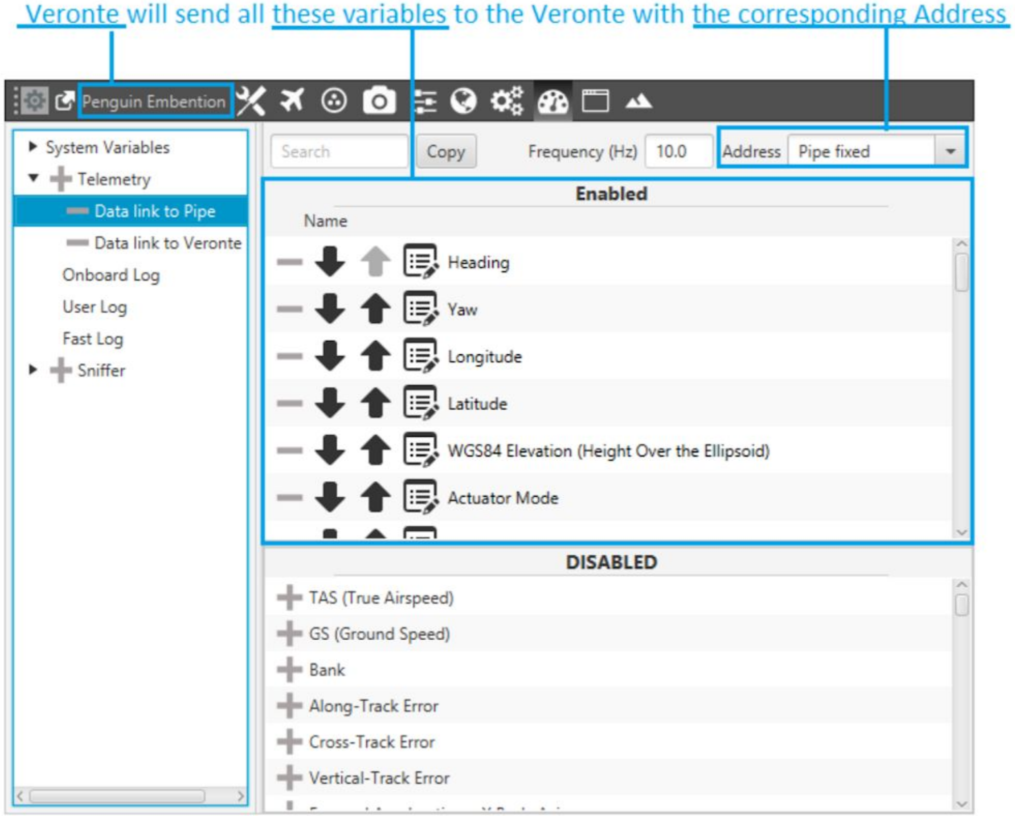
- Phase
- Variable
- Alarm
- Button
- Mode
  - Auto
  - RC
  - Mix
- Route
- Timer

Useful for configuring

- Contingencies
- Rapid response actions
- Scheduled actions

Data link with Flight Controller

- Configure which variables to be sent
- Configure where data is sent
  - Support for multiple destinations



Telemetry Configuration Menu

Avionics Weight Breakdown

Item	Name & Vendor	Mass [kg]
Actuators (x6)	Pegasus: PA-RR-260-9 Redundant Servo Actuator	3.45
High Level Processor	Versalogic: Harrier Embedded Processing Unit	0.28
Flight Computer	Embention: 4x Redundant Veronte Autopilot	0.66
2.4 GHz Radio Antenna + Transceiver	Embention: Veronte Autopilot Kit	0.09
Satellite Transceiver Modem	Iridium: Certus 9770	0.185
L-Band Blade Antenna	Verdant: JL-50	0.055
Emergency Location Transmitter	Sarasota Avionics: Artex ELT 345	0.908
GPS Antenna	Comant Cobham CI-428-200 Waas GPS Antenna	0.176
ATC Transponder	Sagetech: XPS-TR Mode S	0.1
Transponder Antenna	Aircraft Spruce: Comant DME / Transponder CI-105	0.109
VHF Radio Module	Flightline FL-760A + Comant CI-291	0.68
Signal Wiring	Signal avionics wires	0.6
Actuator Power Wiring	1 mm^2 section copper wires	5

Total: 12.153 kg

Avionics Power Requirements

Item	Voltage Range [V]	Power [W]
Actuators (6)	18 - 32 (Typical: 24)	96 (average)
High Level Processor	8 - 17 (Typical: 12)	11.5
Flight Computer	6.5 - 36	17
Satellite Transceiver Modem	12 +/- 2.5	5
VHF Radio	11 - 33	5
GPS Antenna	4 - 24	1.5
ATC Transponder	10 - 32	8
Signal Wiring	N/A	6
Total		**150**

Design Overview & Performance

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Future Development Plan

Flight Operations Topics (feel free to reorder!)

Testing/Launch/Takeoff location, specifics of 9NM9

Mission Overview

Failures & contingency plans (make graphics?), discuss climb rate capabilities and gliding (descending) capabilities

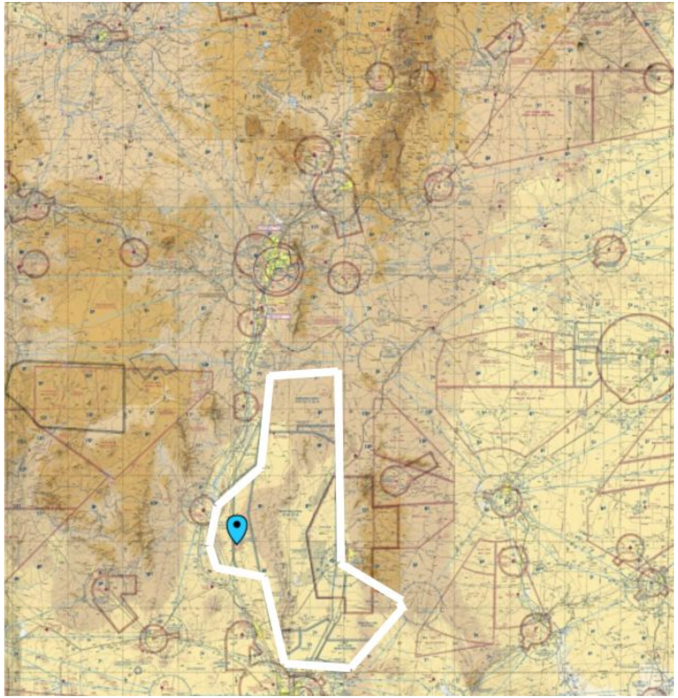
Take off components & landing gear (do we have a drag plate??)

Take off (time constraint, weather constraint, need to get ATC approval before take off, based on historical data can we take off/land every 3rd day on average or?) & same for landing

Operational Risks

Operation Site

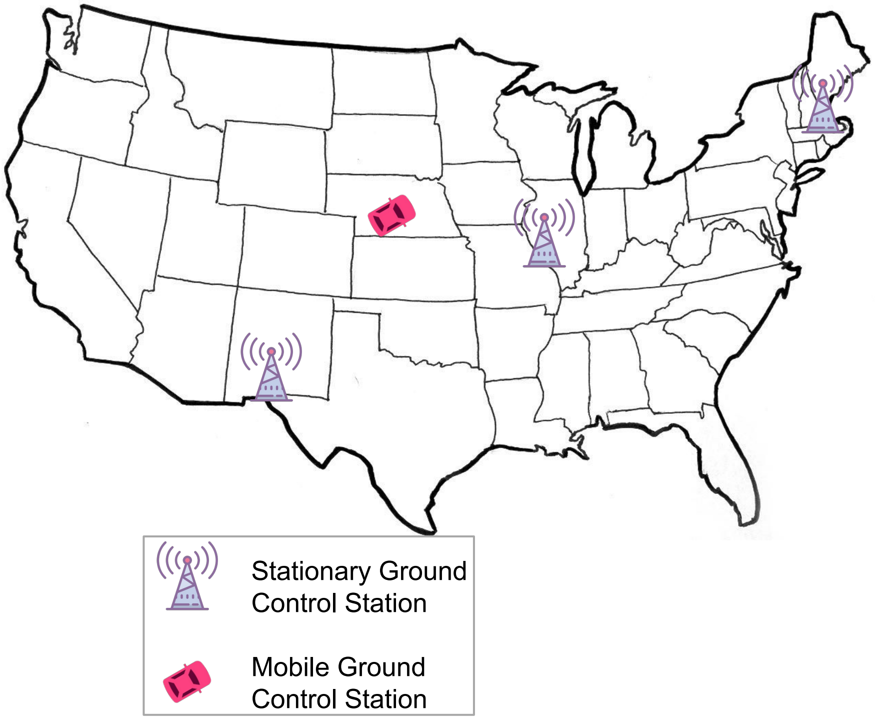
- Spaceport America (9NM9)
  - Work with FAA UAS Test Site at New Mexico State University
  - Perform ascent up to 60,000 feet within White Sands Missile Range (WSMR) Restricted Airspace
  - Elevation: 4595 feet MSL
  - Runway:
    - Direction: 16-34
    - Dimensions: 12,000 ft by 200 ft
    - No obstacles



WSMR Restricted Airspace outlined in white, location of Spaceport America shown as blue dot

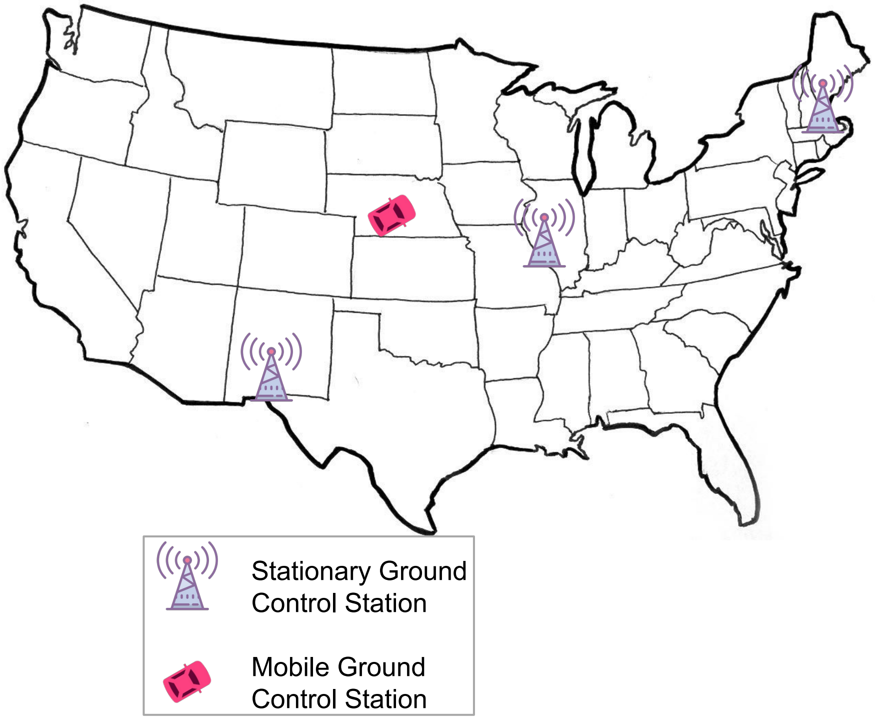
Additional Ground Stations

- Additional ground station benefits:
  a. More frequent data dumps
  b. Potential software updates pushed to the plane
  c. In an event where there were to be a BLOS communication loss, there will be more potential locations for the aircraft to be able to fly towards to establish a LOS connection



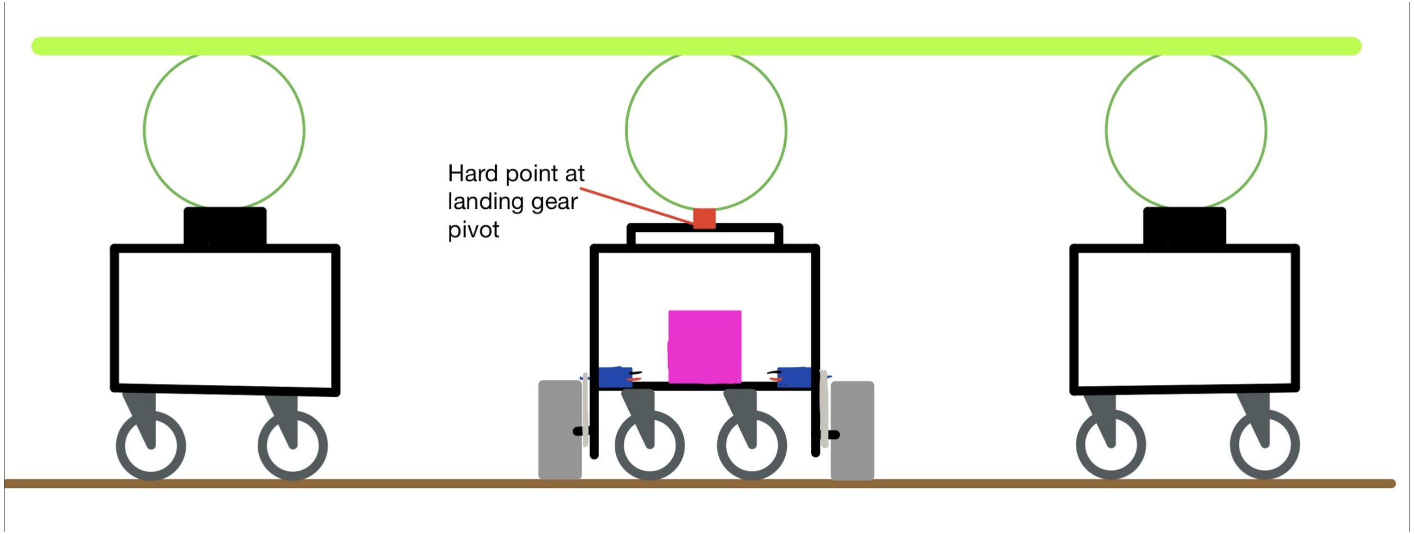
Ground Station Locations

- Locations
  a. Spaceport America
  b. Cambridge, MA
  c. St. Louis, Missouri
- Additional pre-configured mobile ground station
  a. A pre-configured mobile ground station will be developed in case the science team needs more frequent data dumps from the aircraft
  b. In this case, a ground-level chase vehicle will be required



Launch Cart Conceptual Design

- Primary point of support for center boom
- Two power driven wheels
- All other wheels are caster
- ~5° downward tilt for lift



Initial Climb Operational Constraints

- Time window: 0-2 hours before sunrise (~6 am)
- Weather constraint: Winds must be less than 75 percentile if they are coming from 190-270 degrees (~50% likely wind direction)
  - Definitions of percentile winds and constraints for other wind directions can be found in backup slides
- Takeoff distance: ~60m

Initial Climb Procedure (Up to 60,000 ft)

- If airspeed at all times is faster than predicted wind speed (~<60 percencentile winds), fly holding pattern
- If winds are stronger (~60-75 percentile winds), fly into the wind up to 45,000 feet, then fly holding pattern up to 60,000 feet
- Verify aircraft can stay within restricted airspace using winds aloft and corresponding take off procedure
- Request ATC clearance up to 60,000 feet within restricted airspace
- Manual take-off using 2.4GHz line of sight remote control
- Ground operator activates ascent phase

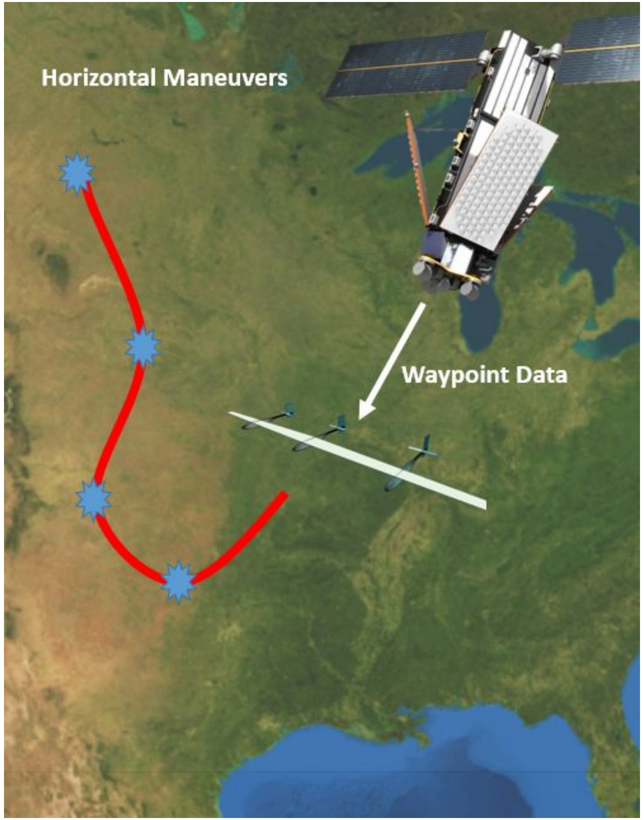
Example holding pattern within WSMR Restricted Airspace

Vertical Profile Operational Details

- Altitude cycling adds science value, but not required to close energy cycle
- Altitude Holding - manual altitude command input
  - Operator inputs desired altitude and optional duration input
  - MPC runs in background to ensure aircraft can close for desired altitude, calculates maximum time aircraft can maintain desired altitude
  - Duration cannot be longer than MPC duration
  - If duration inputted, hold altitude for duration, return to 65,000 ft after complete
  - If duration not inputted, hold altitude for maximum duration from MPC or until new altitude command

Horizontal Maneuvers Operational Details

- Waypoints transmitted to aircraft
- If current waypoint reached and new waypoint not received:
  - Maintain heading
  - If more than 10 minutes, circle most recent waypoint at radius equal to current distance from waypoint

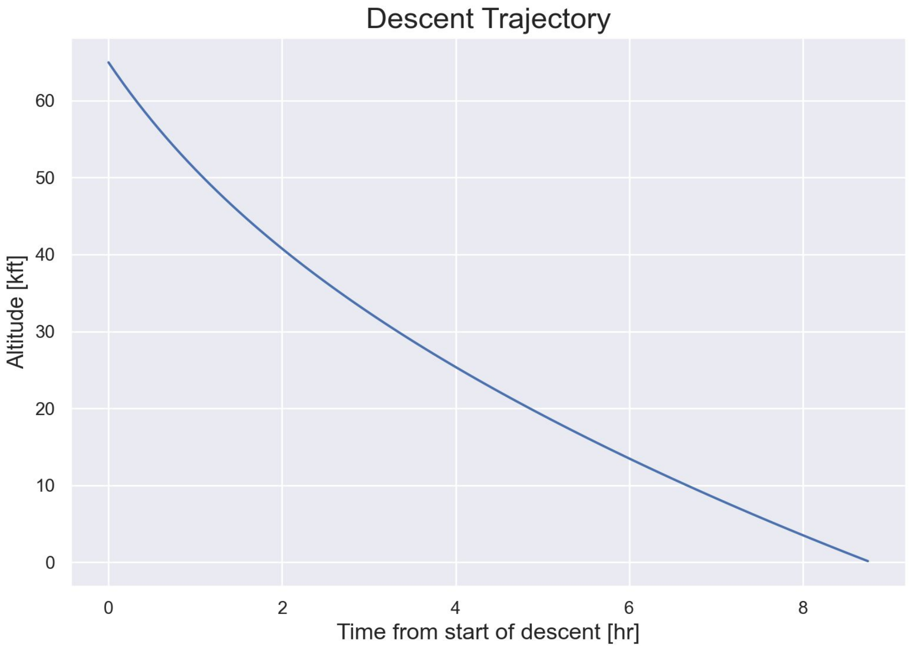


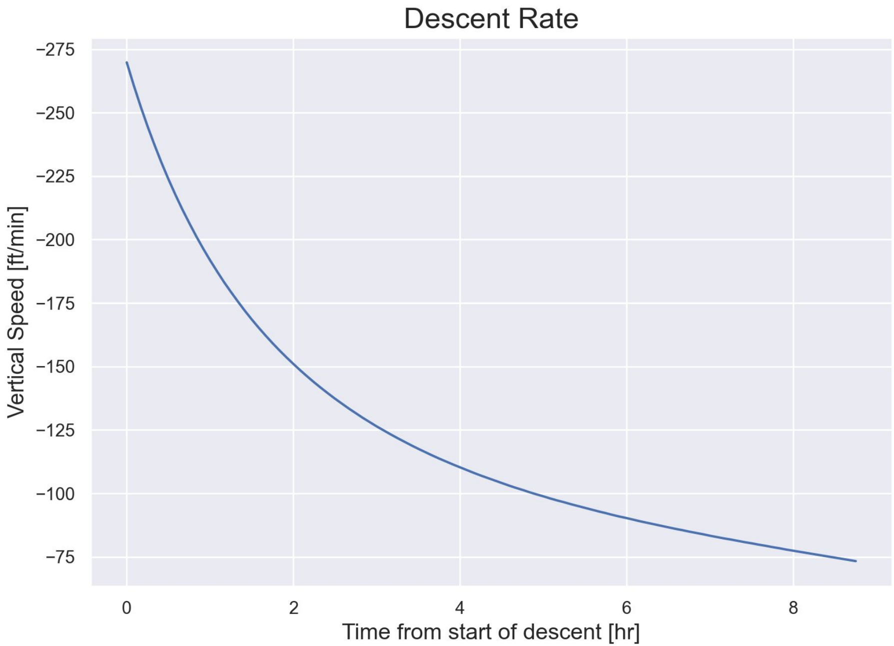
Final Descent Operational Details

- Time to descend: Descent from 60,000 ft roughly 8 hours
  - Will begin descent 8-10 hours before sunrise
- Weather constraint: Winds must be less than 95 percentile (all wind directions) (Definitions of percentile winds can be found in backup slides)
- Landing distance: ~200m
- Descent procedure:
  - Fly to location 5nm upwind of restricted airspace, not descending below 60,000 feet
  - If weather and time constraint met, request ATC entrance into restricted airspace; delayed landing operations discussed in later slide
  - If winds below 75 percentile, fly holding pattern to descend
  - If winds between 75 and 95 percentile, fly holding pattern until 50,000 feet, then fly into the wind until 26,000 feet and resume holding pattern

Descent Trajectory

- IAS = .85 * divergence speed = 11.3 m/s
- Propeller windmilling drag included

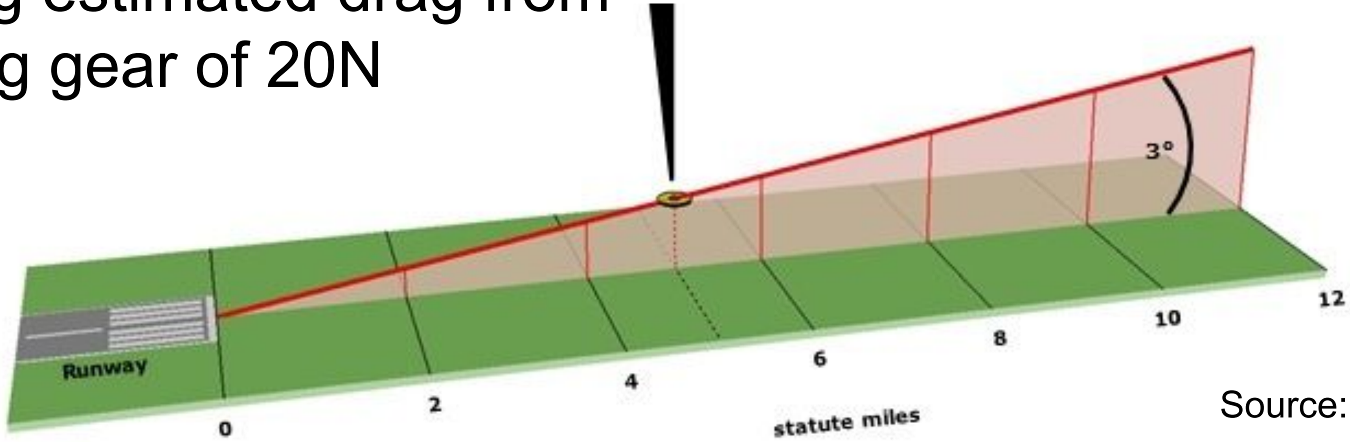




Terminal Descent

- Terminal L/D = 26.5, Decent Angle = 2.2 deg
- Calculated from divergence speed of 13.3 m/s
- Adding estimated drag from landing gear of 20N

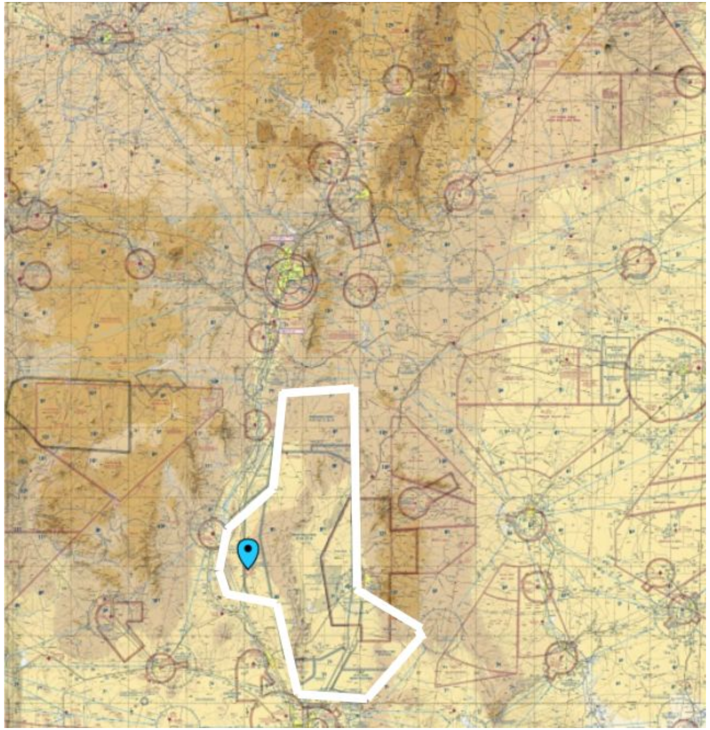
Added complexity from negative thrust on propeller, or drag devices was rejected.
With 6 kts headwind, descent angle is 3 deg



Source: FAA

Delayed Landing

- Mission Ends August 31st
- Fly south towards better sunlight
- Maintain 60,500 ft while circling over Spaceport America
- Hold through October 6th for safe weather



Contingency Operations

- Loss of command up-links (C-1 Contingency)
  - Attempt to regain link by trying LOS/BLOS communication methods, maintaining course
  - After all remaining waypoints are flown to, fly to nearest verified comms zone
  - If still no comms, return to closest ground-station until link re-established
- Return to base contingency (C-2 Contingency)
  - Triggered by loss of sub-system redundancy on flight controller, actuators, or battery pack
  - Return to base via normal mission routing
  - PIC contacts ATC
- Power loss contingency (C-3 Contingency)
  - Prior to flight, establish database of emergency landing airports and locations (>=1 location within gliding distance (~300 miles) of every point in CONUS)
  - In case of complete power loss, make emergency landing at closest location
- Loss of radio communications
  - Before flight, PIC will have telephone numbers of all ATC sector supervisors at disposal
  - If communication via airborne relay fails during flight, transponder will squawk 7600 and PIC will call ATC for follow-on action

Design Overview & Performance

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System Risks

Risks	Strategy
Aeroelastic operational limitations	Utilize ASwing to inform structural design considerations to account for aeroelastic effects and define a no-fly weather conditions (winds, gusts). A 25% structural weight margin is allocated for aeroelastic mitigation.
Thermal runaway of a battery cell/pack	Prevention, active thermal control and monitoring of string voltages and amperage. Develop vetted (dis)charging operational procedures of batteries. Mitigation, ensure off-gasses from thermal runaway are routed out of the aeroshell. Remaining battery strings sized to ensure vehicle can safely return to base.
Cost of solar cells	Carry a secondary supplier (SunPower) for the demonstrator mission as a low cost alternative. Continue researching various solar cell suppliers to find potential donors.
Cost of (development) motors	Continue researching potential suppliers. Select a previously optimized motor that requires minimal redevelopment to suit this application.
Loss of communication	Continue refining and expanding on aforementioned loss of communication procedures

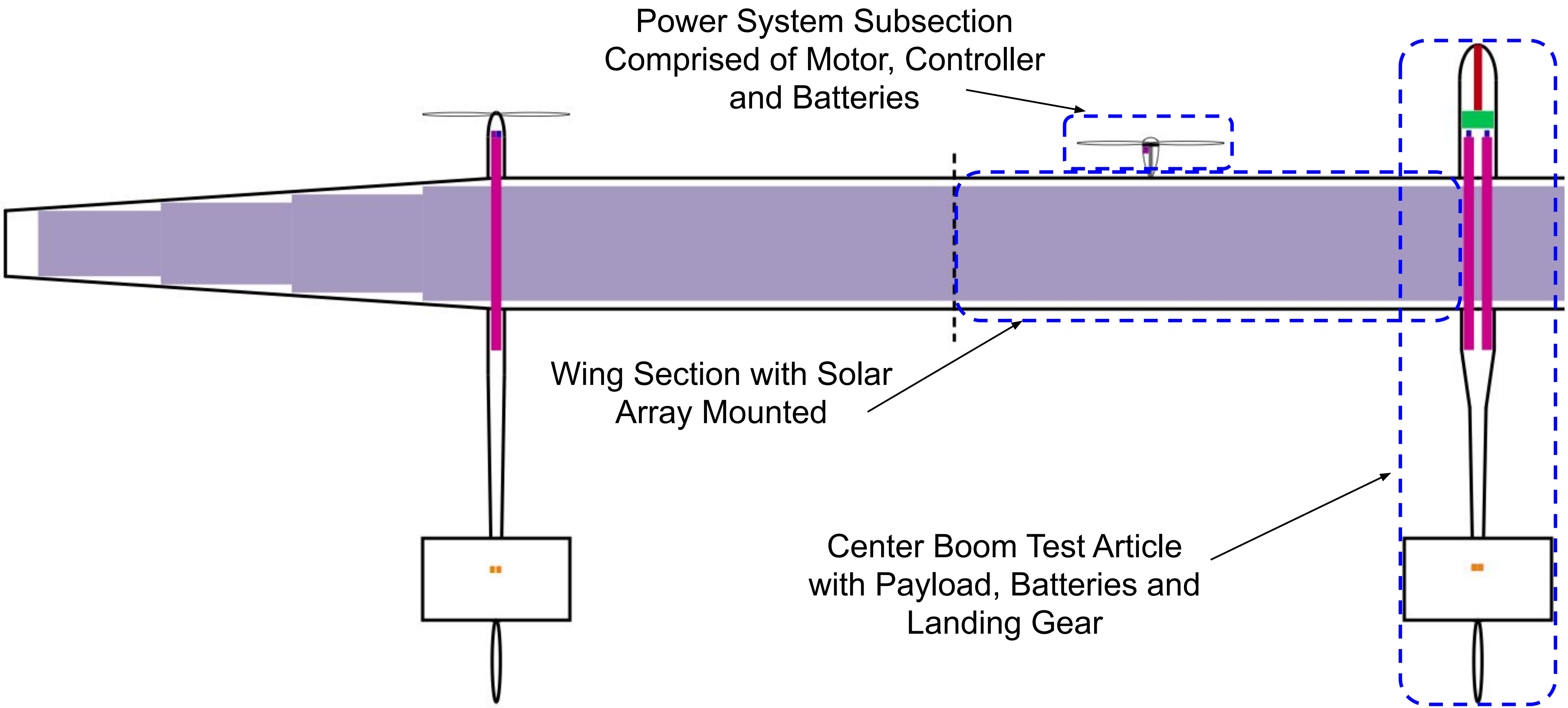
What's Next?

- We have proposed our initial vehicle design that meets the mission requirements, however a more detailed design is necessary before we build the final vehicle
- The following steps outline our path to reduce risk by:
  - Validating design assumptions
  - Testing performance of power system components
  - Identifying build challenges
  - Verifying build quality
  - Integrating components to prove compatibility
  - Proving concept by building a low cost prototype

3 Phase Approach

Phase 1: Component Testing and Prototyping → Phase 2: Low Cost Full Vehicle Initial Prototype → Phase 3: Full Performance Vehicle

Initial Component Testing and Prototyping



Initial Component Testing and Prototyping

- Further ASWing modelling to identify aeroelastic modes
- **Build wing test section**
  - Validate structural mass models
  - Develop fabrication and assembly procedures for extremely lightweight structures
  - Prototype solar panel array to test mechanical properties and adhesion to flexing wing surface
- **Develop propulsion system subsection of motor, controller and battery pack**
  - Test components at altitude pressure and temperature
  - Integrate with wing test section and solar panel array

Initial Component Testing and Prototyping

- **Build a center pod test article to conduct wind tunnel testing:**
  - Evaluate payload position to ensure clean airflow
  - Characterize the performance of battery cooling channels
  - Evaluate if battery heaters are required
  - Drop test to ensure robustness of landing gear and load path to center boom
  - Attach to wing section to develop spar attachment strategy
- Further develop science mission planning to better understand how scientific readings will impact flight plan

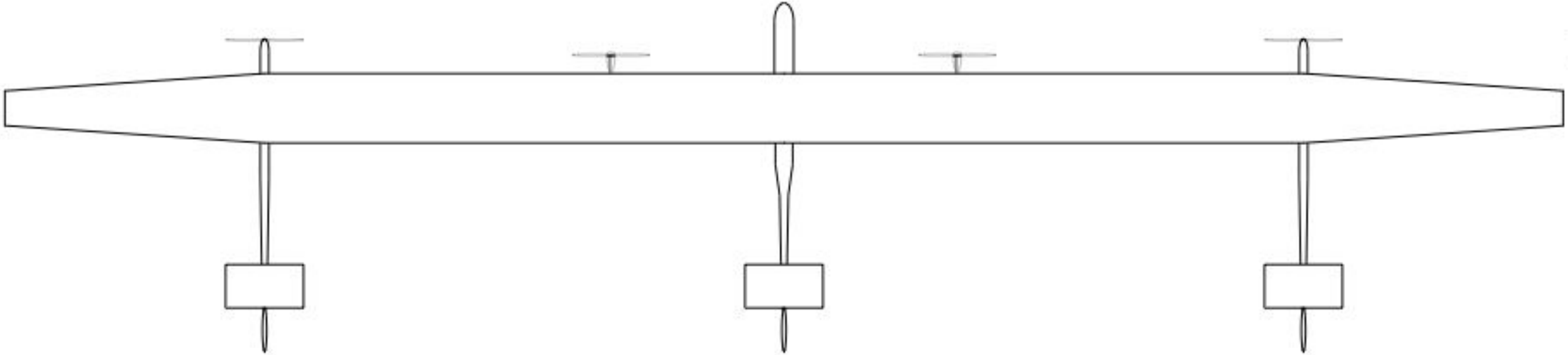
Low Cost Initial Prototype

- Develop a full-scale test aircraft utilizing Sunpower solar cells to **reduce cost**:
    - Capable of sustained flight June 5th to July 5th at or below latitude of Spaceport America (33N)
- Fly without payload to **reduce risk**
- Prototype vehicle will be used to demonstrate long endurance flight is possible in the stratosphere to **acquire project funding** from major science agencies

Image Source: alchetron.com

Full Performance Vehicle

- **Retrofit initial prototype vehicle** with Microlink cells enabling mission in the full continental United States from May 1 to August 31
- Add payload so vehicle has **full science capability**
- Apply this groundbreaking observation platform to **conduct a wide variety of climate related science missions**



Next Steps

- Update model to size for being able to fly above class-A airspace beyond 31st of August
- Risk reduction steps
  - Put together power system test
  - Test battery cells (efficiencies, energy density) & develop operational procedures
  - Test solar cells (efficiencies, areal density)
  - Test motor (efficiencies, torque)
  - Solar cell mounting to wing
  - Build wing prototypes
  - Continued analysis of aeroelastic effects
  - Test autopilot
  - Identify control gains
- Develop plane to fly with SunPower cells and off the shelf motor, w/o payload → demonstrate it is possible → get funding → build the fully capable aircraft!

Backup Slides

Daedalus stuff

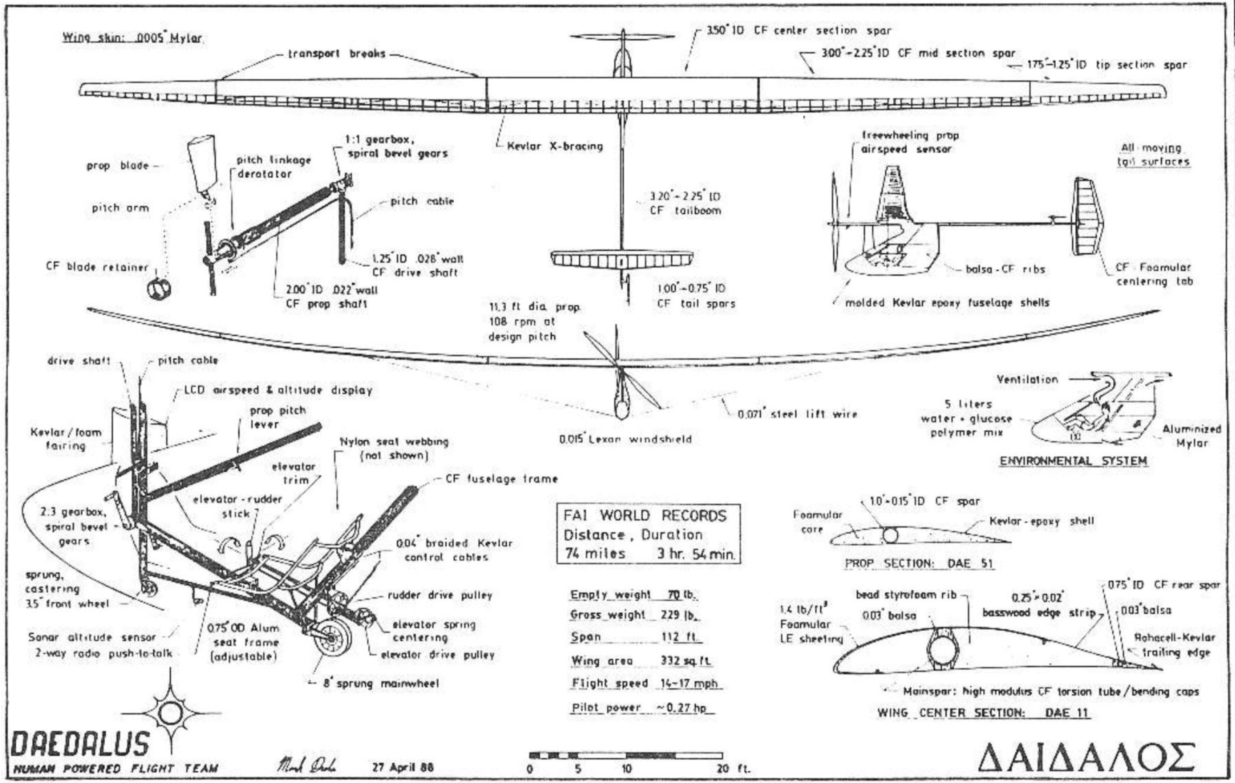
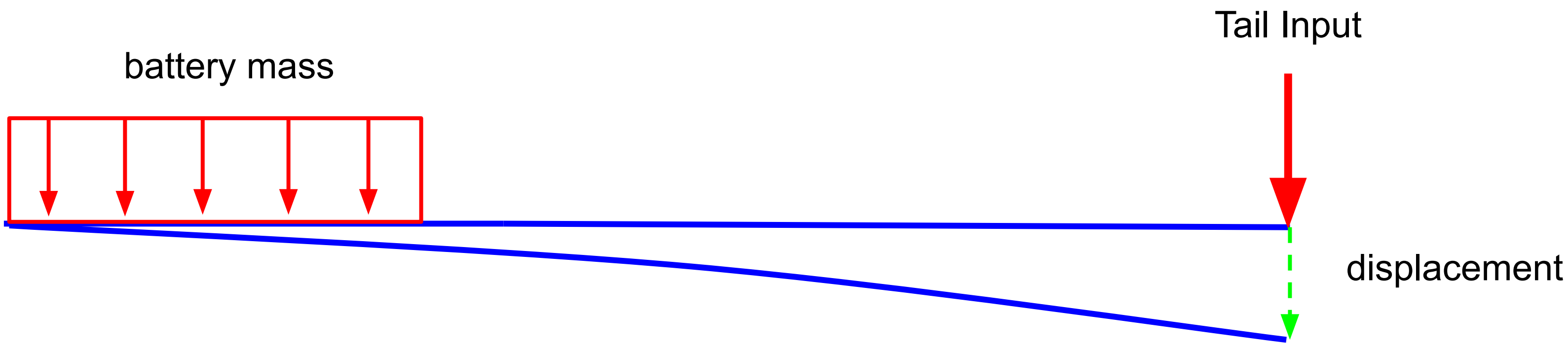


FIGURE 1

DAEDALUS HUMAN POWERED AIRCRAFT

Tailboom sizing



Schedules for structural components

tailbooms

main spar

Cosine Gust

Materials of Battery Pods

- Skin Radiator: COOLPOLY D3612
  - Density: 1.6 g/cm^3
  - Thermal Conductivity: ~3.5 W/(mK)
- Casing: PEEK
  - Density: 1.3 g/cm^3
  - Tensile Strength: 100 MPa
  - Thermal Conductivity: ~0.3 W/(mK)
- Insulator: Vacupor® Insert NT
  - Density: 0.15 g/cm^3
  - Thermal Conductivity: ~0.005 W/(mK)
- Wiring: Pure Nickel Ribbon
  - Weight: 7.6 g/m

Sources:
http://tools.celanese.com/
http://www.matweb.com/search/DataSheet.aspx?MatGUID=2164cacabcde4391a596640d553b2ebe
http://www.morganthermalceramics.com/media/4162/vacupor-insert-nt-data-sheet-english.pdf
https://www.amazon.com/Nickel-0-15mm-Battery-Welding-Shipping/dp/B06XJKMP3Y

Other Thermal System Components

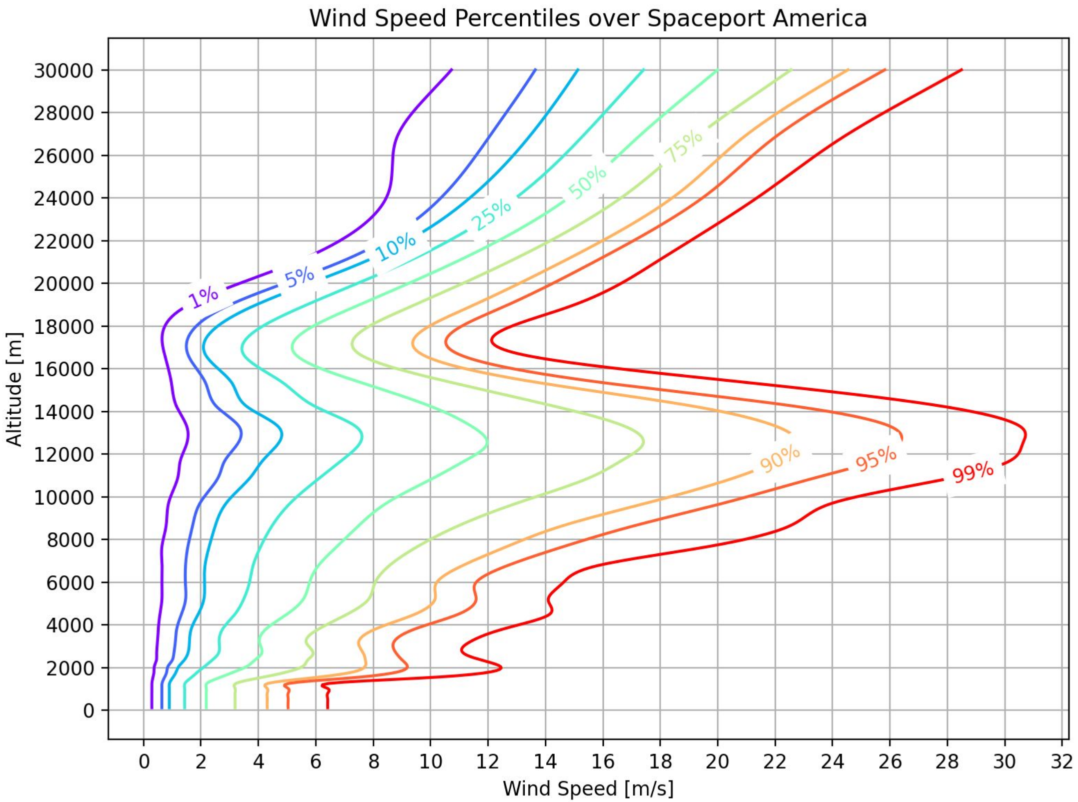
- Temperature Sensor: Omega Glass Encapsulated Thermistor
  - Weight: < 1 gr
  - Accuarcy: +/- 0.2 (0-70°C)
- Thermal Paste: Parker Chomerics T670
  - Density: 3.0 g/cm^3
  - Thickness: ~0.3 mm
  - Thermal Conductivity: 3 W/(mK)
- Heaters: Omega Flexible Silicone Rubber Heater
  - Density: 1.5 g/cm^3
  - Thickness: ~0.7 mm
  - Operational Temperature: 217-505 K

Source:
https://www.omega.com/en-us/sensors-and-sensing-equipment/temperature/sensors/thermistors/55000/p/55005
http://www.matweb.com/search/DataSheet.aspx?MatGUID=2205c3d1871c4001a9e20dab6b983b78
https://www.omega.com/en-us/industrial-heaters/flexible-heaters/srfr-srfg/p/SRFG-206-5-P

Other Battery System Components

- Voltage & Current Sensors:
  - Weight: << 1 gr
  - Breadboard mounted
- Microprocessor/FPGA
  - Weight: ~0.025kg
  - Comparable to Arduino Uno

Percentile Winds over New Mexico



Additional Wind Constraints

- Ascent:
  - 270 to 315 degrees wind direction
    - 0 to 60 percentile: holding pattern
    - 60 to 75 percentile: fly into wind up to 45,000, then holding pattern
    - Beyond 75 percentile: don't fly
  - 315 to 0 degrees, 0 degrees to 190 degrees wind direction
    - 0 to 50 percentile: holding pattern
    - Beyond 50 percentile: don't fly