Critical Design Review

SPECTRE

PURDUE™ AERONAUTICS & ASTRONAUTICS

Professor Spencer

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AAE 450: Spacecraft Design

Senior Capstone Project with objectives:

- Define and flow down requirements from the mission objectives to system- and subsystem-levels
- Understand and implement the design process for aerospace systems
- Solve problems as part of a team
- Conduct open-ended tasks associated with design, integration, testing and operation of space flight missions
- Demonstrate design viability through modeling, simulation and testing
- Organize tasks and establish work schedules
- Give oral presentations and write technical reports required of aerospace engineers

Progress Overview

Improved work of previous semesters by:

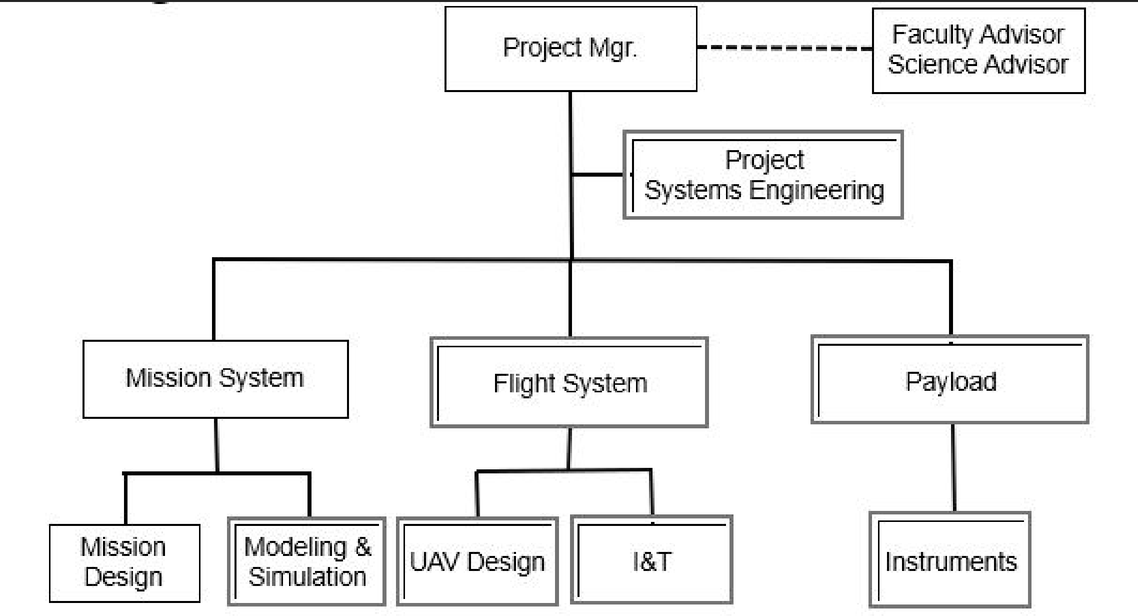
- Selection of a scientific objective and site for survey
- Advanced the design of the UAV to successfully achieve CDR phase.
- Prepare for a test program to demonstrate key aspects of the UAV mission design and flight system.

Challenges included:

- Performing Trade Studies of engineering problems
- Setting design requirements for mission parameters
- Coordinating multiple groups

Class Structure

Class Structure: The class structure has been changed to suit the needs of the senior capstone project



Mission Statement

The mission of the Specialized Terrestrial Rotorcraft Explorer (SPECTRE) will be to enable mesoscale aerial survey within regions of interest (ROI) on the Martian landscape. Visual survey will be conducted of a region, followed by targeted hyperspectral imaging. This data will provide insight into Martian history by examining the presence of hydrated minerals and identifying the presence of biosignatures on the surface.

This mission will also serve as a technical demonstration of the utility of flight-based vehicles on the surface of Mars and provide insight into their applications in future missions.

Mission ConOps Summary

1. The drones collect images of Martian surface during flight, the rover moves concurrently in the same direction to maintain LOS.

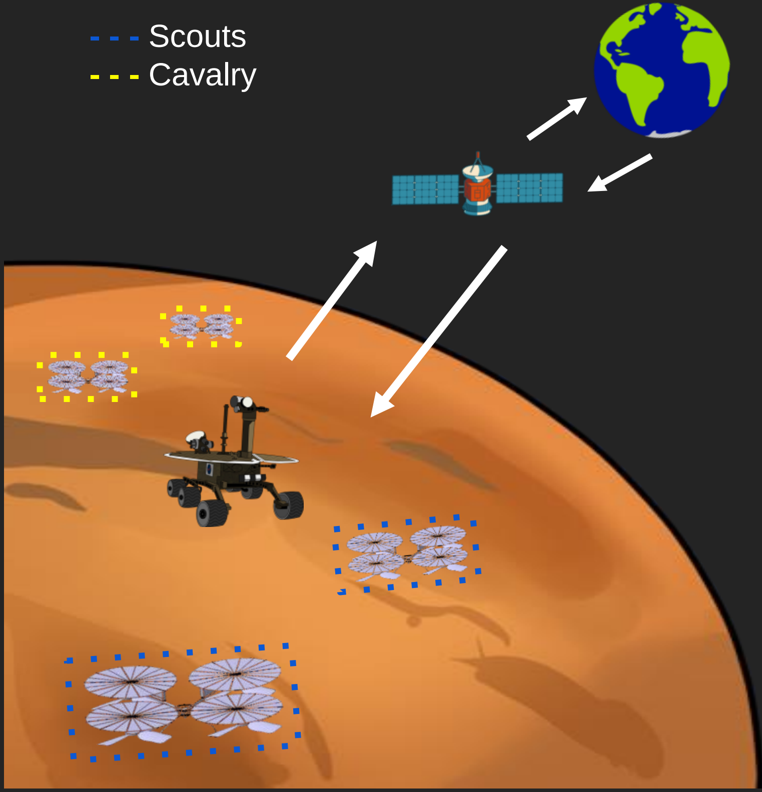
2. The drones land and begin transmitting the information to the rover while charging.

3. The rover sends the information back to Earth.

4. The process repeats, the drones continue surveying the ROI, with the Cavalry drones investigating areas predetermined areas of interest.

6. A team of scientists reviews the information and chooses areas to investigate further, which is sent back to the system.

5. The Scout drones continue surveying while the Cavalry drones investigate the areas of interest selected by scientists, as well as any predetermined areas of interest.



Mission Timeline

- July 2035: Earth Departure
- February 2036: Mars Arrival
- March 2036: Completed Calibration and traveling to the ROI
- March 2037: Mission Completed
- March 2037: Increased Risk for Global Storms during any post-mission operations

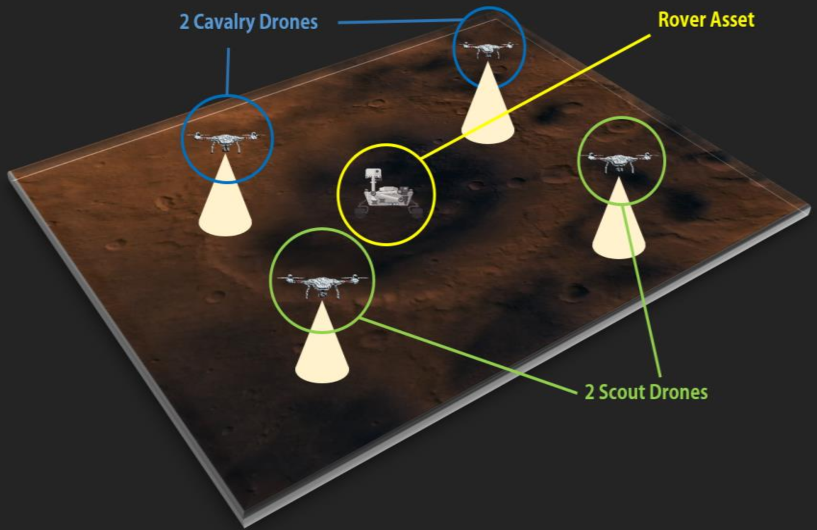
ROI: 50 km2

Mission Time: 375 sols

Drone Flights: 103 sols

Hyperspectral Area: 2.5 km^2

High Resolution Area: 0.05 km^2



SPECTRE

SCIENCE OBJECTIVES

Science Objectives

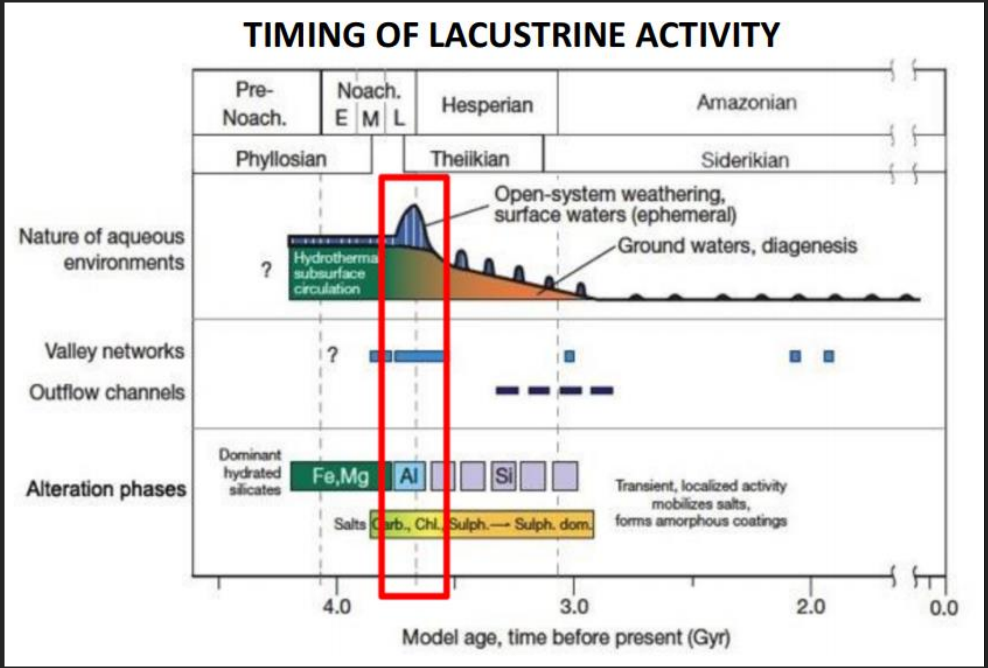
Primary: Hi-res hyperspectral imaging of hydrated minerals

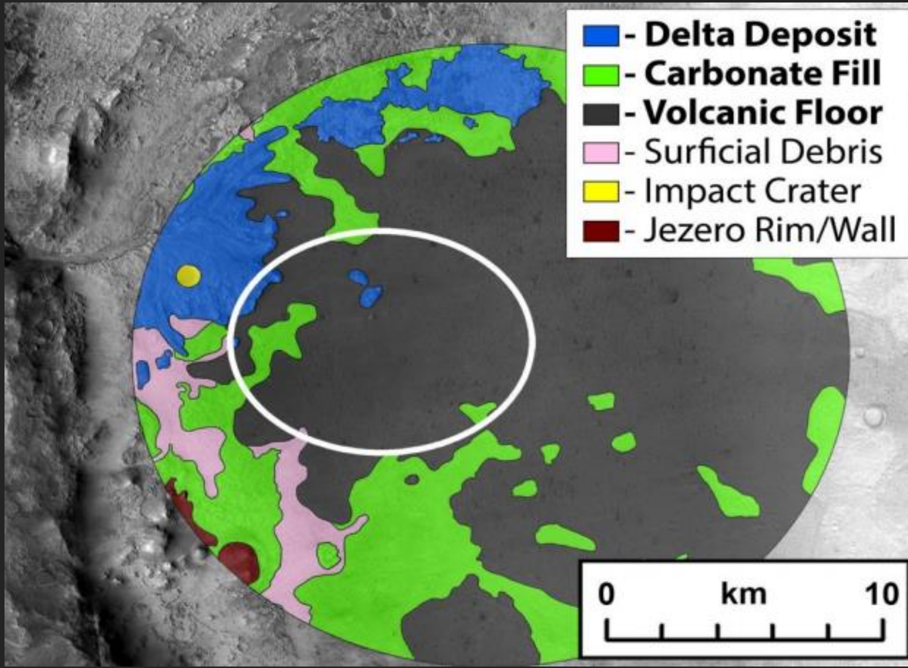
- Characterize mineral content and geological history of Jezero Crater
- Map potential hydrated mineral resources for future exploration missions
- Gain knowledge of the sediments deposited by ancient river systems

Secondary: Identification of stromatolites (or other interesting structures)

- Stromatolite presence is a strong indicator of ancient microbial life
- Recent erosion features may hide better sources for stromatolites/organic matter
- Aerial visible light imagery of Mars may be scientifically valuable for unrelated reasons

Deposition of Hydrated Minerals





[From Mars 2020 Site Selection]

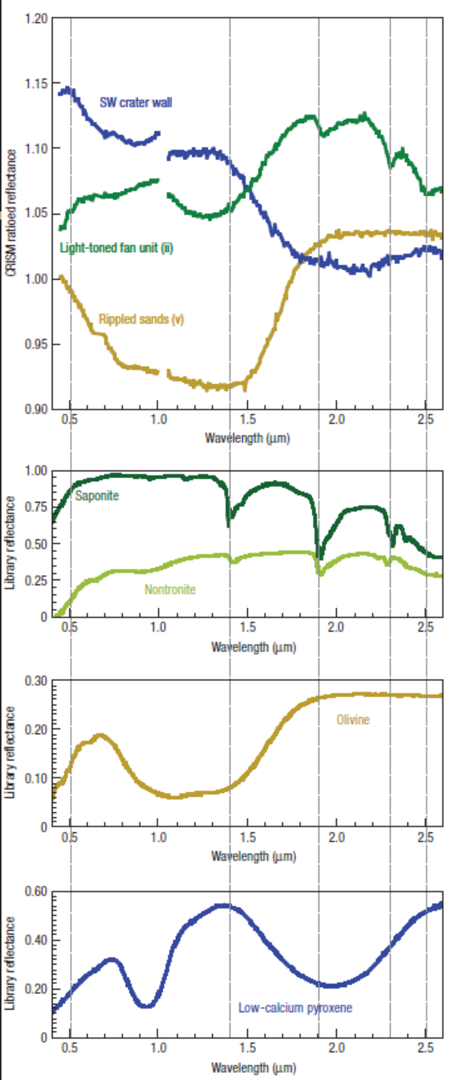
Geographic Analysis

1.9 μm absorption due to H_2O present in minerals

[Ehlmann et. al. 2008]

Image of western fan

“Phyllosilicate-bearing materials are green, olivine-bearing materials are yellow, low-calcium pyroxene-bearing materials are blue and purple–brown surfaces have no distinct spectral features.” (Clay Minerals)



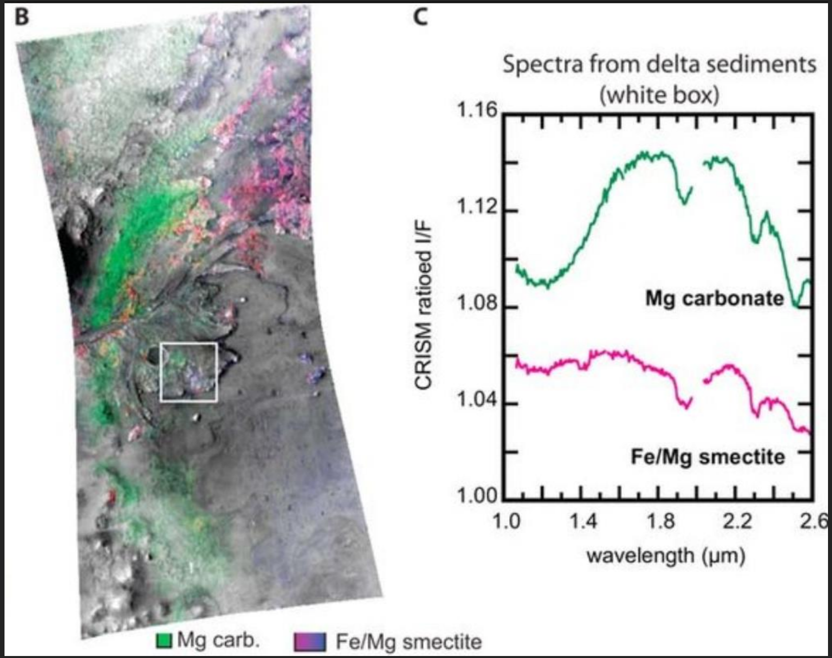
Hyperspectral Imaging of Present Minerals

Two main hydrated minerals:

- Iron-Magnesium Smectite
- Magnesium Carbonate

Necessary bands:

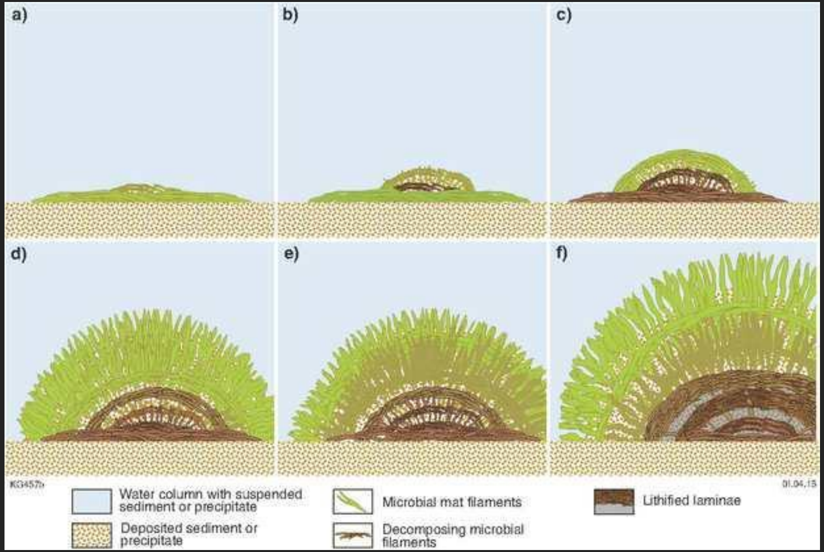
- ~1900 nm (water absorption in hydrated minerals)
- ~2300 nm (metal-OH absorption - Fe vs. Mg)
- ~1400 nm (another absorption wavelength of smectite and zeolite)
- ~3400 nm (characteristic of carbonate)



[Ehlmann et. al. 2009]

What Are Stromatolites?

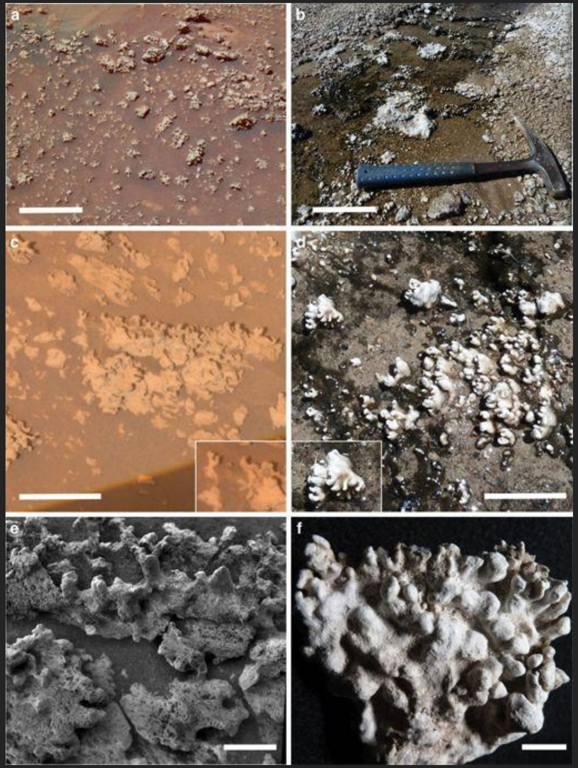
- Biosignatures of prokaryotic bacteria
- Formed by accretion of mats of bacteria
- Mats are slowly calcified into sedimentary rock
- Some of the most ancient evidence of life on Earth



Stromatolite Identification

Micro-digitate silica form

- Difficult to detect (relatively small)
- Prospective example already identified by Spirit
- Hard to verify without very high resolution
- Lower probability of identification
- Higher probability of formation



[Ruff and Farmer 2016]

Bar Scale: top - 10 cm, middle - 5 cm, bottom - 1cm

Stromatolite Identification

Columnar/Mound form

- Much larger, discernable at reasonable resolution
- Can be analyzed consistently at high resolution
- Lower probability of formation
- Higher probability of detection

[Current]

[Fossilized]

Science Traceability Matrix (STM)

Program Objective	Science Objectives	Observational Objectives	Specific Observations	Science Requirements	Instrumentation	Instrumentation Requirements
Conduct mesoscale aerial survey of the Martian Landscape	Conduct survey of hydrated minerals	Confirm presence of hydrated materials	Search for large scale collections of hydrated minerals	Create distribution map of hydrated minerals with ground sampeling distance less than 15 cm/pixel	Hyperspectral Camera	Capable of viewing 1400 - 1500 nm, 1800-2000 nm, 2200 - 2600 nm, 3300 - 2600 nm
		Characterize properties of hydrated materials	Determine composition of hydrated minerals	Collect detailed hyperspectral imagery of locations of interest within targeted region		
			Determine geological origin of hydrated minerals			
	Collect data quantifying biosignatures on the Martian surface	Identify possible biosignatures	Search for possible organically created rock formations	Create topographical images with ground sampling distance less than 2.5 cm/pixel	Visible Camera	Capable of viewing 390 - 700 nm
		Verify presence of biosignatures	Retrieve high resolution images of possible biosignatures	Retrieve images of possible biosignatures with ground sampling distance less than 0.25 cm/pixel		

SPECTRE

SYSTEM REQUIREMENTS

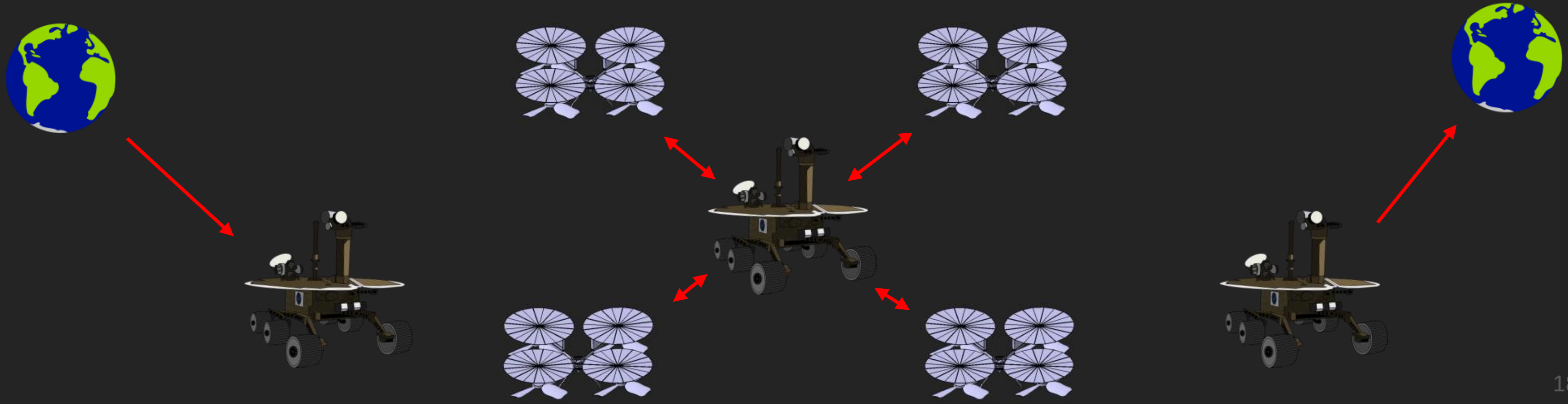
Basic Operations

Operate independently of Earth during flight:

Step 1:
Instructions
from Earth

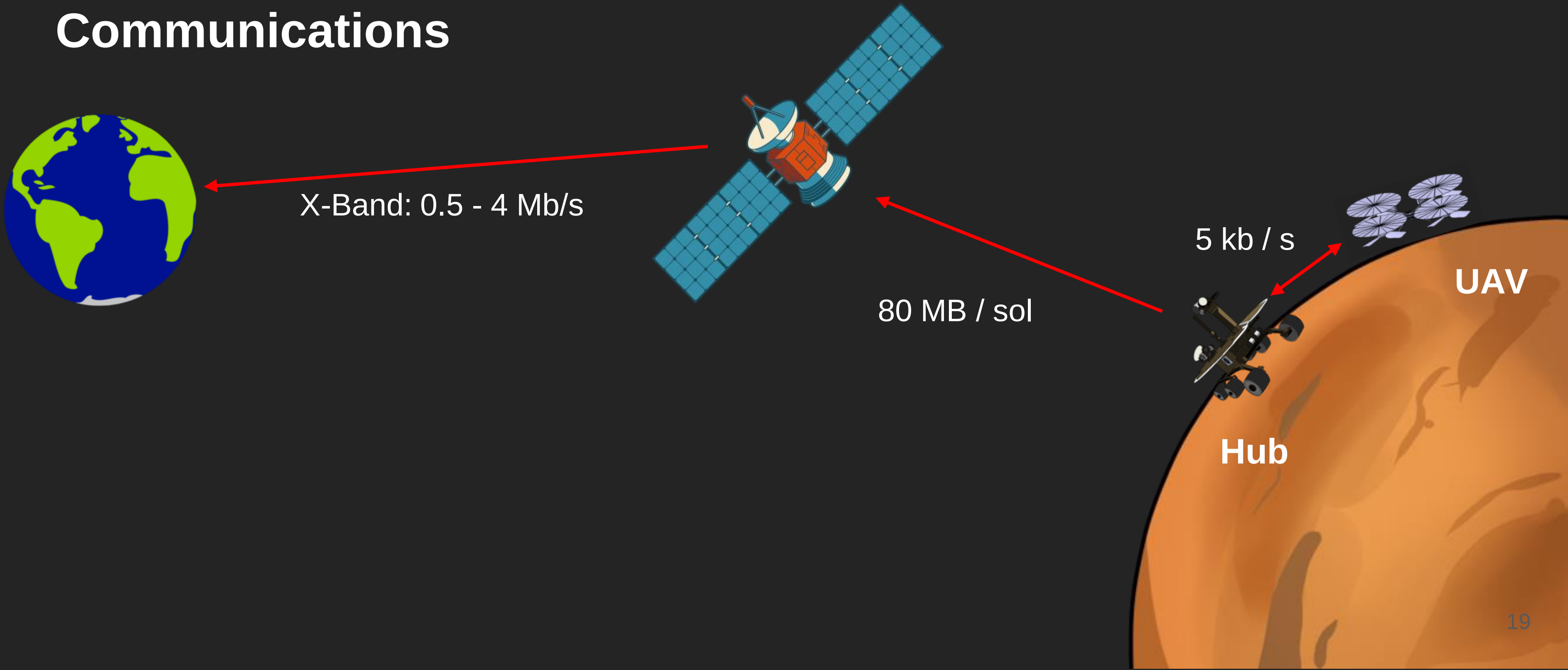
Step 2:
Collect data

Step 3:
Report to
Earth



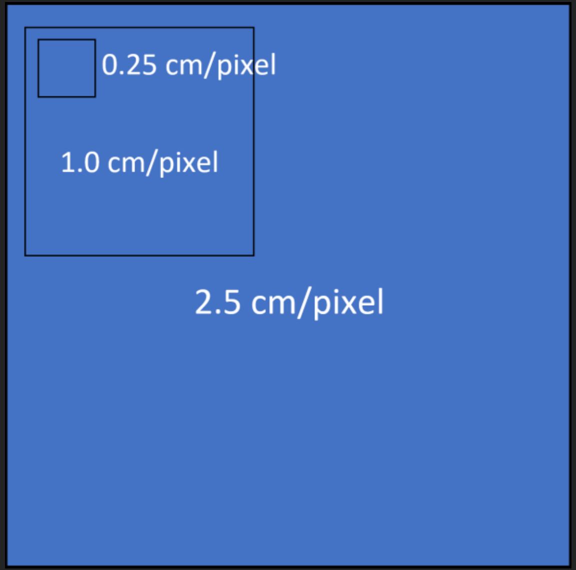
Communications Requirements

Communications



Data Requirements

Flight Area:	50º N 50º S
Drones:	x4
Low Resolution Visual Data:	2.5 cm/pixel for 50 km^2
High Resolution Hydrated Mineral Data:	1.0 cm/pixel
High Resolution Visual Data:	0.25 cm/pixel
Hyperspectral Data Collection:	5% ROI
High Resolution Visual Percentage:	0.1% ROI
High Resolution Survey Location:	x6
High Resolution Survey Regional Area:	100 m^2



Operational Cycle

- Time of Mission
  - Min. 100 flights
  - 375 sols
- Operational Cycle
  - Consists of 3 phases
    - Set-up - System Checks
    - Flight - Flying + Locating
    - Maintenance - Transmitting + Charging + Night
- Sols per Operational Cycle
  - Maximum 3 sols per each operational cycle

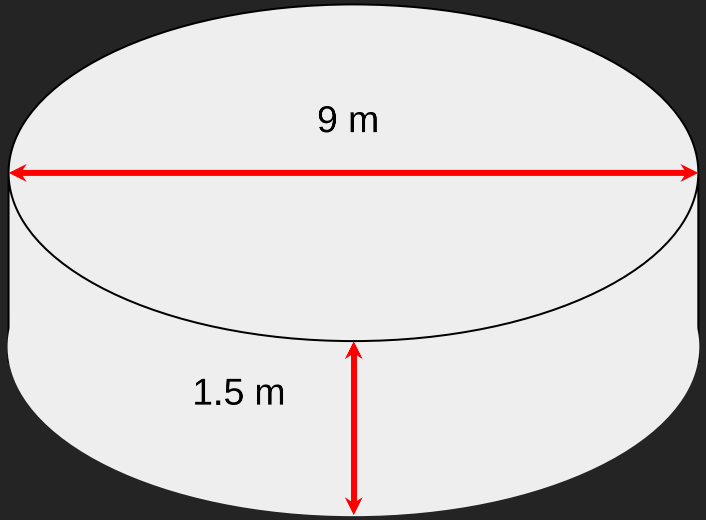
Flight sol

Setup	Flight	Maintenance
5 min.	8.5 min.	24 hrs.

Delivery Dimensions Requirements

Total System Mass: 1300 kg

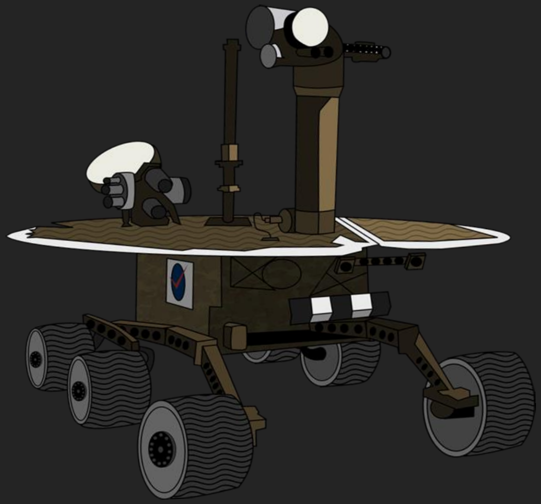
Packed Dimensions: 9 m diameter circle, 1.5 m height



Note: Requirements based off SLS scale launch vehicle

Hub Requirements

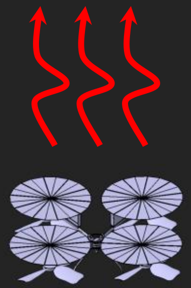
Maximum Mass:	1000 kg
Packed Dimensions:	4m x 4m x 0.75m
Range:	600 m / sol
Weather:	Detect adverse conditions within 1 km



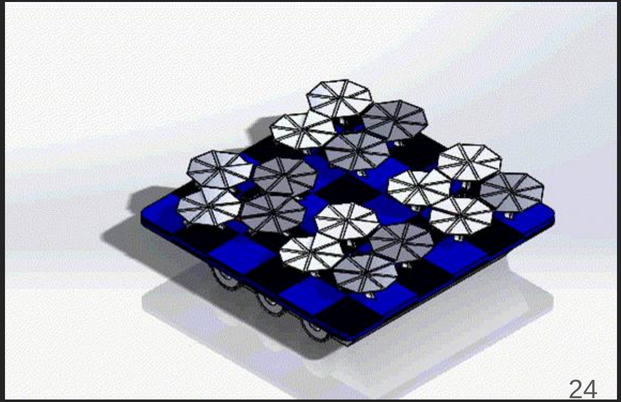
**Disclaimer: This is purely a visual representation, not the exact hub design.*

Safety Requirements

- Temperature Survivability
  - Mars Temperature Range: -120º C → 20º C
  - Drones and their components need to survive these temperatures
  - High Radiation Detection



- Deployment Safety
  - Drones secured until ready for first flight
  - ½ a blade radius separation of drones when packaged
  - 1 drone lengths between grounded SPECTRE vehicles
  - 3 drone lengths between drones in parallel flight
  - SPECTRE detects local dust devils when grounded



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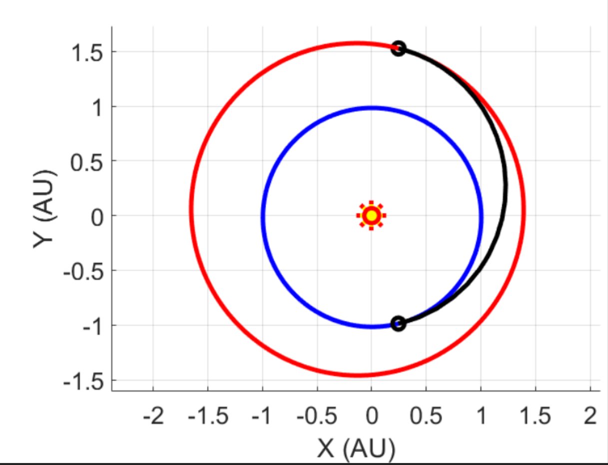
MISSION

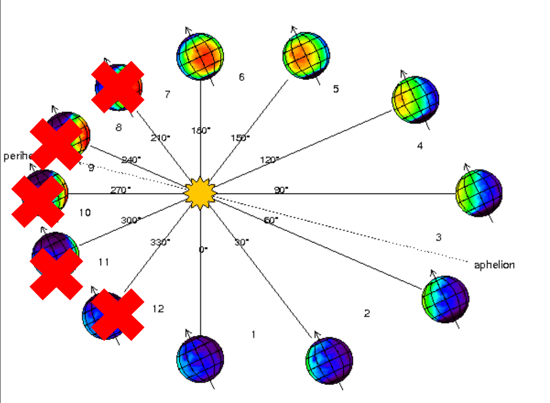
Launch Date



Mission Trajectory

Mission Phase	Date
Earth Departure	7/6/2035
Mars Arrival	2/17/2036
Travel Time	227 days

- Using SLS Block 2 Launch Vehicle
- Possible Launch Years: 2028-2035
- To avoid Global Storms, the mission is between 0° and 180° L_s.[Missions 6]

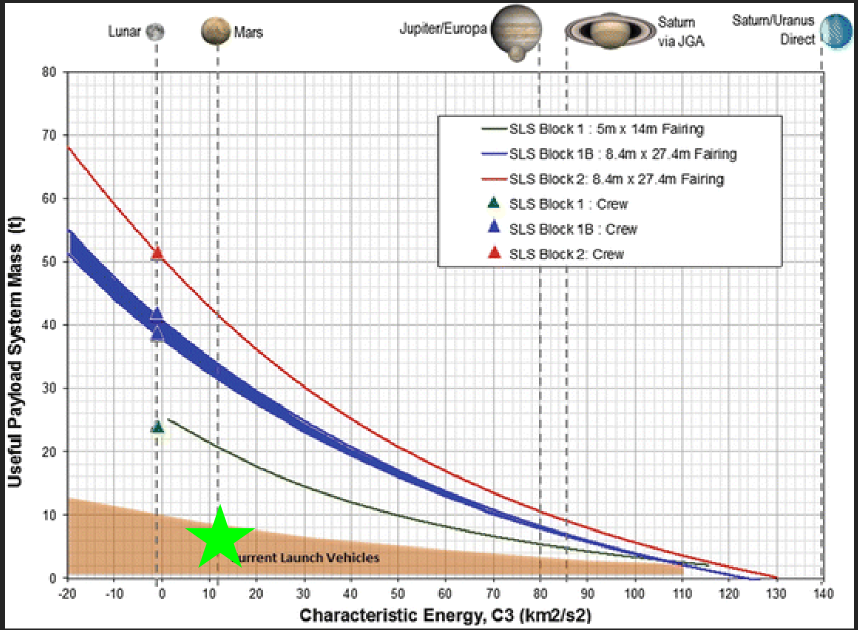


Martian Solar Longitude Chart [Missions 2]

Mission Time

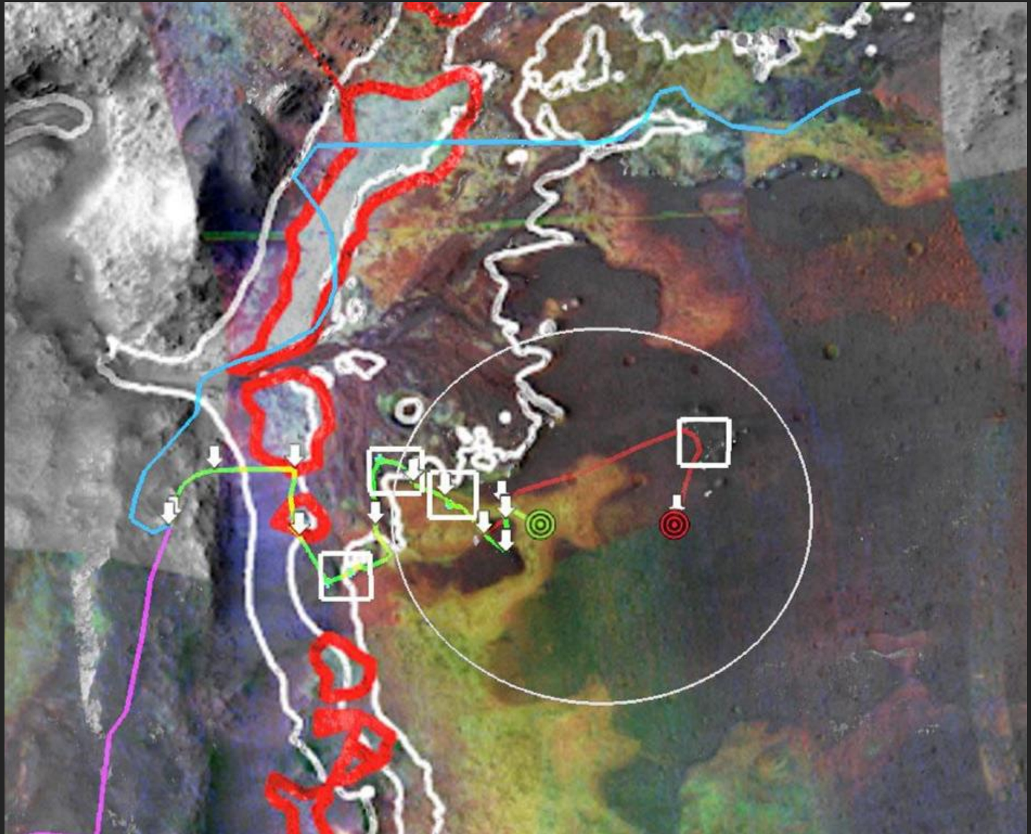
Mission Phase	Date	L_s
Mars Arrival	2/17/2036	355.7
Calibration Period Ends	3/8/2036	5.7
Primary Mission Completed	3/8/2037	176.3

Total Mission Time
375 Martian days (Sols)
385 Earth days

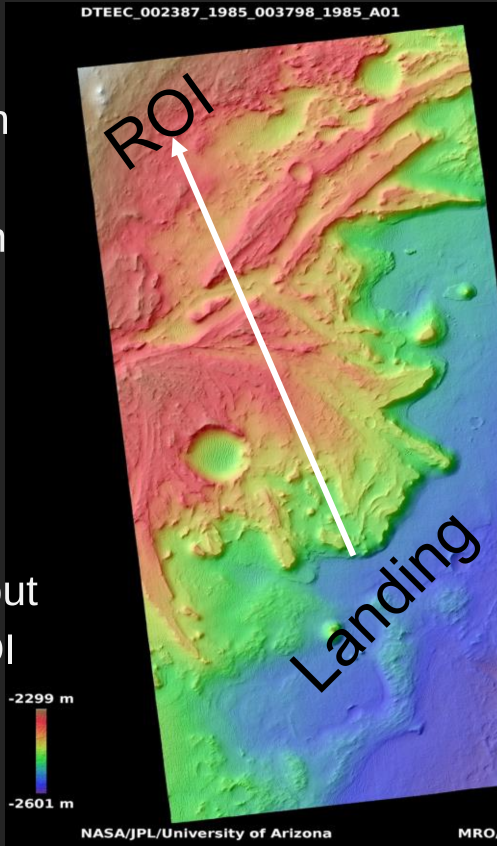


SLS Payload Sizes [Missions 7]

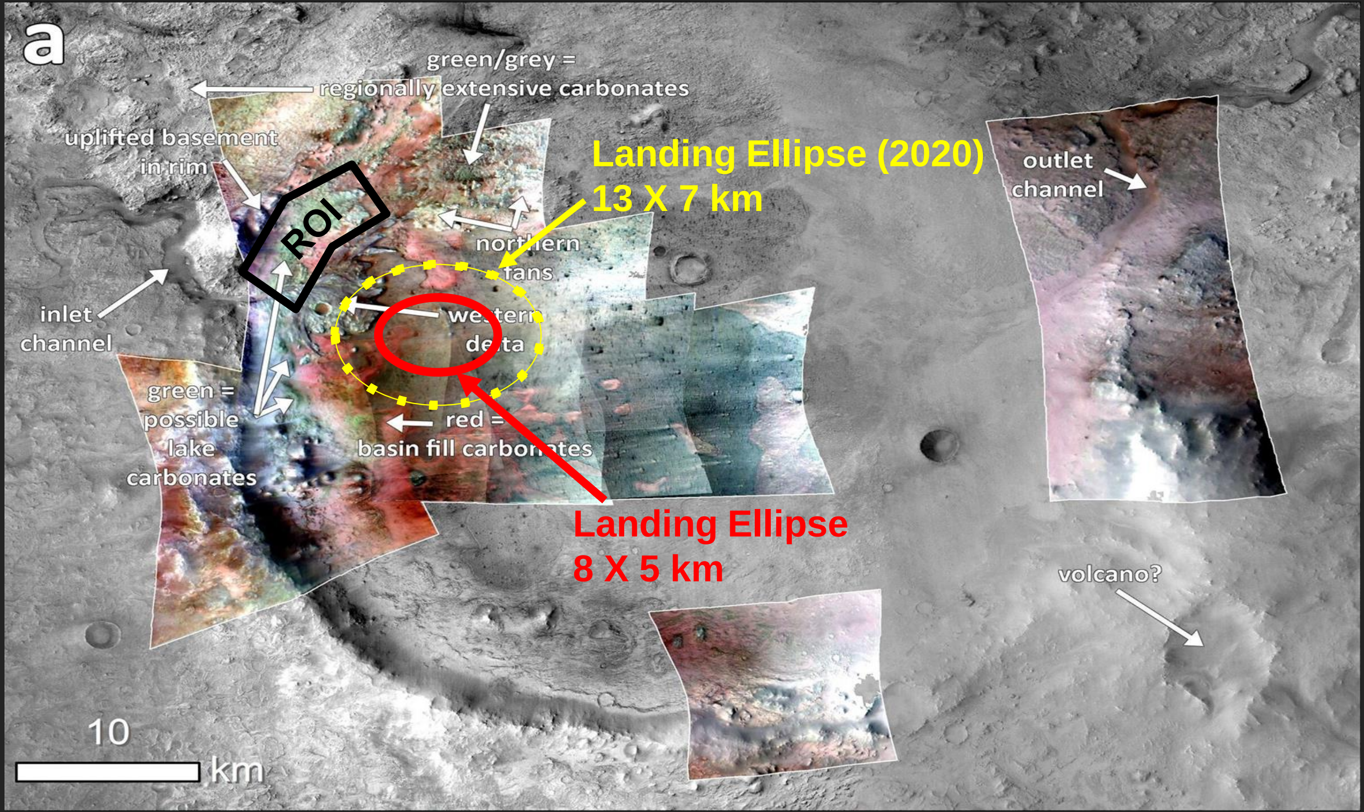
Landing Site Analysis



- 300 m elevation difference
- Investigating an area similar to Mars 2020
- Images demonstrate additional information about landing and ROI

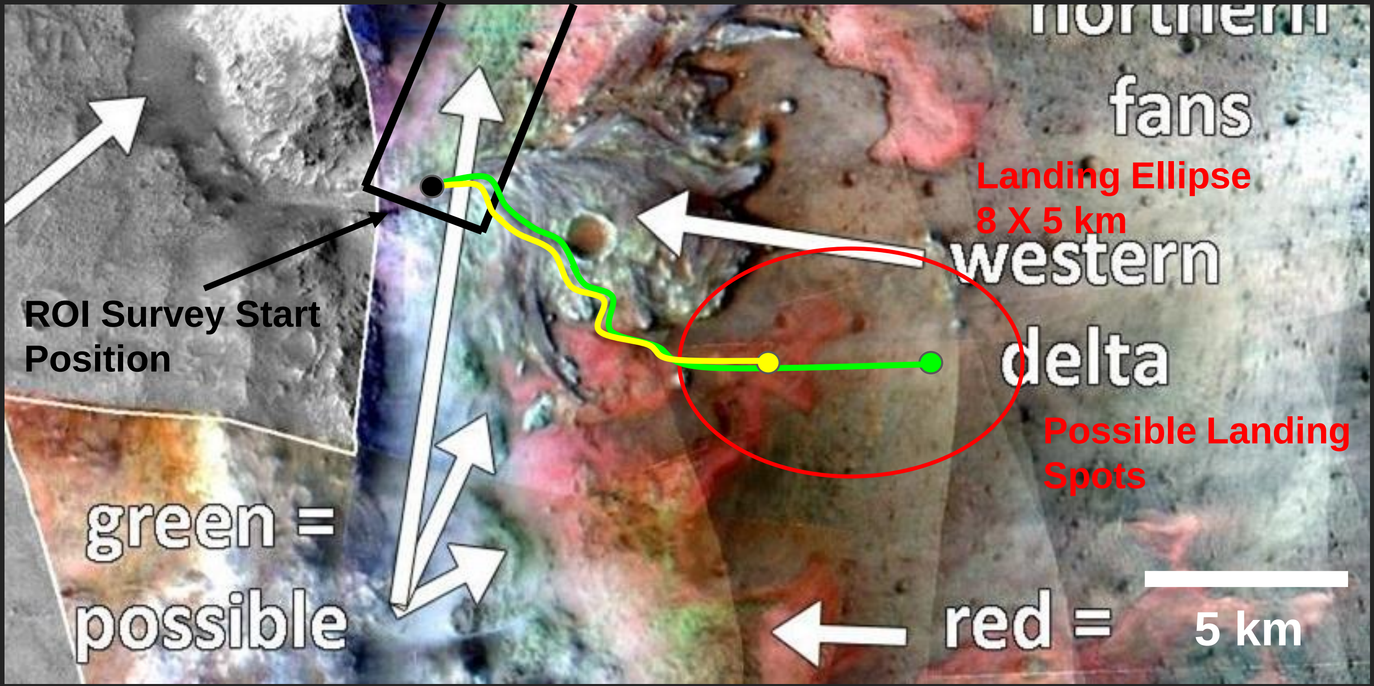


Landing Ellipse



Landing Ellipse

Traveling from Landing Ellipse



Traveling to ROI

Landing Site - 1
8 km traverse to ROI

Time to ROI
@ 600m/sol = 13 sol + 1.2 sol (calibration) = 14.2 total sol

Landing Site - 2
13 km traverse to ROI

Time to ROI
@ 600m/sol = 22 sol + 1.2 sol (calibration) = 23.2 total sol

Calibration Assessment

Test	Device	Time	Example Data
Weather Instruments	Hub	4 hours to take multiple samples	Temperature, pressure, wind
Wheel Turning	Hub	30 minutes done multiple times	Angle of turned wheels
Location Test	Hub and Drone	30 minutes done multiple times	Coordinates
Communications	Hub and Drone	30 minutes to contact earth during passover phase	Sends signals from each device to make sure they are able to communicate
Cameras	Drone	16 hours to send and receive data back	Pictures from each drone and each camera
Solar Panel Folding	Drone	8.5 minutes to open	Angle and Spring data
Power Consumption	Drone	3 hours to go through multiple phases	Voltage used for different modes and operations
Alignment Tests	Drone	1 hour	Response to inputs

Total Testing time min. = 20 hours, suggested 8 hour buffer Test time = 28 hours

Drone Roles

Scout (UAV)

- Primary Function: Maps the area in front of the rover using low resolution visual imaging and identifies areas with potential biosignatures
- Secondary Function: Identify areas where terrain may be unsuitable or risky for the rover.
- **2 Scouts total**

Cavalry (UAV)

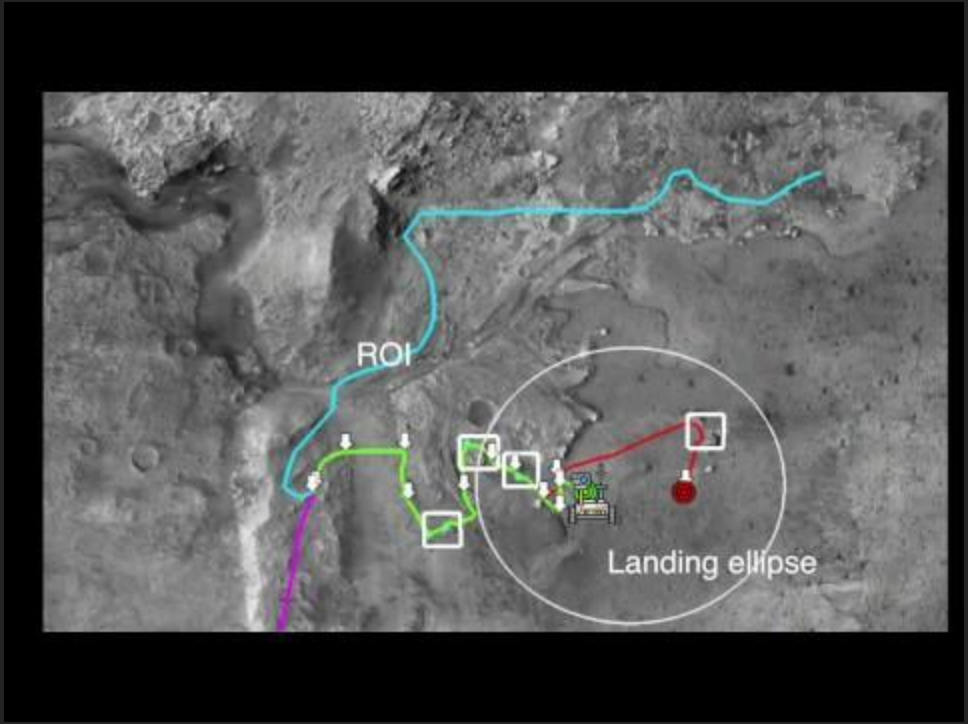
- Primary Function: Takes hyperspectral photos of selected areas where scientists suspect there are concentrations of hydrated mineral areas
- Secondary Function: Takes high resolution visual photos of stromatolite areas
- **2 Cavalry total**

Hub (Rover)

- Mission Function: Receives data from UAVs and sends them to orbiting satellites
- Adjusts travel path depending on results found by the Scout and Cavalry

Rover Capabilities

- Communication station and a “brain” for autonomous driving
- Store image data and process them into low resolution format
- Send all the data back to Earth and receive coordinates for Cavalry high resolution examination
- Design its own path without human commands and be able to “see” the surroundings

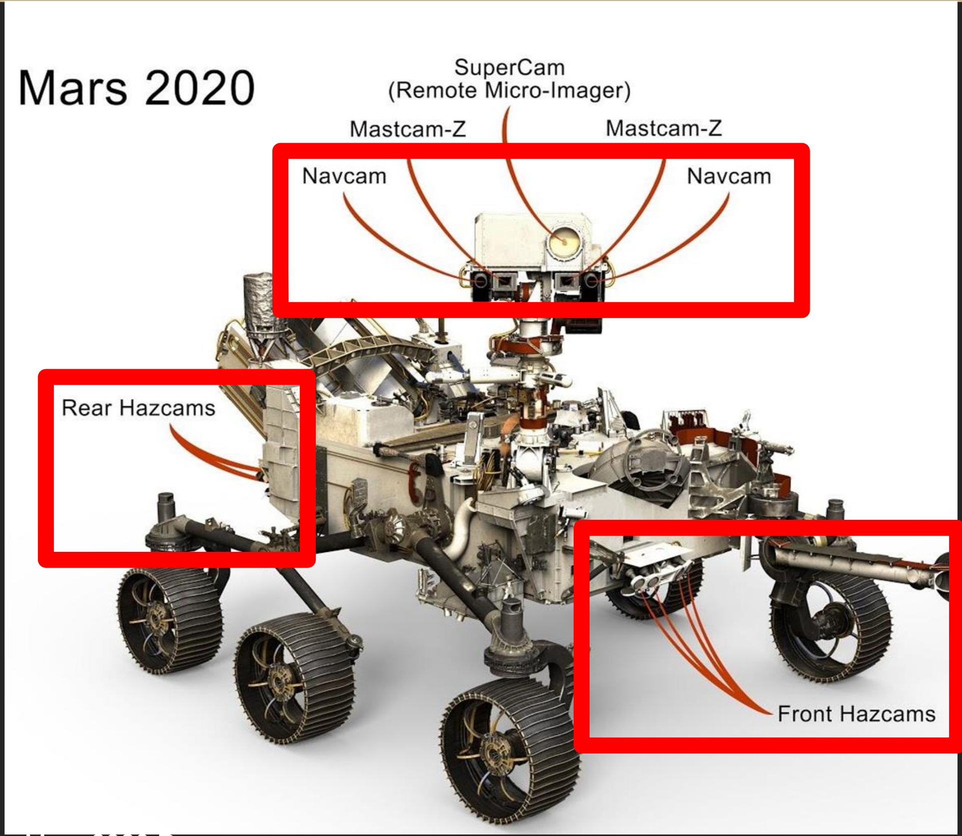


Rover path animation

Machine Learning

Machine learning is limited to navigation, because:

1. Lack of knowledge of microbialites on Mars and data to train the machine learning
2. We will collect data valuable for training process of machine learning for future missions and geoscience analysis
3. We have sufficient amount of time to wait for commands from image selecting team on Earth

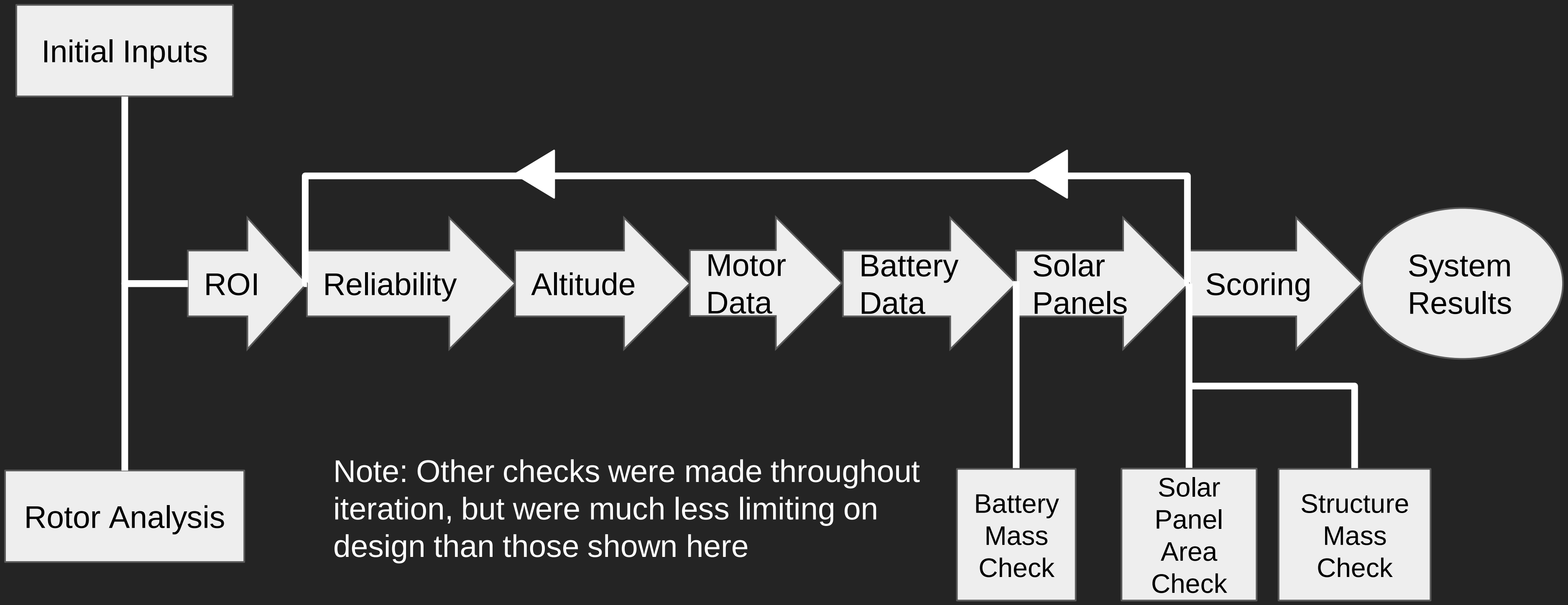


Mars 2020 Rover

SPECTRE

Vehicle Design and Mass Budgeting

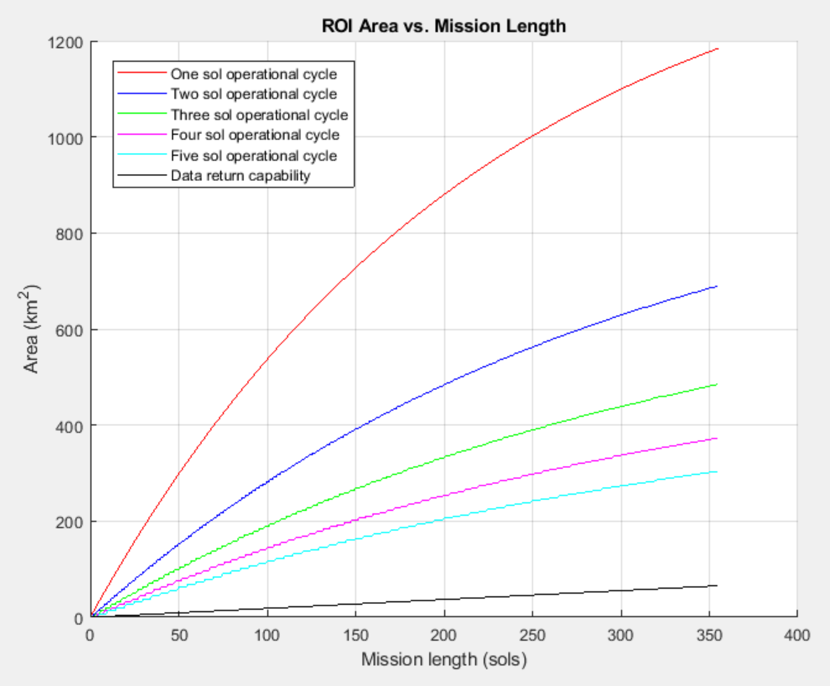
Mass Budgeting Code Logic



Note: Other checks were made throughout iteration, but were much less limiting on design than those shown here

Drone Performance

- Collect list of potential faults
  - Determine probability and impact on area
  - Associate events with discrete behavior
- Determine expected capture area
  - Fly maximum range each flight
  - Collect data through entire cruise
- Compare capture area to area returnable to Earth
  - Greater capture to return ratios indicate greater reliability
  - Recommend capturing at data return rate in actual operations



Ranking System Performance

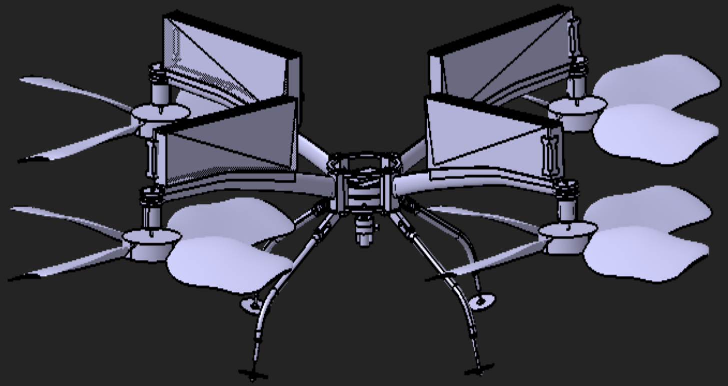
- Scoring system rubric
- Specification ranking:
  - Drone mass: -4
  - Cruise alt: -3
  - Sols/cycle: -3
  - Reliability: +5 (2.5+2.5)
  - Rotor radius: -1
  - Range: +4
- Code finds top three results
- Compare these results for general system overview

Weighted Decision Matrix

		OPTIONS					
Criteria	Weighting	Option 1		Option 2		Option 3	
		Score	Total	Score	Total	Score	Total
Criteria 1	1	1	1	5	5	5	5
Criteria 2	2	2	4	4	8	5	10
Criteria 3	3	3	9	3	9	5	15
Criteria 4	4	4	16	2	8	5	20
Criteria 5	5	5	25	1	5	5	25
	TOTAL:		55		35		75

Drone Specifications

- Drone mass: 31 kg
- Packed drone dimensions: 3.0m x 3.0m x 0.5m
- Cruising altitude: 30 m
- Maximum range per flight: 7.85 km
- Maximum cruise time per flight: 523 sec



Bonus Slides

Vehicle Design and Mass Budgeting

PSE - Code Logic - Inputs

- Number of drones
- Max mission time
- Region fraction using each camera
- Battery fraction night and flight
- Sensor power draws
- Payload mass
- Transmission rate
- Number of rotors
- Number of blades
- Environmental conditions
- Max speed cruise and vertical
- Mass of avionics
- Avionics power draws
- Rotor information (rpm, radius, power)
- Iterated values
  - Overall mass [kg] 10:50
  - Range per sol [m] 150:8000
  - Sols per cycle 1:5

PSE - Code Logic - Functions

- Mission Function
  - Determines total ROI area using data transfer limits
  - Input max mission time, % of ROI to be imaged by hyperspectral and high res cameras
- Reliability Function
  - Determines expected area coverage
  - Input max mission time and vary sols per operational cycle
  - Uses likelihood/consequence estimations from risk assessment and probability to reduce expected area as mission progresses
- Altitude Function
  - Determines ideal cruising altitude for specified image quality
  - Input total ROI area from Mission Function and vary range per sol

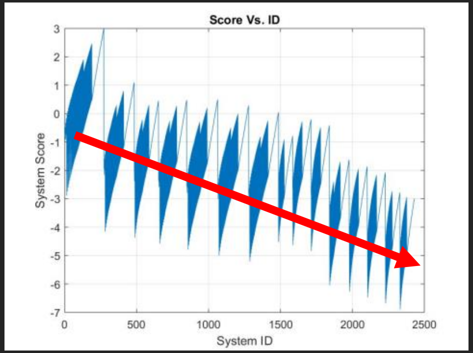
PSE - Code Logic - Functions

- Motor Function
  - Determines motor mass and efficiency
  - Input power required by each mode of flight
  - Uses Rimfire Brushless Outrunner motors for comparison based on required power
  - Linearly interpolates when required power exceeds existing motor specifications
- Battery Function
  - Determines mass, volume and voltage capacity of battery
  - Input power draw from each system and required battery remaining after night and flight
  - Uses extrapolated specific energy [energy/mass] and energy density [energy/volume] values

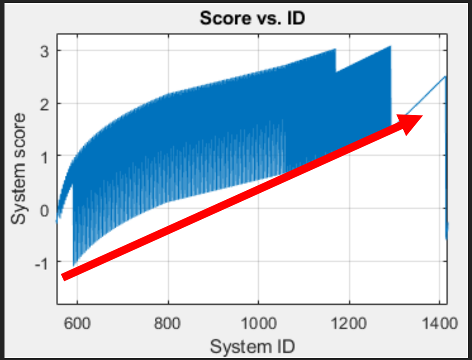
PSE - Code Logic - Functions

- Solar Panel Function
  - Determines mass and area of solar panels
  - Input battery specs from Battery Function, charge time and solar flux data
  - Uses typical solar panel efficiencies to determine required area and resulting mass
- Decision Matrix function
  - Grades design based upon defined scale
  - Input all system specs determined by code
  - Uses Decision Matrix logic to score each design

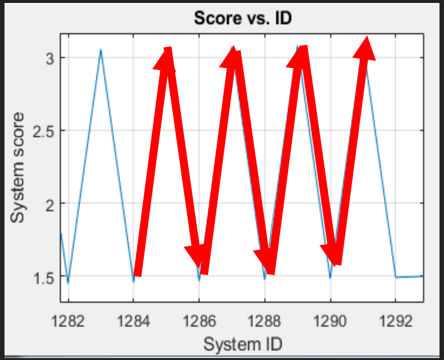
PSE - Code Logic - System Scoring



- Lower system mass increases the system preference



- Increasing range per sol increases system preference



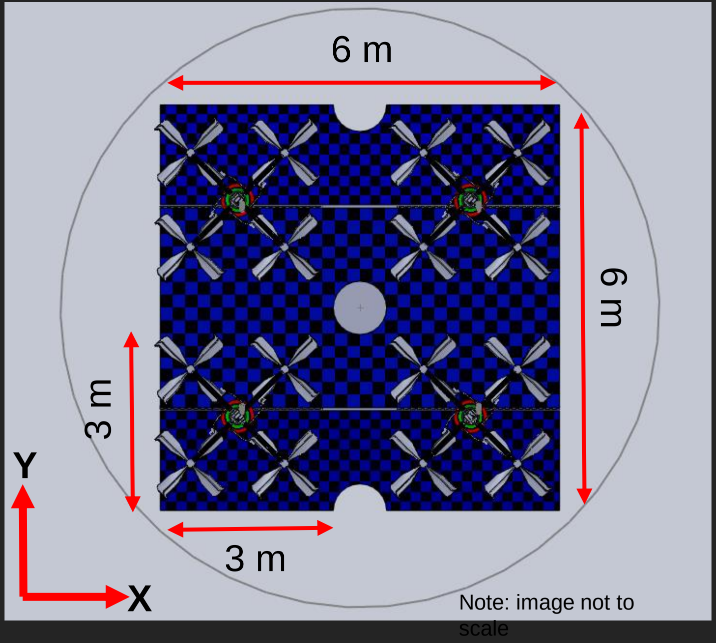
- Increasing sols per cycle increases system preference

SPECTRE

Packaging

Packaging Specifications

SLS Fairing diameter size: 9 m



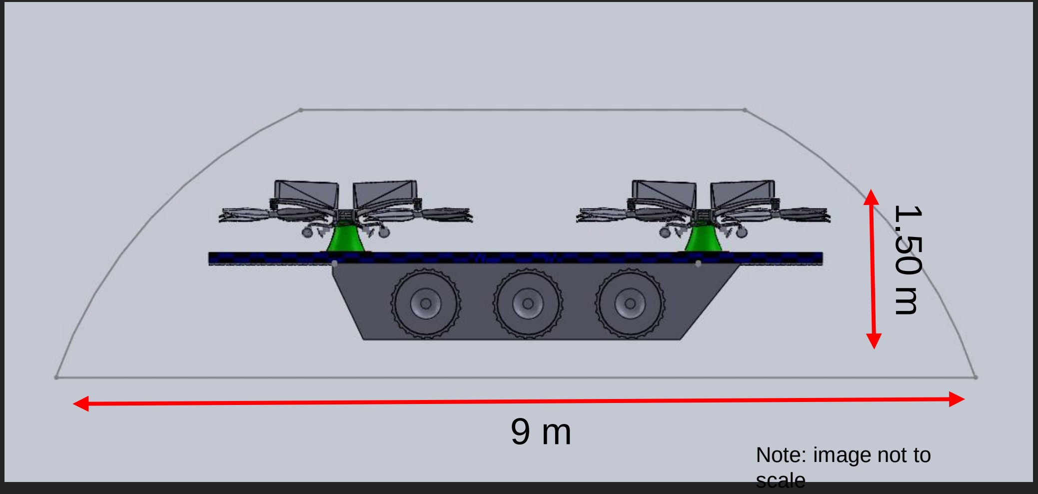
Packaging Dimensions with Fairing Top View

<u>Top View</u>

- Drone height = 0.65m
- Drone overhang limited by 9 meter diameter
- Solar Panel Platform

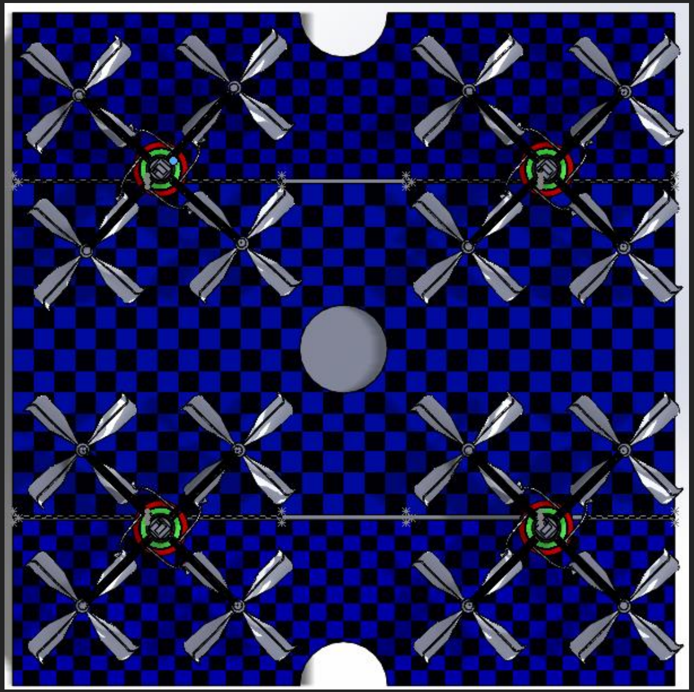
<u>Side Profile</u>

- Hub height = 0.85m
- Total packed height = 1.5m
- Assembly fits in the envelope of 9m X 1.5m



Packaging Dimensions with Fairing Side View

System Packaging



System Packing Top View

Rotor Clearance = 0.46 m

Drone Rotor Length = 1.26 m

Drone total length = 2.98 m

Platform sides = 6 m

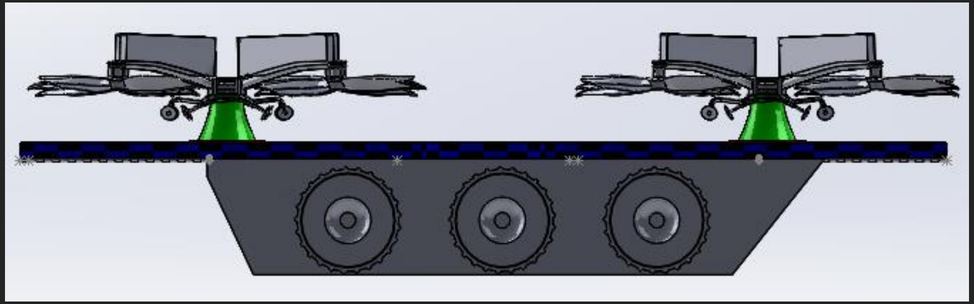
Diagonal distance = 8.49 m

Max diameter of Aeroshell = 9 m

Drone height = 0.65 m (With locking mechanism)

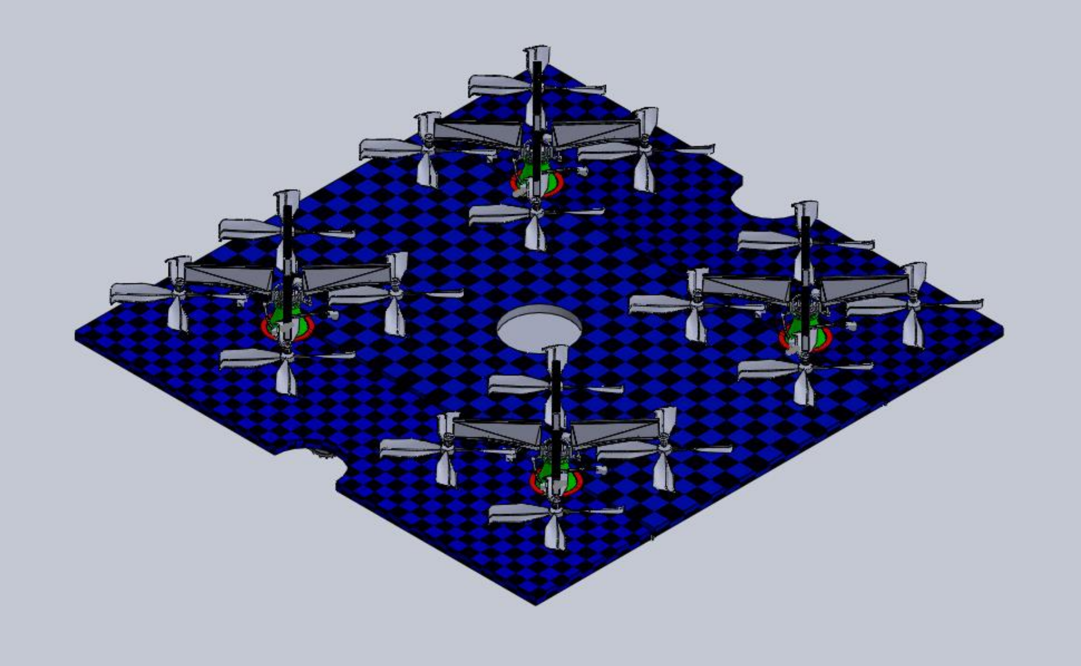
Rover Height = 0.85 m

Total Height = 1.50 m



System Packing Side View

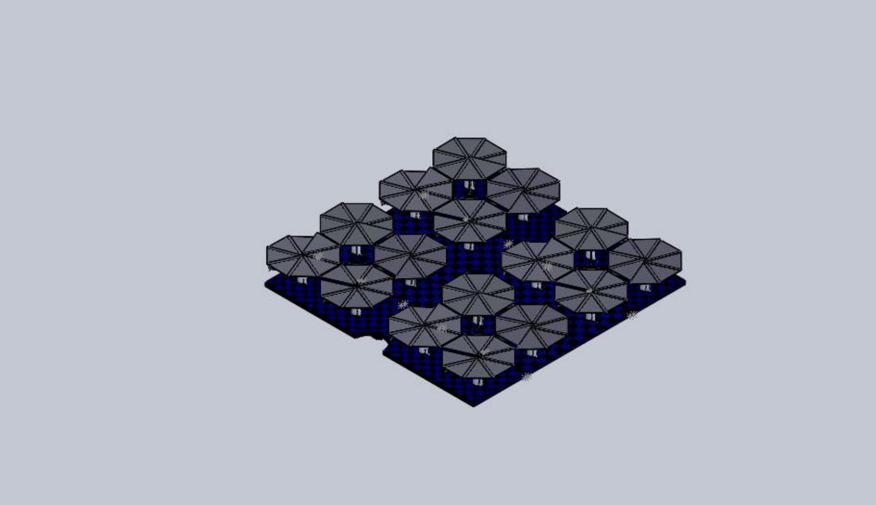
Packaging Order of Operations



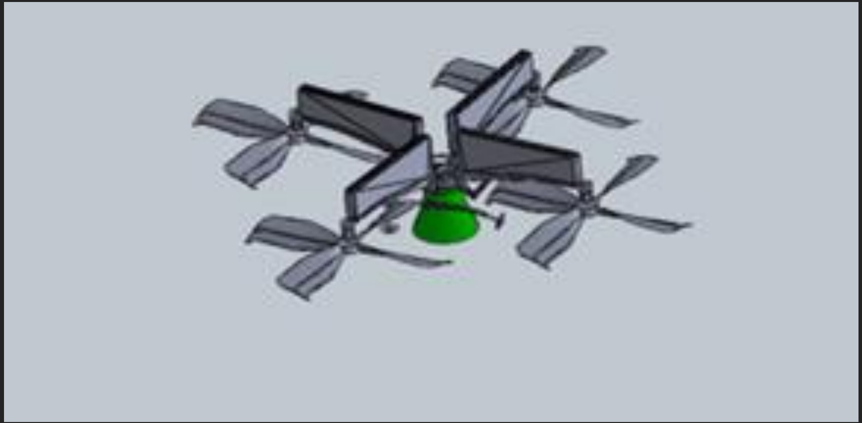
Drones on the rover platform

- Designed as per the SLS payload fairing specifications.
- Using skycrane, SPECTRE will be lowered and the hub will move away from the fairing. Then it will release drones one at a time.
- Once drones are in the air, the folded legs will lock into the landing position and also will release on the locking mechanism.
- Drones are secured with locking mechanism (green colored piece) which protects camera gimbal.

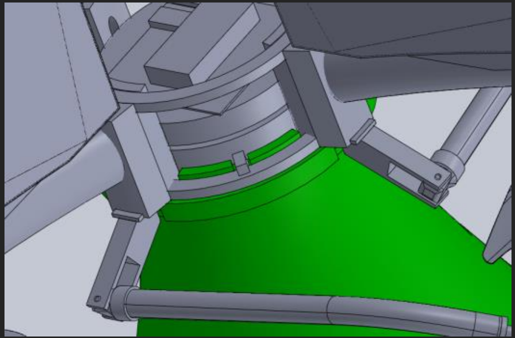
Operations from Packaged State



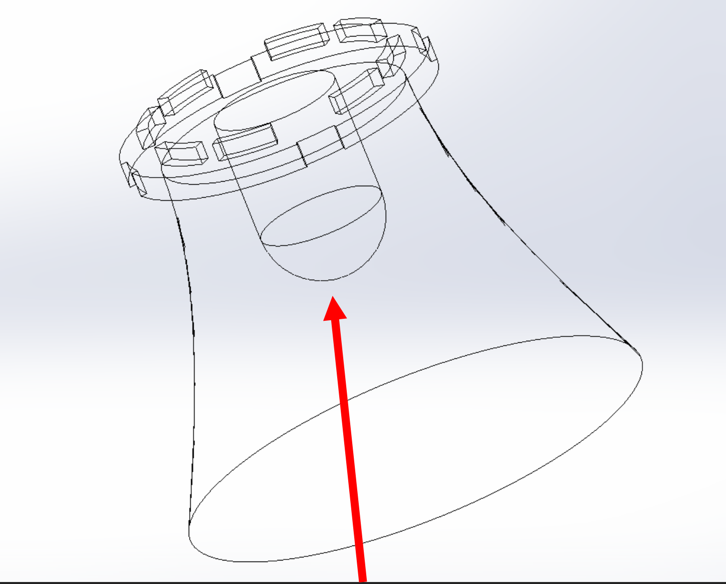
1. The drones deploy from the top of the platform.



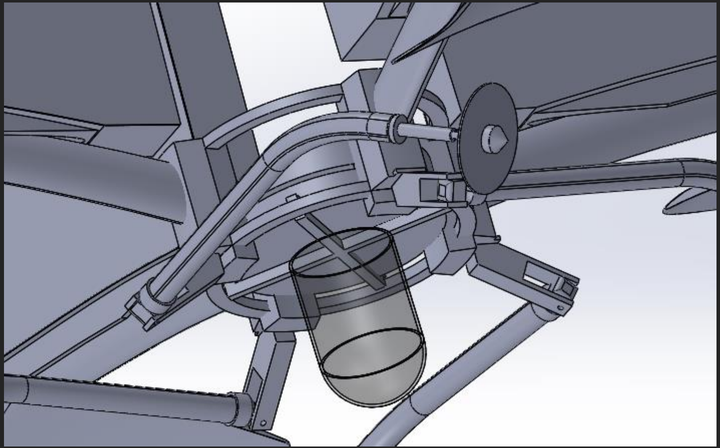
2. They drop the green locking mechanism during flight and continue the mission.



Camera Protection



Locking Mechanism has been created with the shell in mind.



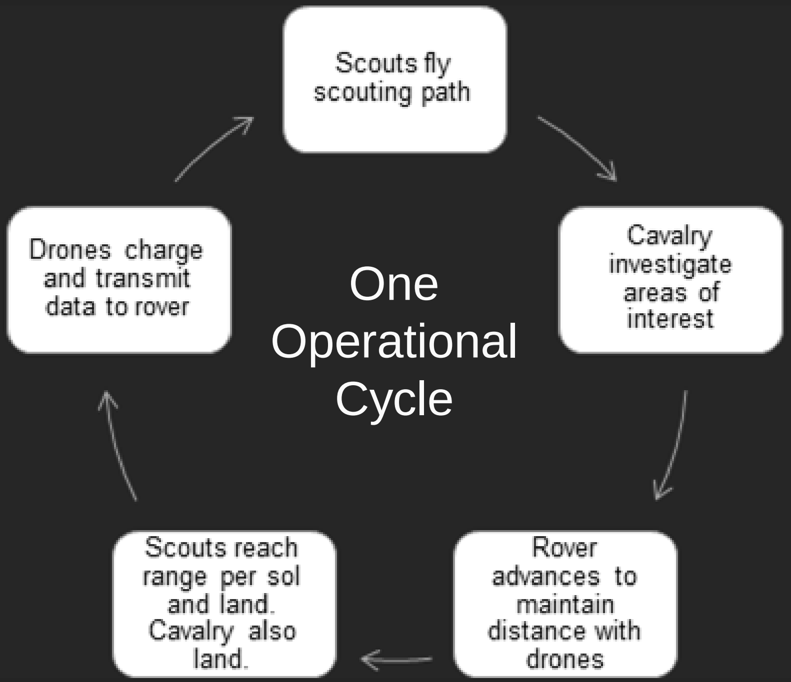
Cameras and Gimbaling prosthesis is contained inside of plexiglass shell.

Camera Protection Characteristics	Measurement
Height	0.1016 m
Diameter	0.09652 m
Hempisphere Diameter	0.09652 m

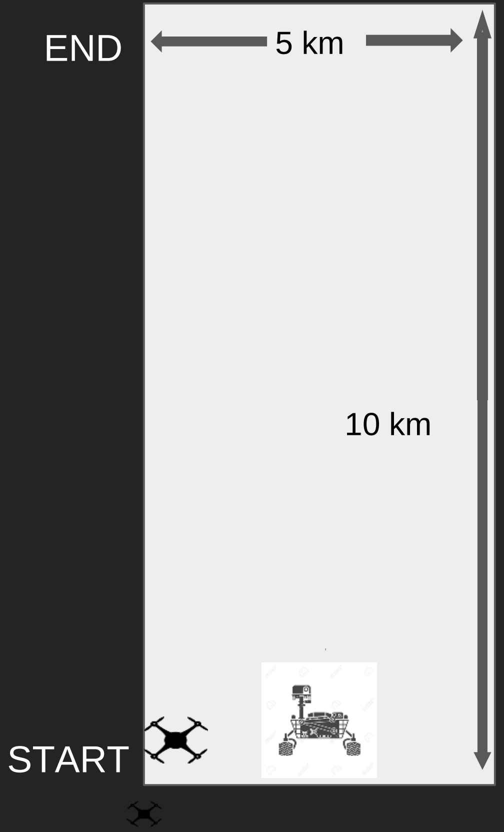
SPECTRE

Flight Path

Flight Path Operations



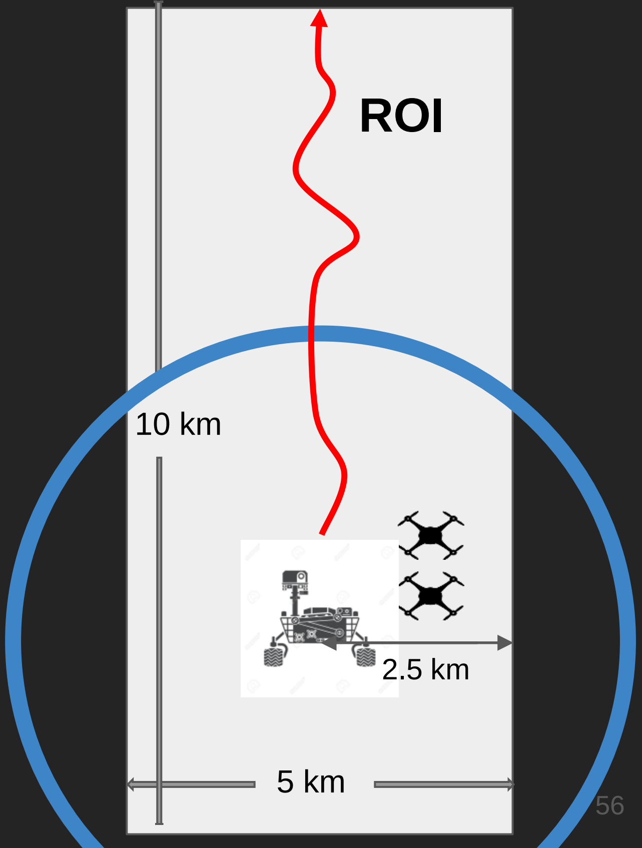
Flight Path Timeline



- Rover and Drones arrive at respective starting points in ROI
- Scout Drones begin scouting path
- Cavalry Drones investigate predetermined areas of interest
- Rover advances to maintain reasonable distance with drones
- Scout Drones reach their maximum range per flight
- Scout Drones transmit data to Rover
- Scout Drones continue scouting paths in the next operational cycle
- Areas of interest are identified by science team
- Cavalry Drones investigate areas of interest (possible stromatolites)
- Cavalry Drones transmit data to Rover
- Cycle repeats until ROI completely investigated

Flight Path ROI

- Selected a ROI size of 5 km by 10 km
  - Flight path and ROI size ensures LoS between drones and rover always maintained
    - 4 km LoS requirement enforced
  - Rectilinear ROI shape selected to maximize efficiency of capturing and stitching rectangular images
- Rover matches the drones' progression "up" the ROI
  - Rover will not fall behind given the distance it can travel per sol and the range of the drones per cycle
  - Average rover motion follows the ROI centerline



Flight Path Simulation

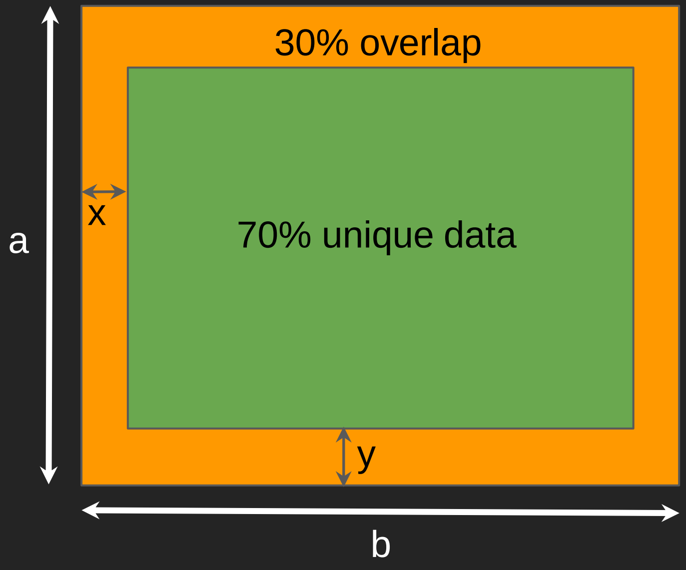
Image Overlap

- Since the image is a rectangle with two unique border widths, we took:

$$\frac{x}{y} = \frac{b}{a}$$

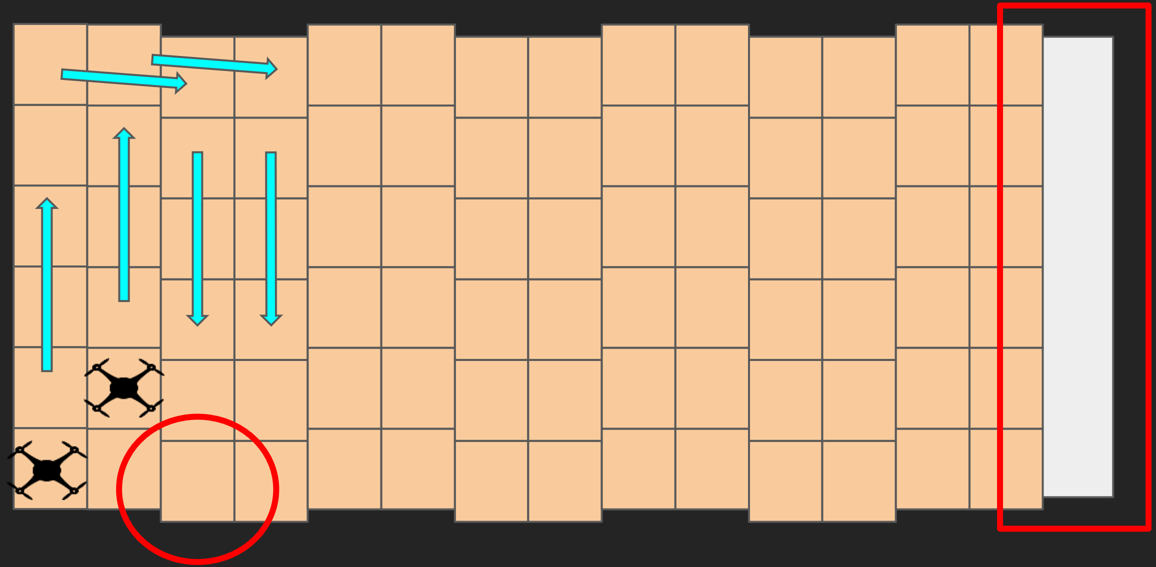
- We were able to use that relation and the quadratic below to solve for these overlap distances, which are needed to find the distance the drone must move between each picture and pass.

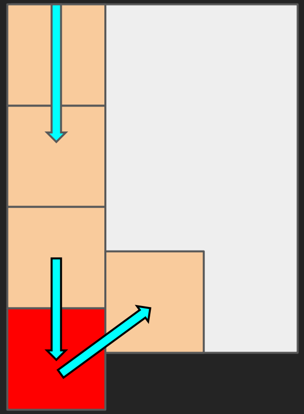
$$-\frac{4a}{b}x^2 + 4ax - (1 - p_o)ba = 0$$



p_o = overlap percentage

Flight Path Boundaries





Red image spills across ROI boundary

*Image not to scale

Flight Path Considerations

- Drone Failure/Redundancy
  - Flight path design remains the same if 1-2 drones fail
    - Flexible drone roles allow for adaptation based on mission needs
    - A single failed drone likely wouldn't affect mission time, any additional failure could result in increased mission time.
- Collision Avoidance
  - Drones are staggered to avoid any collisions
  - Each drone's flight path is separated by 33 m

Flight Path Parameters

Using an ROI size of 10km x 5km (and a drone range of 7850 m/cycle at 30 m cruise altitude) the system design is:

Total Passes per Drone	150
Passes per Cycle	1-2
Max Lengthwise Distance per Cycle	136.6 m
Percent of ROI imaged per Cycle	0.976 %
Number of Scout Flight Cycles Required	103
Total Area Imaged	50.11 km^2

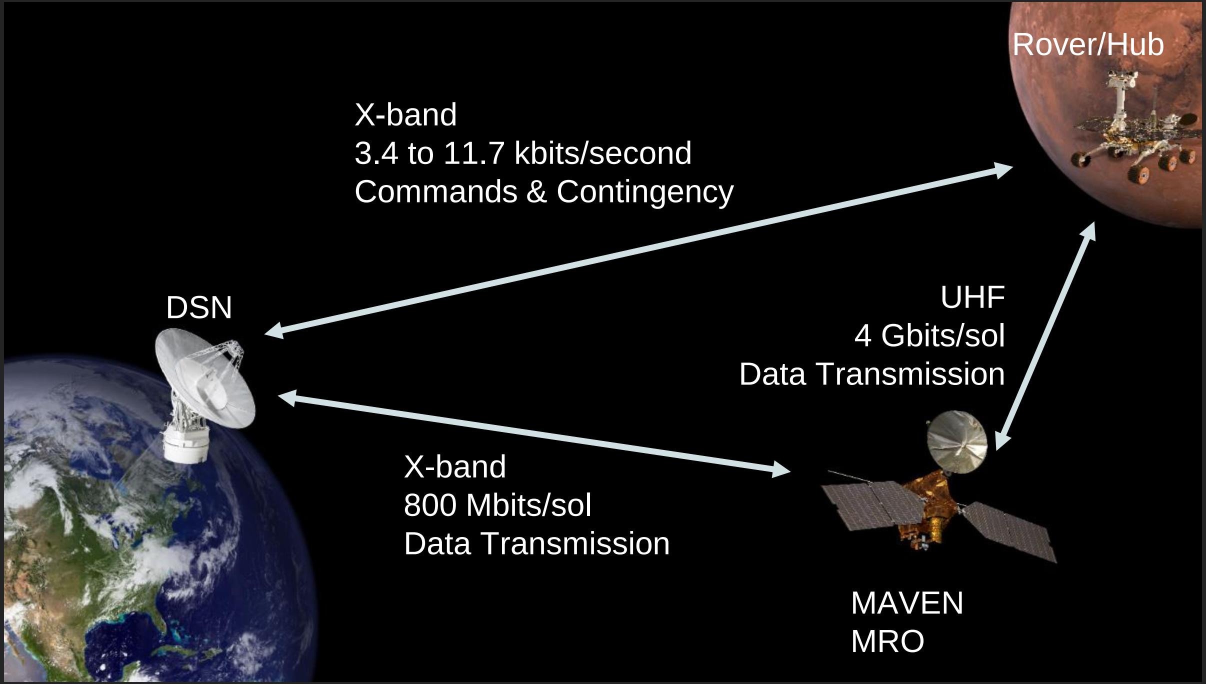
SPECTRE

Communications

Data/Command Relay

- Orbiter to DSN link is the limiting communications factor.

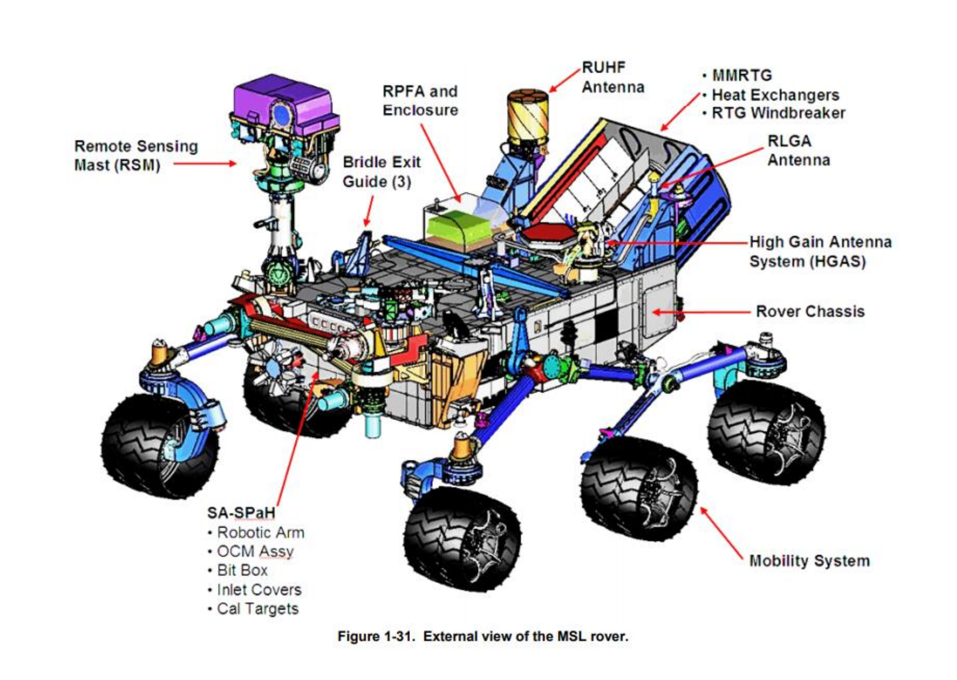
- To maximize ROI covered, data collected must be minimized.



Communications Architecture

Communications Hardware

- Rover hardware and orbital elements are already determined by existing assets.
- MSL communications and the use of two orbiters were the basis for our data rate assumptions.
- UHF band transmission from Rover to Orbiter. X-band transmission from Rover to Earth.



MSL Communications Architecture

Transceiver Specifications

- Chose a transceiver to do preliminary analysis with. (RFM69HCW ISM Module V1.1)
- Estimate antenna gain is zero for monopole antenna.
- Table shows key preliminary values for UAV to Hub communications.

Data Rate (FSK modulation)	300 kbps
Power Input During Transmission	0.507 Watts
Frequency	433 MHz

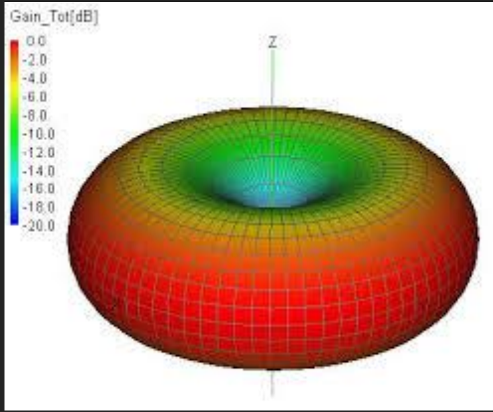
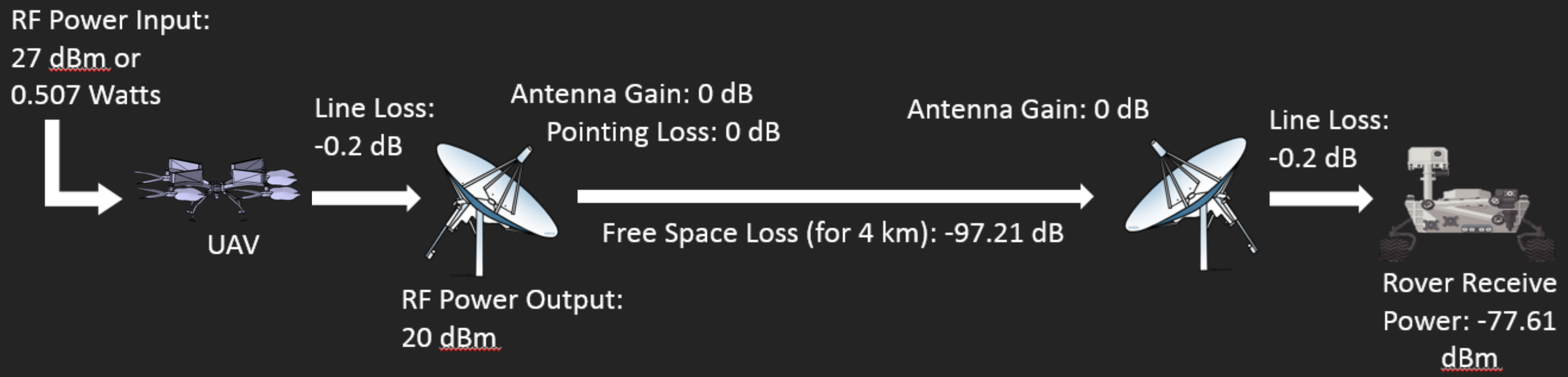


Image of a monopole antenna transmission

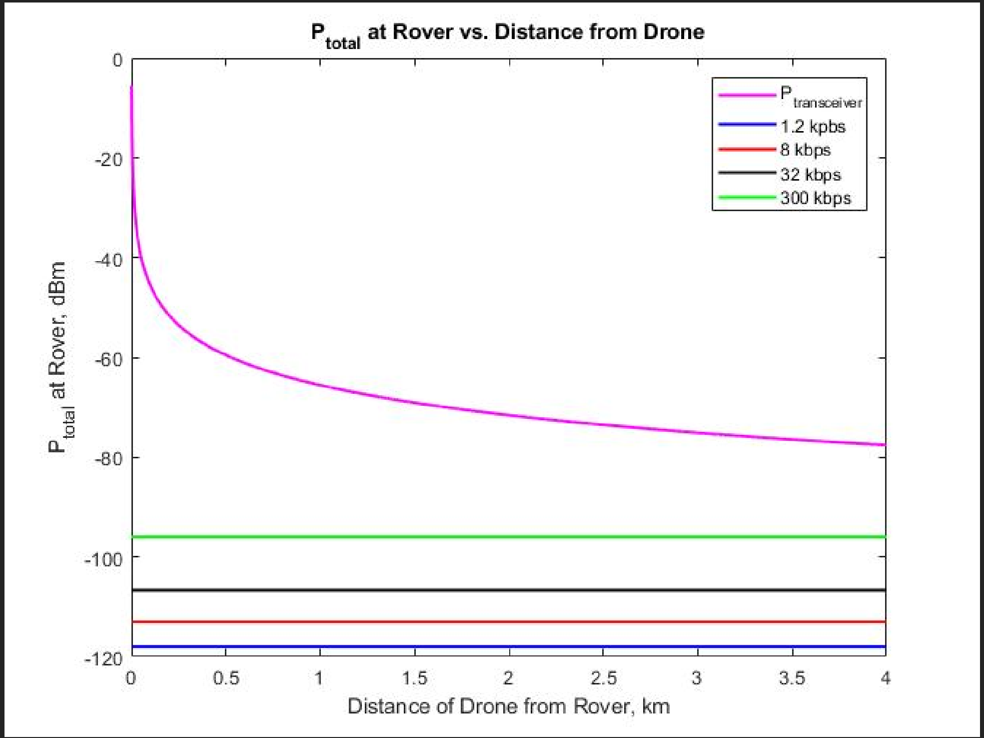
Communications Link Architecture

The receiver power indicates the maximum data transfer rate.



Transfer Rates

- Receive power decreases as distance between drone and rover increases
- Receive power dictates maximum data transfer rate
- With large margin, 300 kbps transfer rate is viable

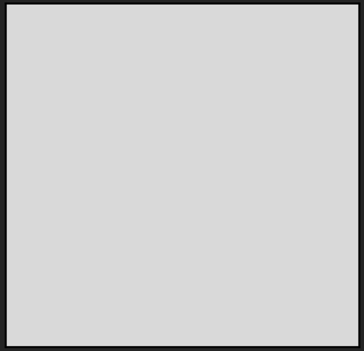


Photography Data Communications

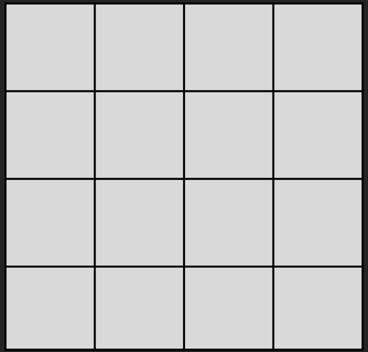
- To identify stromatolites, low resolution imaging of 2.5 cm is necessary
- In order to cover significant ROI, images are taken at 2.5 cm resolution and processed to 10 cm resolution
- If science team requires more detail, the hub can send the stored 2.5 cm images

Low Resolution Resolvable Distance	ROI Size
2.5 cm	20.2 km^2
10 cm	62.7 km^2

10 cm representation



2.5 cm representation



Mission Parameters

Mission parameters are driven by image properties and data transmission capabilities

Range per Cycle	7,850 m/cycle	Drone Transmission Time per cycle	6.013 Hours
Cruise Altitude	30 m	Total Mission Length (excluding calibration)	355 sols
Scout Drone Number of Cycles	103	ROI Size	50 km^2
Percent of ROI Imaged using Hyperspectral Imaging	5%	Area of ROI Imaged using Hyperspectral Imaging	2.5 km^2
Percent of ROI Imaged Hi-Res	0.1%	Area of ROI Imaged Hi-Res	0.05 km^2

Data Parameters

Image and data transmission definitions are shown below.

Low Resolution Visual Image Size	0.13 MB	Low Resolution Compression Ratio	1/5
Hyperspectral Image Size	12.98 MB	High Resolution Compression Ratio	1/10
High-Resolution Visual Image Size	4.8 MB	Hyperspectral Compression Ratio	1/3
Data Quantity transmitted by Rover (per sol)	100 MB		

SPECTRE

PAYLOAD

Mission Deliverables

There are three sets of pictures to be taken:

Low-Res Vis
- Taken by the Scout
- Represent a survey of the entire area
- Science Objective: Stromatolites
- Resolution: 2.5 cm

High-Res Vis
- Taken by the Cavalry
- Represent a set of structures that warrant closer study
- Science Objective: Stromatolites
- Resolution: 0.25 cm

Hyper Spectral
- Taken by the Cavalry
- Represent a set of areas chosen based on CRISM data
- Science Objective: Hydrated minerals
- Resolution: 15 cm

Con-ops: 10 cm Low-Res → 2.5 cm Low-Res → .25 cm High-Res

Optics Equations

Camera Properties	
$S_{picture}$	File size of one picture
h_{sensor}	Height of camera sensor
w_{sensor}	Width of camera sensor
P_V	Number of vertical pixels
P_V	Number of horizontal pixels
b_{depth}	Bit depth of image
f	Focal length of camera

Mission Properties	
D	Cruise altitude (working distance)
$A_{picture}$	Physical area of each picture
R_{trans}	Daily data transfer rate (Mb/day)
$\eta_{picture}$	Picture efficiency (1-overlap)
A_{roi}	Area of region of interest
r_{comp}	Compression ratio of image
d_r	Minimum resolvable distance

$$A_{picture} = \frac{D^2}{f^2} * h_{sensor} * w_{sensor}$$

$$S_{picture} = r_{compression} * P_H * P_V * b_{depth}$$

$$T_{mission} = \frac{S_{picture}}{R_{trans}} * \frac{A_{roi}}{\eta_{picture} * A_{picture}}$$

$$d_r = 2\frac{D}{f} * \max\left(\frac{h_{sensor}}{P_V}, \frac{w_{sensor}}{P_H}\right)$$

($\eta_{picture}$ = 1 assuming image stitching)

Justification for Two VL Cameras

- We need to either have variable magnification, ability to cruise @300 m, or two visible light cameras

$$d_r = 2\frac{D}{f} * \max\left(\frac{h_{sensor}}{P_V}, \frac{w_{sensor}}{P_H}\right) = constant * D$$

$$(d_r = 0.25 * 10^{-2}\ m, D = 30\ m) \rightarrow constant = \frac{D}{d_r} = 12{,}000$$

$$(d_r = 2.5 * 10^{-2}\ m) \rightarrow D = 12{,}000 * d_r = 300m$$

Camera Properties Optimization

- Camera properties don't contribute to transmission time!
- Minimize weight
- Ensure efficient high-res cruise altitude ≥ 30 m
- Minimize efficient cruise altitude of low-res camera
- Efficient = at altitude prescribed by resolution equation

$$\frac{Picture\ Area}{Picture\ Data\ Size} = \frac{A}{S} = \frac{{d_r}^2}{4 * r_c * b_d}$$

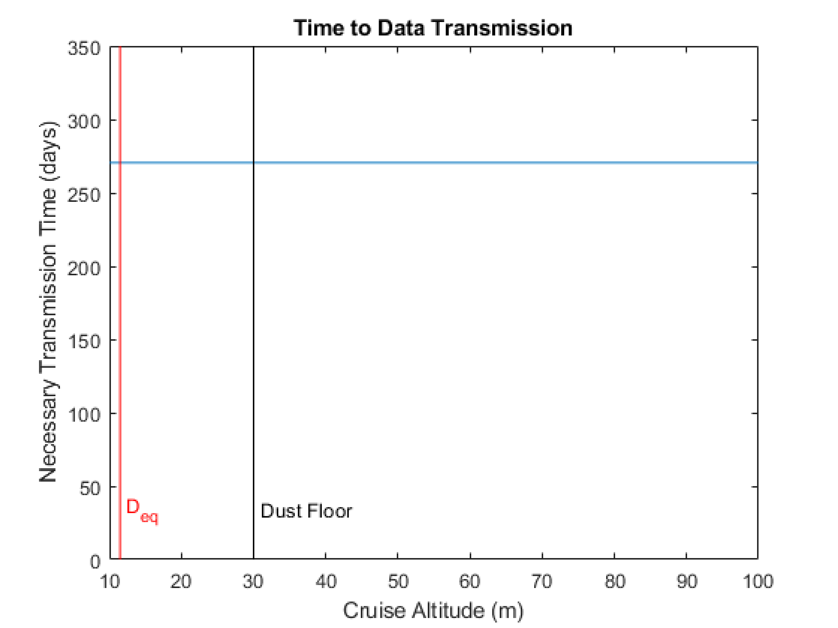
Credit: Mission Systems

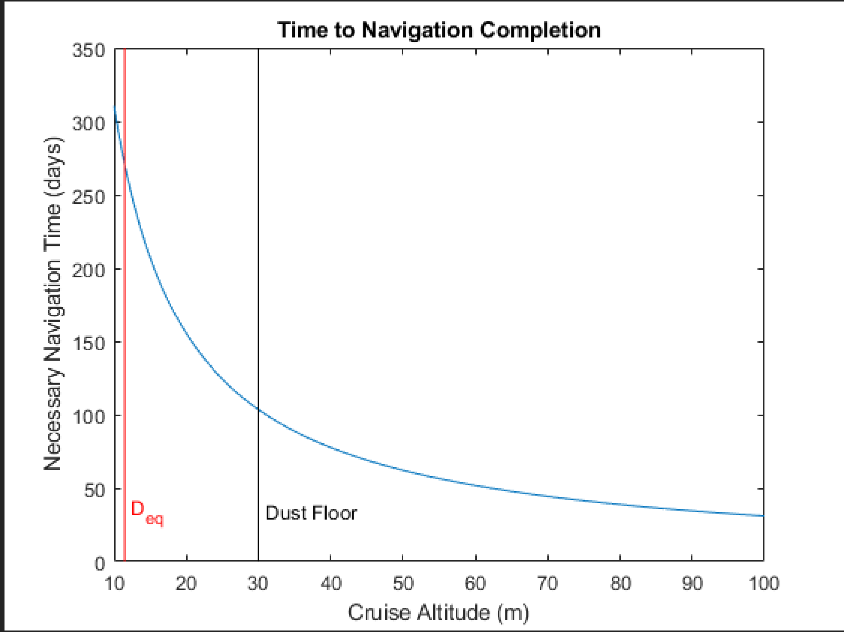
$$T_{days} = \frac{S * A_{roi}}{A * R_{trans} * \eta_{picture}} = \frac{A_{roi}}{A/S} * constant = \frac{A_{roi}}{d_r^2} * constant$$

Comparison of Data Collection

$$T_{data} \propto constant$$

$$T_{nav} = \frac{A_{roi}}{2 * D * n_{drones} * \tan\left(\frac{FOV}{2}\right) * R * \eta_{picture}} \rightarrow T_{nav} \propto \frac{1}{D}$$





Low-Res Camera

- Based on Raspberry PI Camera V2

RasPI Properties	
m	3 g
P_H	3280 px
P_V	2464 px
w_{sensor}	3.674 mm
h_{sensor}	2.76 mm
f	3.04 mm

Modified Properties	
m	4 g
P_H	3280 px
P_V	3280 px
w_{sensor}	3.674 mm
h_{sensor}	3.674 mm
f	2.693 mm

d_r	2.5 cm	D	30 m	b_{depth}	8	$S_{picture}$	10.26 Mb	FOV	68.7°

High-Res Camera

- Based on Arducam

Arducam Properties	
m	54 g
P_H	3280 px
P_V	2464 px
w_{sensor}	3.674 mm
h_{sensor}	2.76 mm
f	25 mm

Modified Properties	
m	65 g
P_H	4096 px
P_V	4096 px
w_{sensor}	3.674 mm
h_{sensor}	3.674 mm
f	25 mm

d_r	0.25 cm	D	34.8 m	b_{depth}	24	$S_{picture}$	48.00 Mb	FOV	8.4°

Hyperspectral Camera

- Based on OCI-UAV/Headwall Micro-Hyperspec

OCI - UAV Properties	
m	180 g
P_H	2040 px
P_V	linescan
w_{sensor}	12 mm
h_{sensor}	12 mm
f	35 mm
N_{bands}	100

M-HS Properties	
m	1600 g
P_H	640 px
P_V	linescan
w_{sensor}	—
h_{sensor}	—
f	—
N_{bands}	267

Modified Properties	
m	600 g
P_H	640 px
P_V	linescan
w_{sensor}	12 mm
h_{sensor}	12 mm
f	15 mm
N_{bands}	50

d_r	15.0 cm	D	60.0 m	b_{depth}	16	$S_{picture}$	39.06 Mb	FOV	43.6°

Camera Mount

- Walkera G-2D used for technical specs.
- Weight Analysis
  - Mount Mass
    - 200g
  - Total Camera Mass
    - 600-700g
  - Designed to hold 600g camera system
- Camera Mount Features
  - Gimbaling
    - Allow for viewing at different angles
      - Cliffsides
  - Damping
    - Uses semi-elastic mounting points and gimbaling motors to reduce the effects of motor vibrations on image quality

Visible Camera Image Smear

With the goal of blur in each pixel still being 0.2 pixels (0.5 cm):

$$b = \frac{V * l_f}{h * f_r * l_p}$$

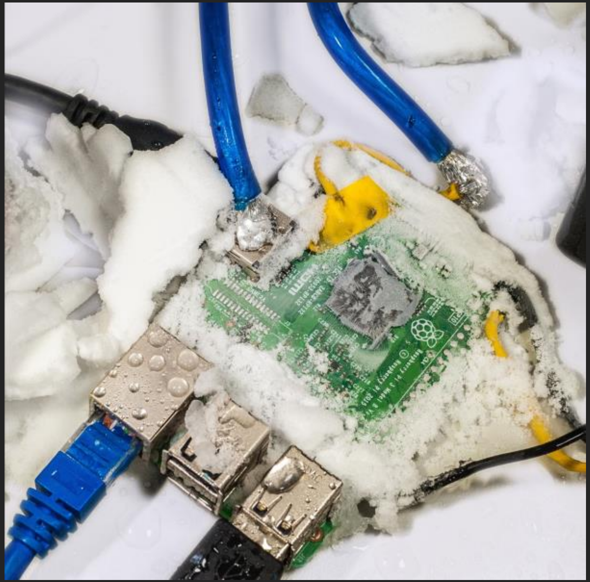
Blur Equation

Variable	Value
B (Blur)	0.2 pixels
l_f (Focal Length)	2.693 mm
h (Altitude)	30 m
V (Velocity)	15 m/s
l_p (Length of Pixel)	1.12 µm

Using the Blur equation: The camera technology used in SPECTRE must reach about 6000 frames per second, currently, cameras used in the Mars Science Laboratory exhibit this capability and beyond

Temperature Concerns

- Camera Sensor
  - Should not require heating
- Memory
  - Will require heating, most extreme rated to around -25°C
- Battery
  - Biggest concern with heating is battery, drains much faster at lower temperatures
- Raspberry Pi Camera
  - Board rated from -20°C to 60°C, will require heating

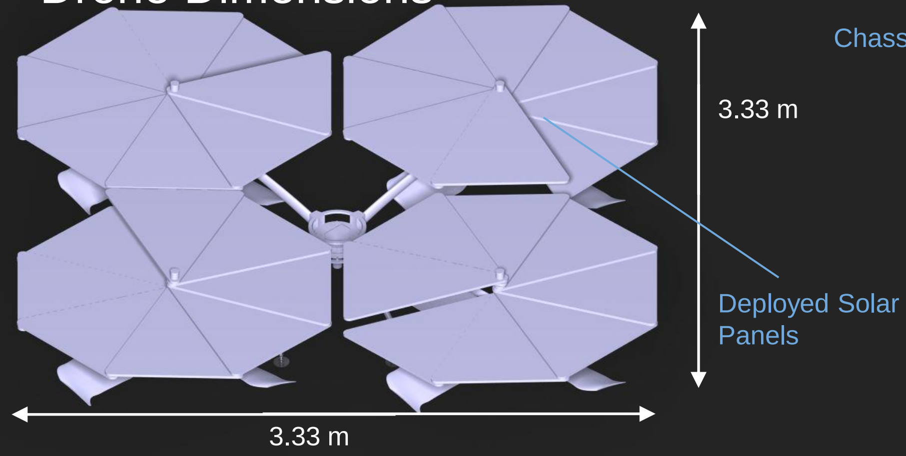


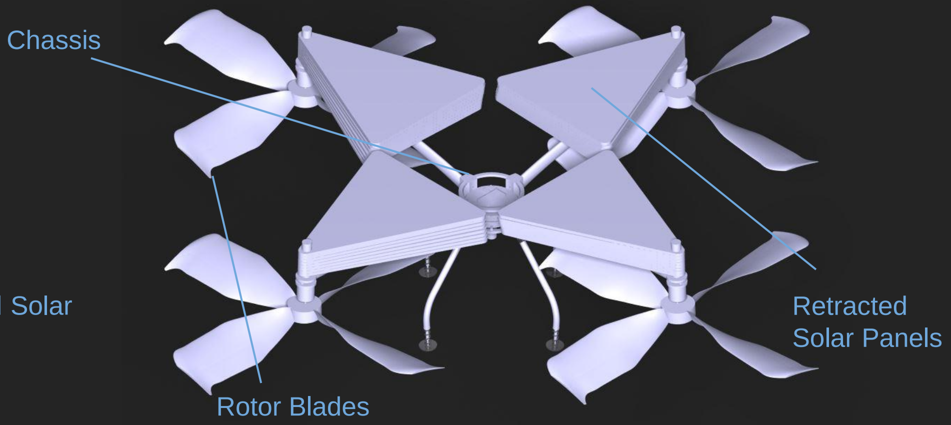
SPECTRE

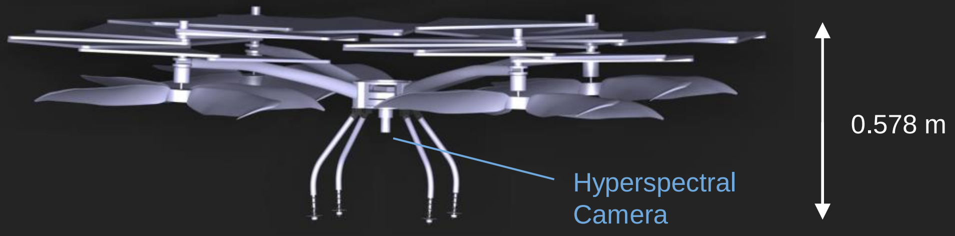
FLIGHT SYSTEMS

Preliminary Design

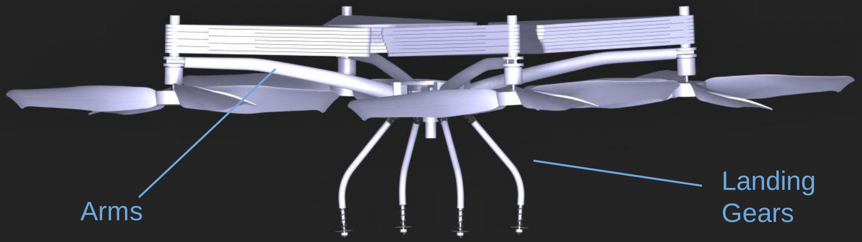
Drone Dimensions







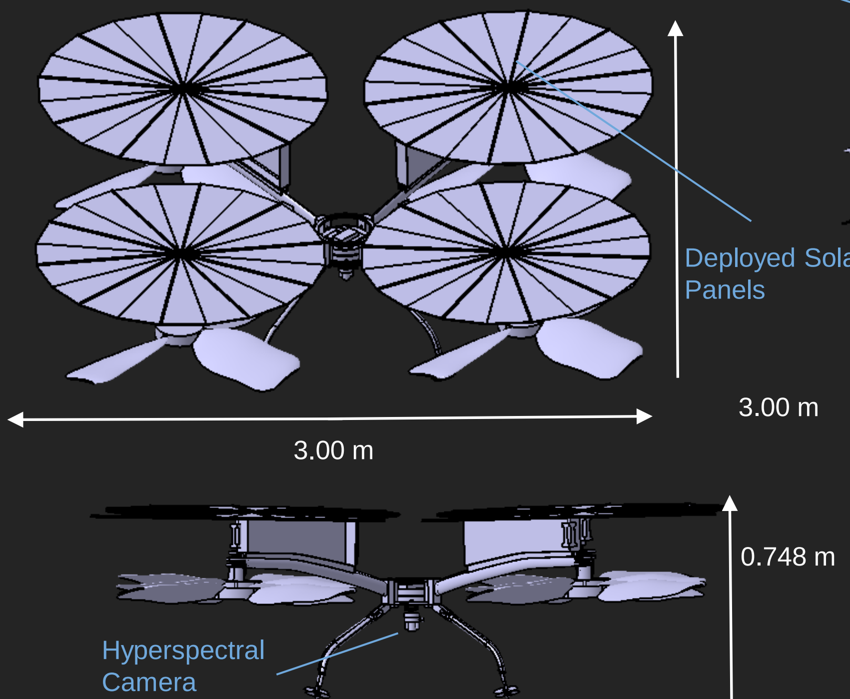
Drone with Solar Panels Deployed



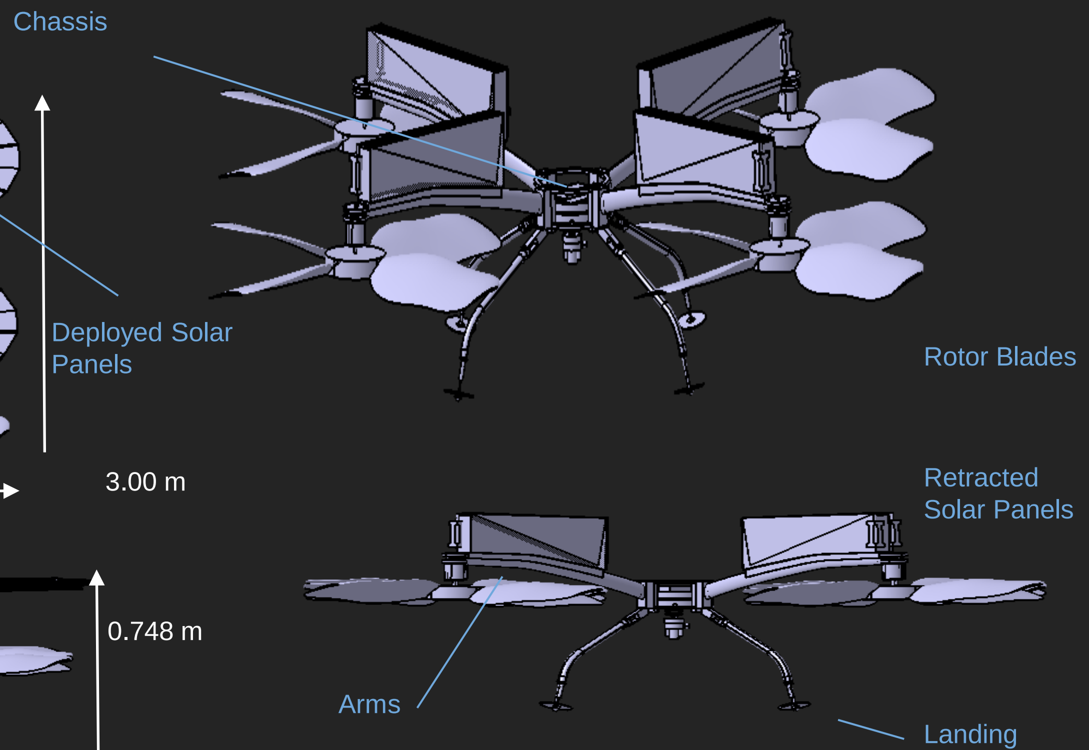
Drone with Solar Panels Retracted

Current Design

Drone Dimensions



Drone with Solar Panels Deployed



Drone with Solar Panels Retracted

Changes since PDR

- Overall size reduction
- Structural health monitoring system
- New rotor design and more in-depth analysis
- New motor selected
- New solar panel design
- New autonomy testing platform and more robust autonomy
- New thermal systems for both heating and cooling

FLIGHT SYSTEMS

AIRFRAME

Material Selection

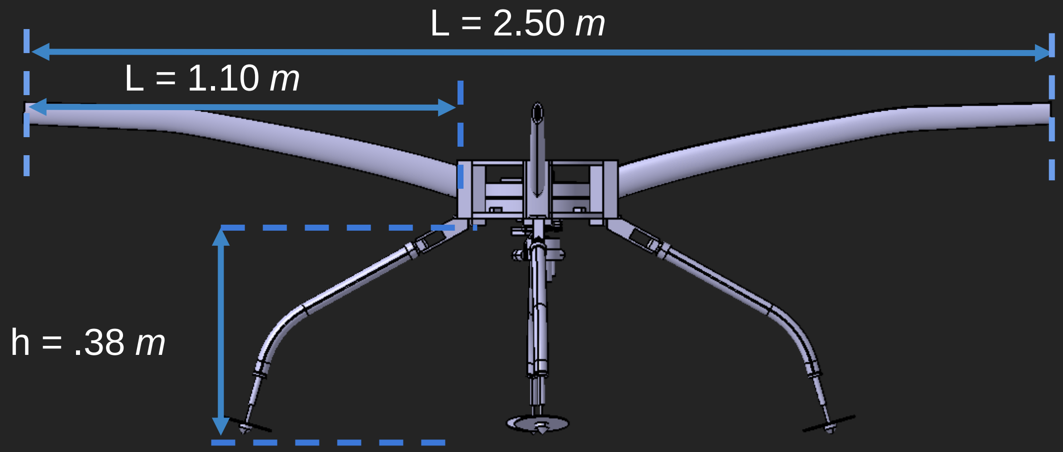
- What material is the Drone made of?
  - Carbon Fiber M60J & Cyanate Ester
- Carbon Fiber Properties
  - low density, high tensile ultimate strength
- Cyanate Ester Properties
  - toughness, strength, low moisture absorption, electrical properties, and ease of use

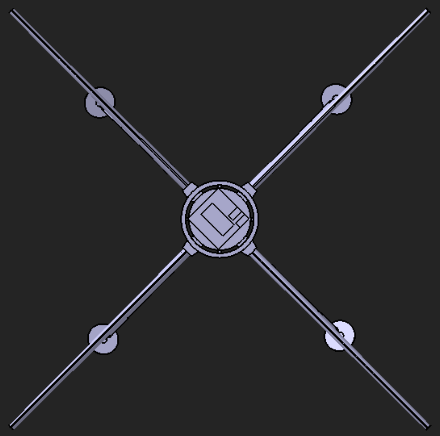
Airframe Design

Total structural mass: 6.2 Kg

Design Highlights

- 4 arms, varying elliptical cross section
  - Sized from propeller dimensions
  - Structural analysis from last semester confirms arms meet load requirements
- 4 damped and retractable landing gear
- Circular chassi section





Top View

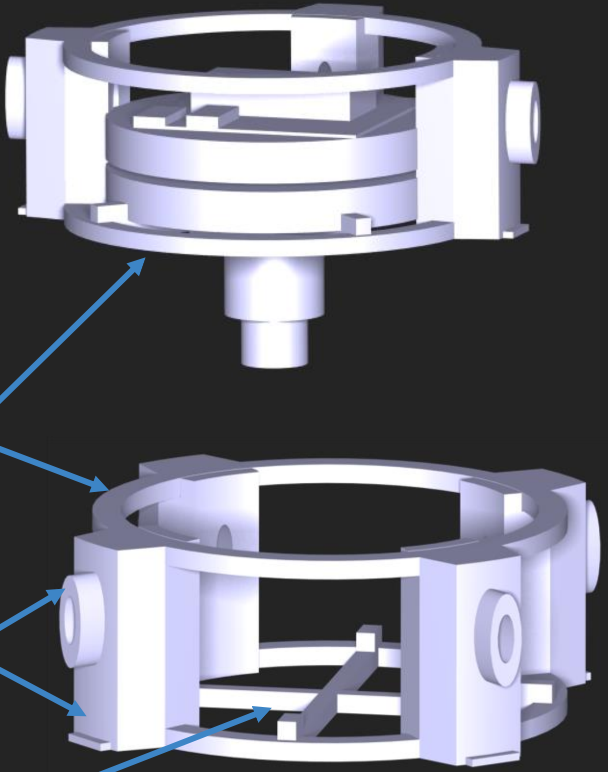
Chassis Design

Volume for
- Batteries / memory
- Flight computers / sensors
- Extra space
    - Wires / heating cooling

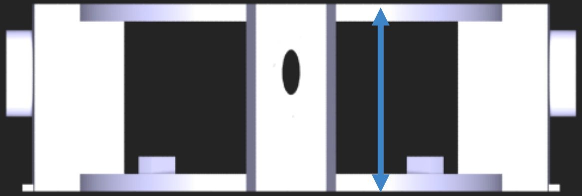
Carbon fiber structural rings
- Interference / adhesive bond to arm mounts

Aluminum arm / leg mounts

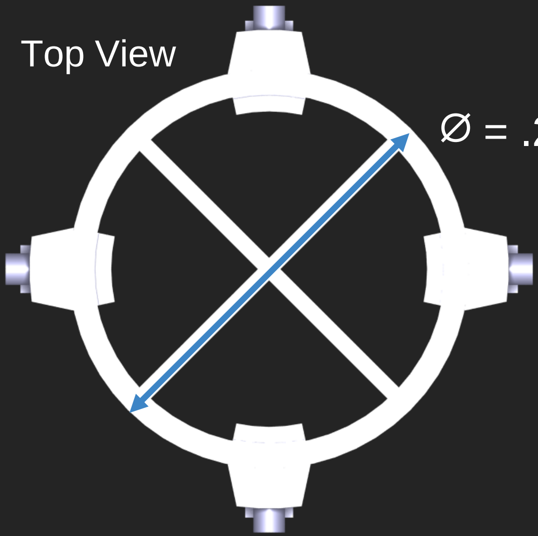
Payload mounts



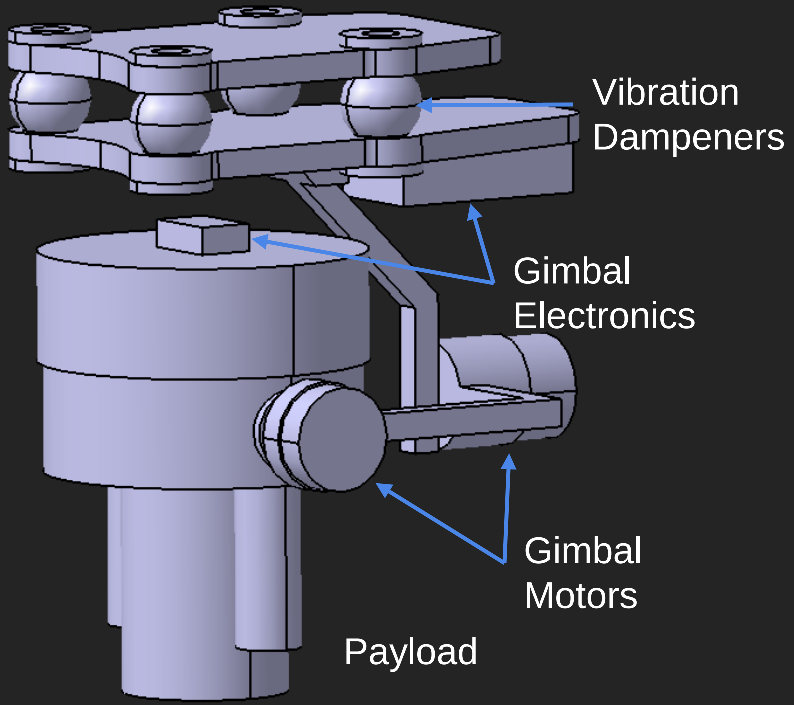
Side View



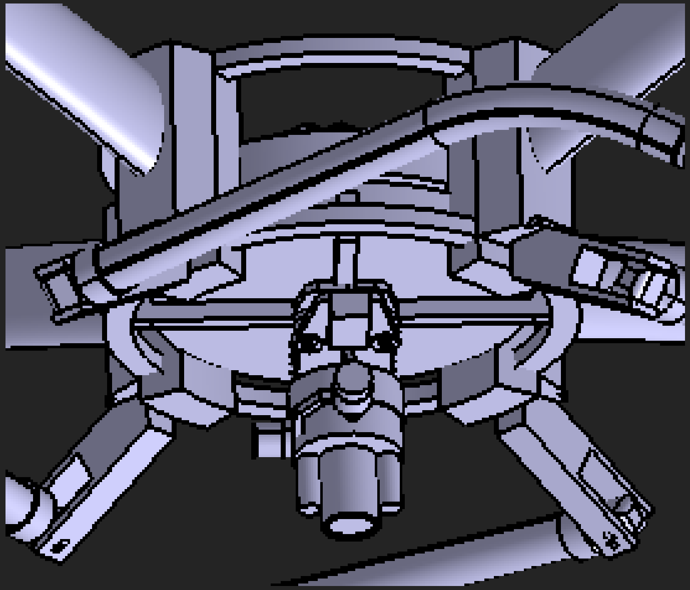
Top View



Payload Mount



Payload

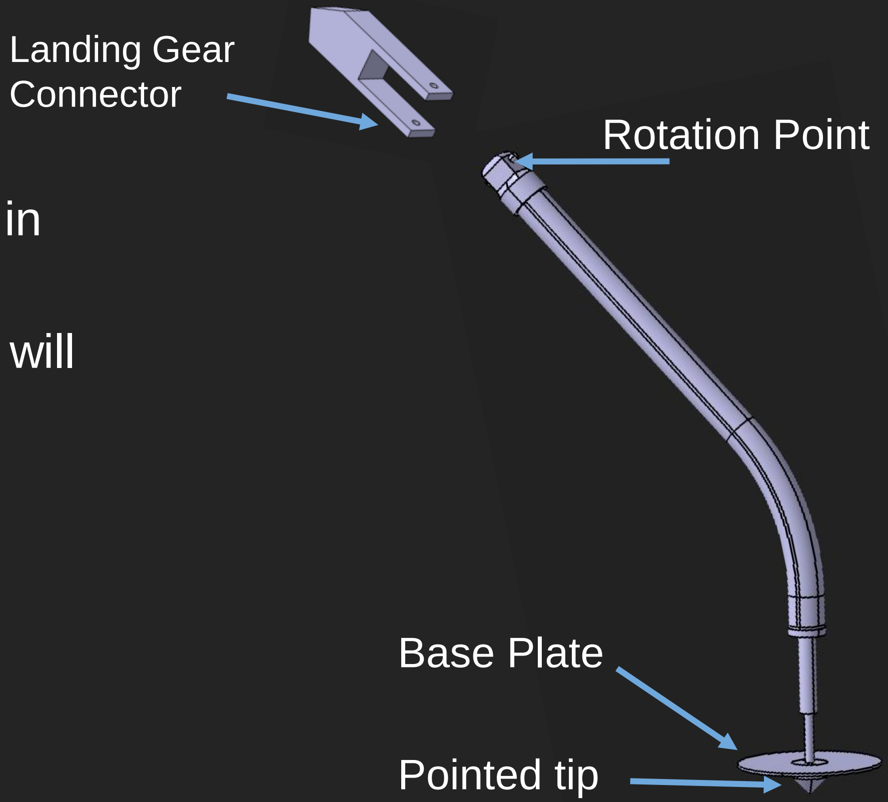


Payload Mounted to Chassis

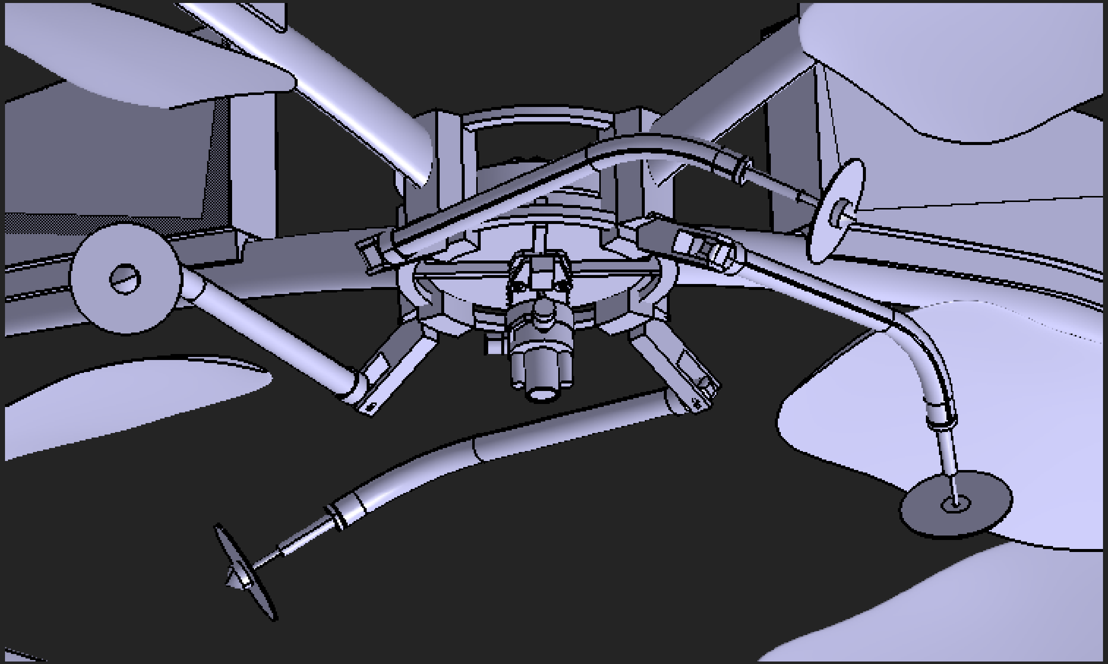
Landing Gear Design

Foldable Landing Gear Legs

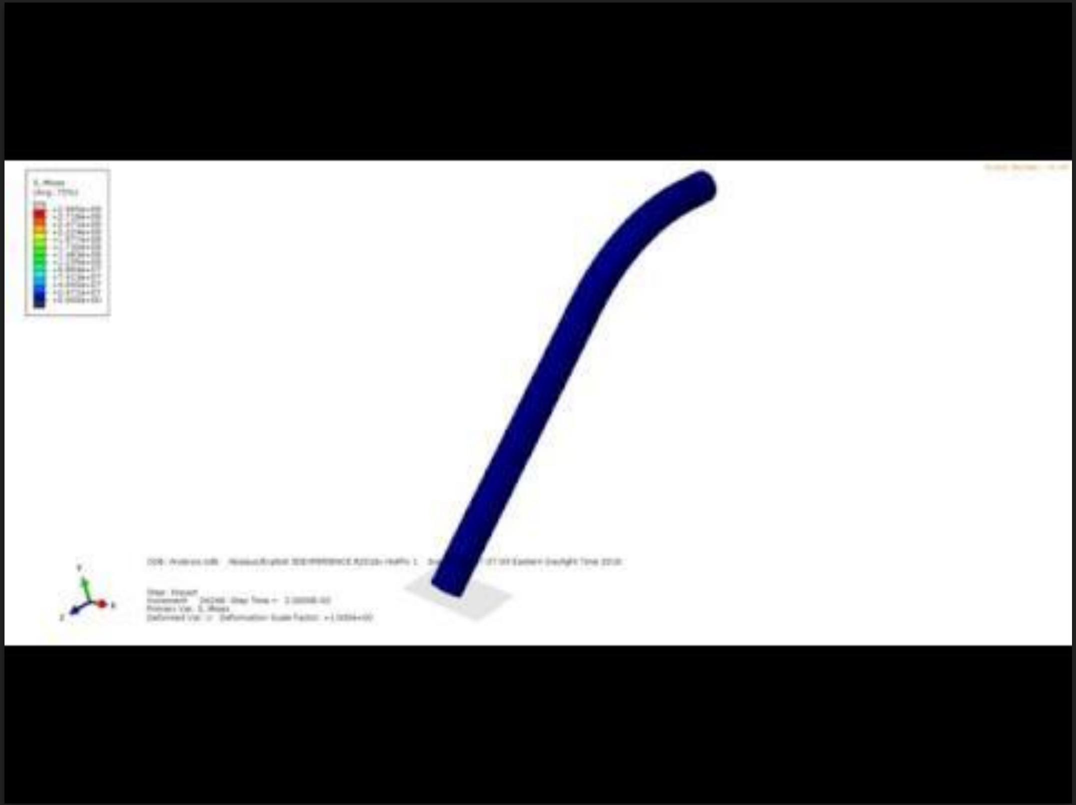
- During the flight to Mars, the landing gear legs will be folded in the orientation shown below.
- During the first ascent, the legs will unfold by their own weight, and lock into place, once fully expanded



Landing Gear Stored Orientation

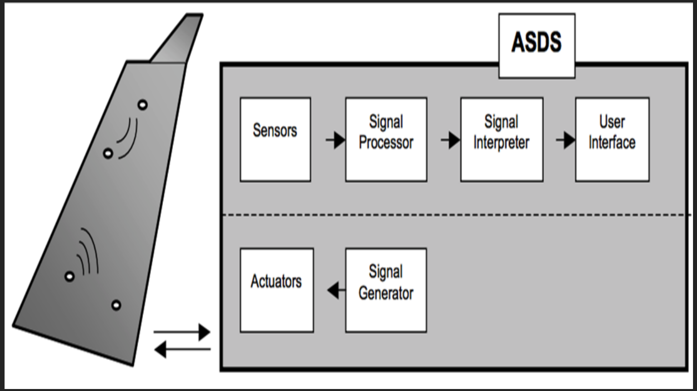


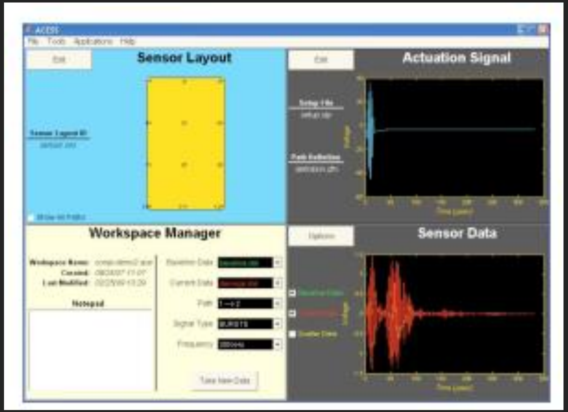
Landing Gear Leg Impact Test

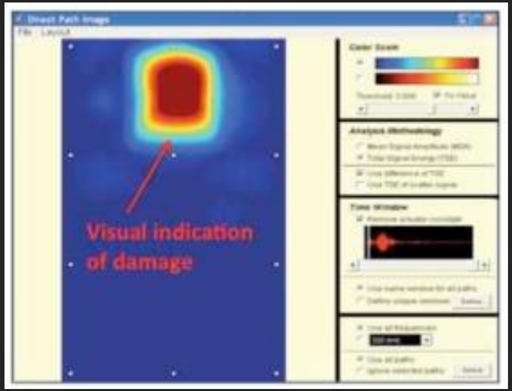


Structural Health Monitoring Technology

- Method of determining the integrity of structures
    - Active Sensing Diagnosis System (ASDS) using Piezoelectric wafers (PZT)
        - An array of PZT are bonded to the structure, one of them is submitted to a electric burst, the others capture the elastic waves produced; the process is repeated, any damage at the path between two sensors will change the received signal





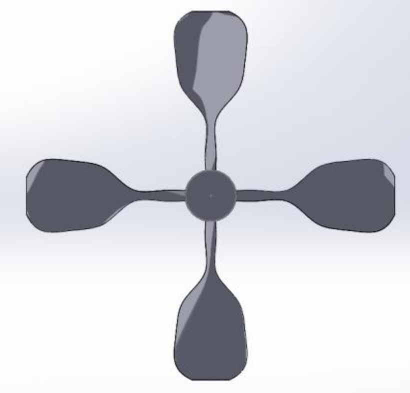


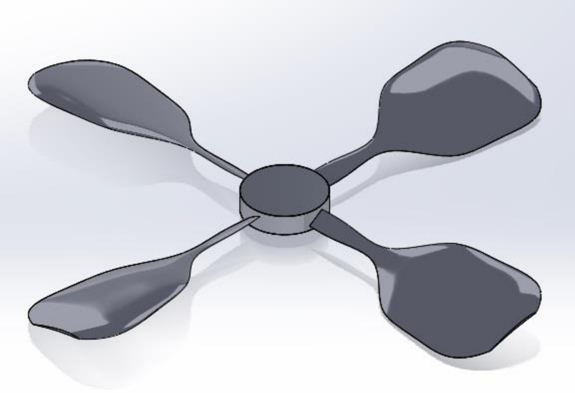
FLIGHT SYSTEMS

ROTOR DESIGN

Rotor Blade Design

- Chord maximized at tip
  - Increases thrust generated
- Chord minimized at root
  - Decreases weight of the blades
- Radius maximized
  - Increases thrust
  - Decreases power required

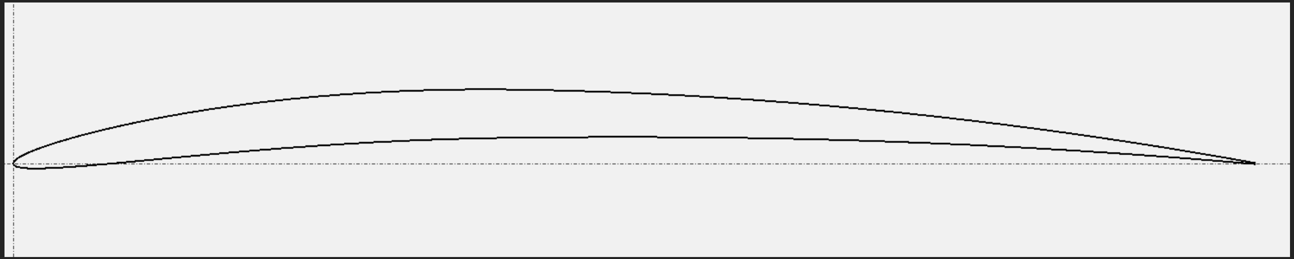




Rotor Blade Airfoil

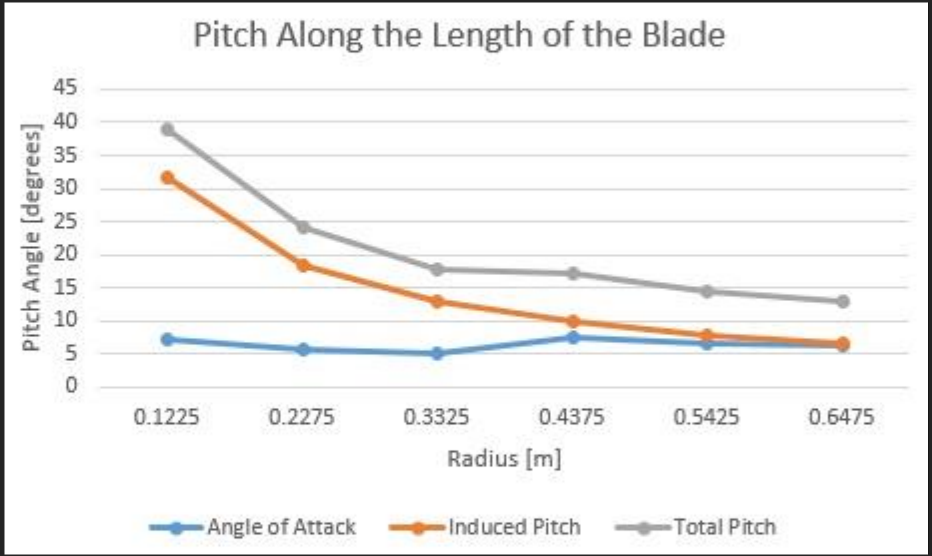
Airfoil: NACA 4404

- Selected for high Lift to Drag ratio
  - Retains performance in low Reynolds numbers
  - Retains performance at high subsonic Mach numbers
- Similar to airfoil used in NASA’s Mars 2020 drone [FS 1]
  - Cambered flat plate



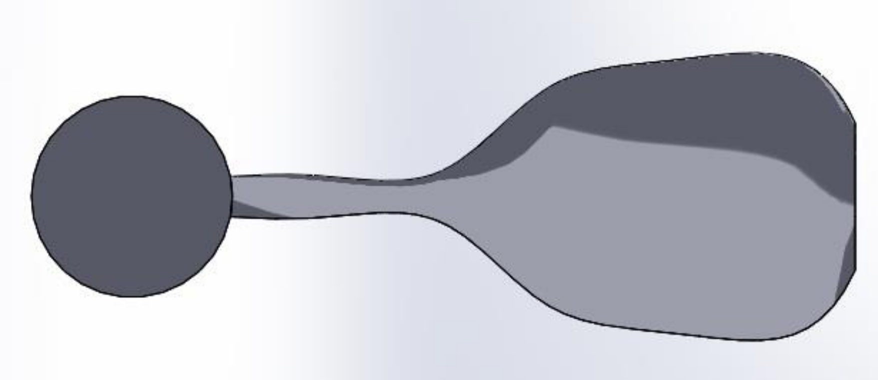
Rotor Blade Pitch

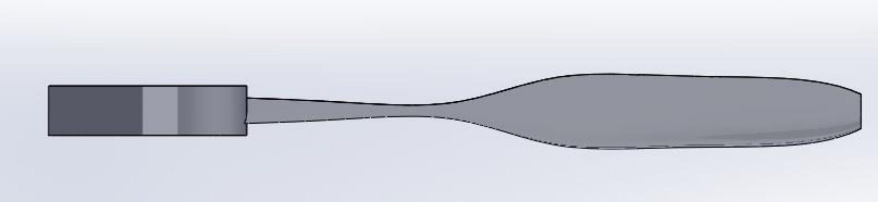
- Angle of attack
  - Maximizes lift to drag ratio
  - Decreases along length of the blade but increases about halfway through
- Pitch
  - Decreases along length of the blade



Rotor Blade Specifications

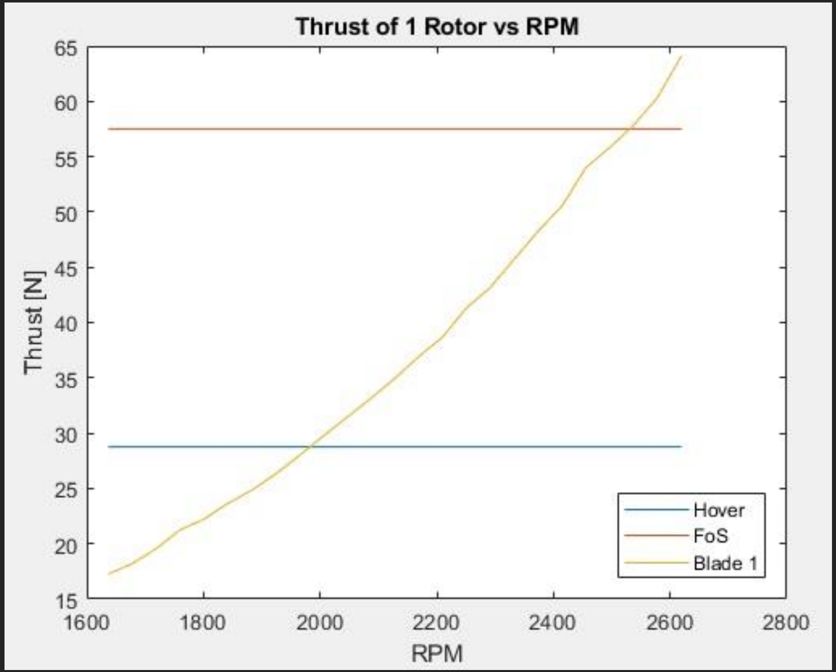
Blade Radius (m)	0.70
Maximum Chord (m)	0.28
Maximum Thrust (Rotor) (N)	64.1
Drag Torque in Hover (Rotor) (Nm)	4.16
Mass (Rotor) (kg)	2.20
Maximum Thrust to Weight Ratio	2.23





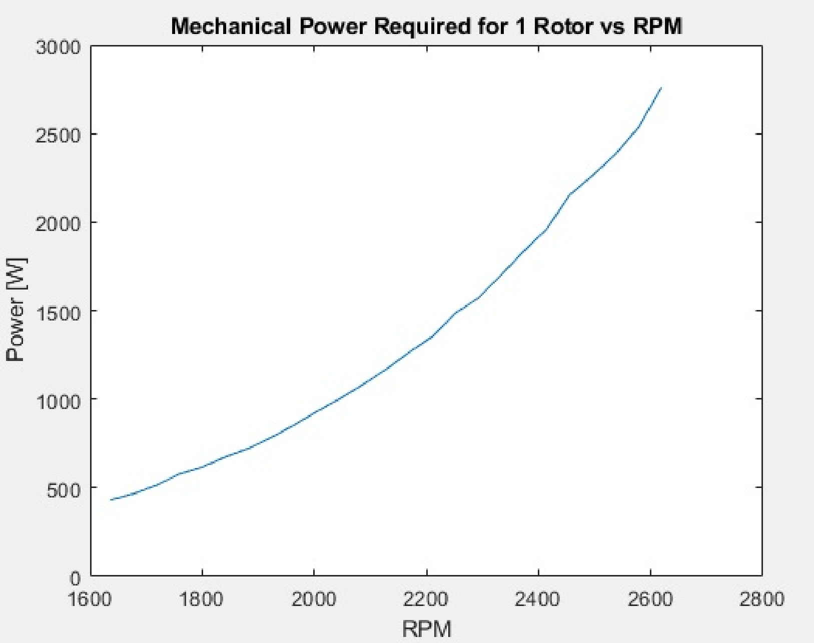
Rotor Blade Thrust

- Generates maximum thrust to weight ratio of 2.23
  - Exceeds minimum requirement of 2
- Thrust increases parabolically with RPM



Rotor Blade Mechanical Power

	Required Power (W)	Torque (Nm)	RPM
Hover	850	4.16	1950
Climb (2 m/s)	1150	5.28	2100
Descent (2 m/s)	550	3.04	1800



Finite Element Considerations

- Tetrahedral Mesh with limited run time and seed count in order to limit run time
- Forces active on element were: lift force, drag force, which were calculated from a MATLAB script that analyzed the characteristics of the selected airfoil and conditions on Mars

Material Properties	Values	Units
Young's Modulus	360	*GPa*
Poisson's Ratio	0.2	
Denisty	1.93	*g/cm^3*

Computational Fluid Dynamics - Set Up

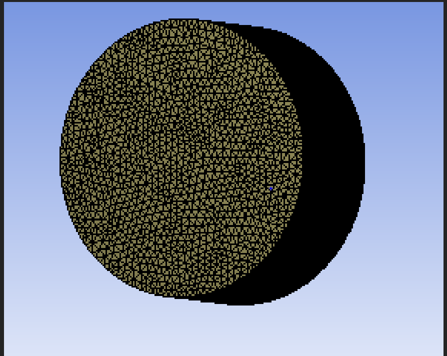
Mars Atmospheric Data

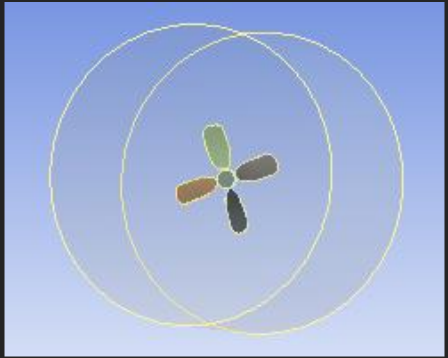
Density (kg/m^3)	.020
Pressure (Pa)	600
Molecular Weight (kg/kmol)	43.34
Average Flight Temperature (K)	290
Dynamic Viscosity (Kg/m-s)	1.422 * 10^-5
Constant Pressure Specific Heat (kJ/kg-K)	.86

RPM	2700
Pressure (Pa)	600
Residual Target	10^-5
Max. Iterations	250

Computational Fluid Dynamics - Mesh

Single mesh with fluid domain (Mars Atmosphere) and solid domain (rotor)





Unstructured tetrahedral mesh for all fluid and solid domains.

Mesh Statistics:

- Nodes: 1,332,141
- Elements: 956,870

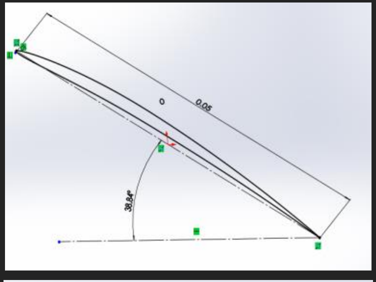
Computational Fluid Dynamics

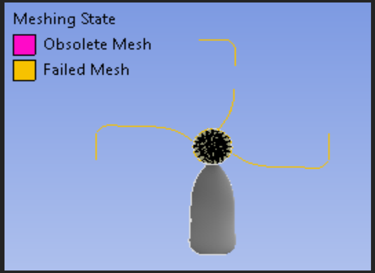
Blade Design

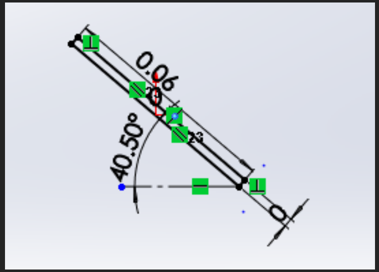
- Problem with mesh with NACA 4404 airfoil based rotor
  - Flat Plate Assumption

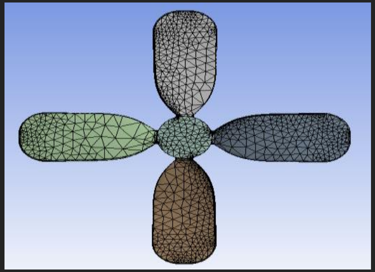
Results

- Thrust = 62.297 N (269.188 N for all 4 motors)
  - Drone Hovering Requires 137.307 N
- Efficiency = 68.3%









FLIGHT SYSTEMS

MOTOR

Motor Design

- Previous Motor: Rimfire 65cc
  - Conflicts with design
    - Too large (increases mass, adds to inefficiencies, more strain on arms)
    - Open to environment (dust contamination)
    - Outrunner (difficult to cool without heat pumps)
- Conflict resolution research:
  - Heat dissipation (Statorade, phase change wax)
  - Dust hardening(dust boot, blocking air intake)
  - Downsizing (Trade studies into different motors)
- Trade study
  - Required power
  - Efficiency (work at near full load)
  - Mass reduction
  - Thermal and dust hardening

Motor Selection

- Rimfire 50cc [FS 2]

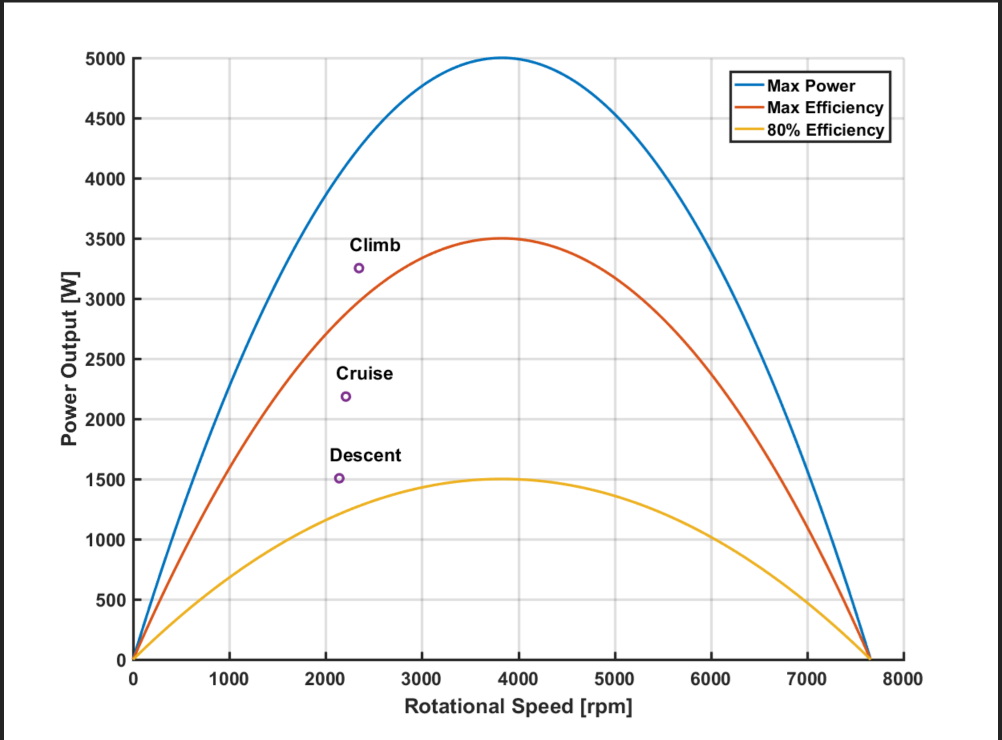
Requirements for Rotor Blade	
Cruise RPM	2800
Max RPM	3600
Cruise Power	1600 W
Max Power	2700 W

https://www.towerhobbies.com/cgi-bin/wti0001p?&I=LXXJW5&P=EP

Motor Specifications	
Diameter	80 mm
Weight	1.25 kg
Max RPM Range	7,659 - 12,765
Power Range	5000 W - 6000 W
Current Range	110 A - 135 A

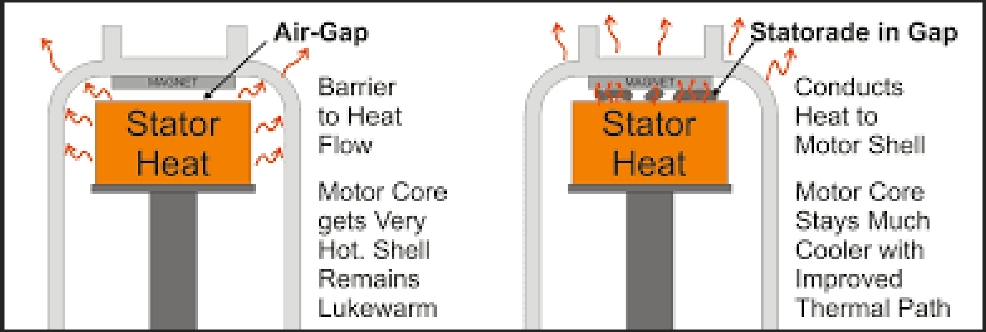
Motor Performance

- Rimfire 50cc motor meets required performance with high efficiency.



Motor Thermal Controls

- Outrunner motors rely on air flow
  - Mars atmosphere is too thin
  - Heat pumps too heavy for drones
  - Dust can infiltrate the motor
- Solution:
  - (Exterior) Phase Change Wax
    - Ferrofluid based thermal oil
    - Mounted outside outrunner motor can
      - Either spinning with motor and oiled and stationary
  - (Interior) Statorade, ferrofluid thermal oil
    - Placed on permanent magnets, transfers heat to spinning drum
      - Loss 0.3 mL of fluid every 10,000 km on eBikes
      - Minimal torque loss in motor



https://www.ebikes.ca/product-info/statorade.html

Motor Dust Mitigation

- Outrunner motor allows dust to come in via air intakes
  - Statorade lets heat dissipate without air flow
    - No need for airflow means intake can be blocked
- Shaft exit still open to dust infiltration
  - Use a dust boot
    - Plastic cuff between rotor blades and motor
      - Covers shaft and shaft hole, slottled for flexibility

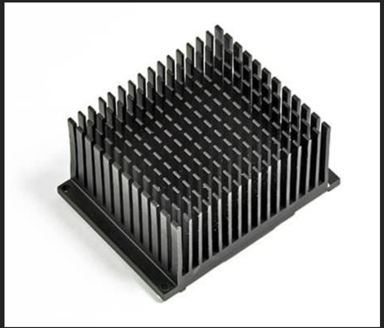
https://www.amainhobbies.com/great-planes-electrifly-rimfire-50cc-8075230-brushless-outrunner-motor-230kv-gpmg4800/p219663

http://www.copters.com/R22_Preflight/Main_Rotor/Main_Rotor.html

Electronic Speed Controller

- ESC with heatsink installed can receive equivalent heat flux on Mars as heat-shrink covered ESC on Earth. (~0.35 W)

- RotorStar 120A HV (4~14S) Brushless Speed Controller [FS 3]
    - 120A (140A Burst)
    - Up to 51.8V
    - 240,000 rpm max
    - Dimensions
        - 68x53mm



https://www.solid-run.com/product/HS00012K

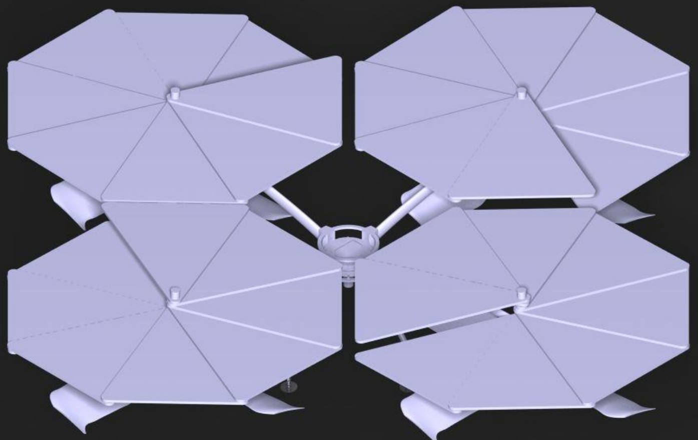
https://hobbyking.com/en_us/rotorstar-120a-hv-4-14s-brushless-speed-controller-opto.html

FLIGHT SYSTEMS

SOLAR PANELS

Preliminary Solar Panel Design

- When deployed, covers 100% of reference area of blades when viewed from above the drone, and 1/8th of reference area of blades when retracted.
- Airflow is significantly restricted when panels are in the retracted position.
- Dust intrusion in between the solar panels could be potentially problematic while in the retracted position.
- Deployment dependent on a servo above the motor mount.

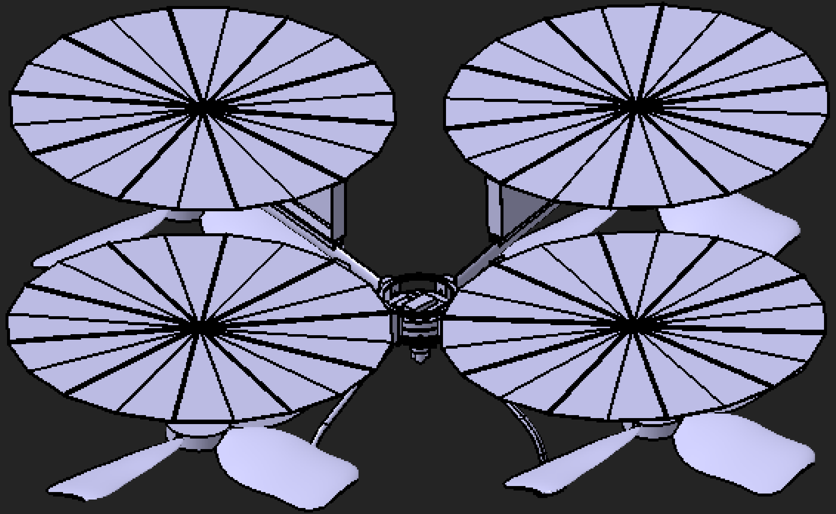


Solar Panel Airflow Test

- A test quadcopter was attached to a string along with a spring-mass system.
- Deformation in the spring was used to measure the thrust of the quadcopter.
- The “simulated” solar panels began at 100% blockage of the top of the quadcopter rotors, and would decrease at 25% intervals for each repetition of the experiment.
- When simulated solar panels were in the stored orientation there was a significant decrease in thrust.

Current Solar Panel Design

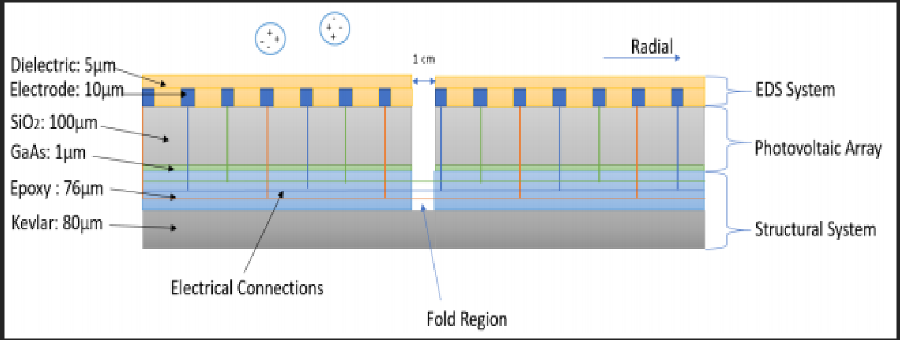
- Fan Folding Mechanism
- Has previously been used on the Mars Phoenix lander and will be used on the Insight Lander.
- Total Solar Panel Area: 4.2 m^2
  - Each unfolded solar circle: 1.05 m^2
  - Radius of solar panels : 0.6 m
- Total Solar Panel Mass: 5 kg
  - Each unfolded solar circle: 1.25 kg
- Solar Cells: SolAero ZTJ Triple Junction GaInP/InGaAs/Ge
- When folded and stowed in the panel storage unit (PSU) the rotor blockage is significantly reduced.
- The PSU would protect the solar panels against dust when not in use.

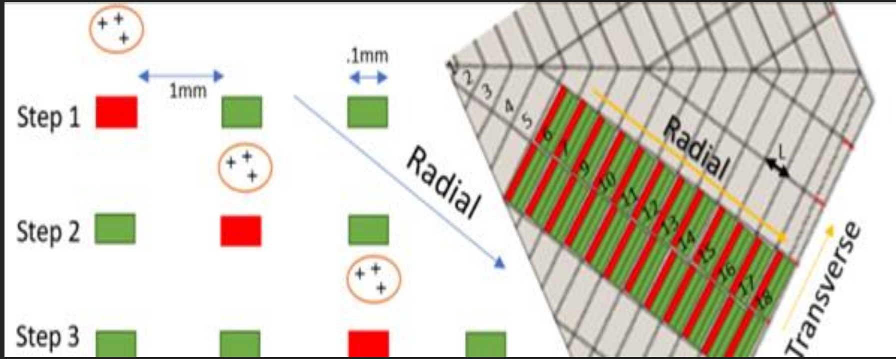


Solar Panel Dust Mitigation

- Dust build up is dangerous to the system
  - Inefficient charging
  - Open/Close mechanism jamming

- Electrodynamic dust repellant
  - Dielectric material (Indium Tin Oxide)
  - Propagating electricity repels dust
  - Less than a Watt of power
  - Time < 60 seconds

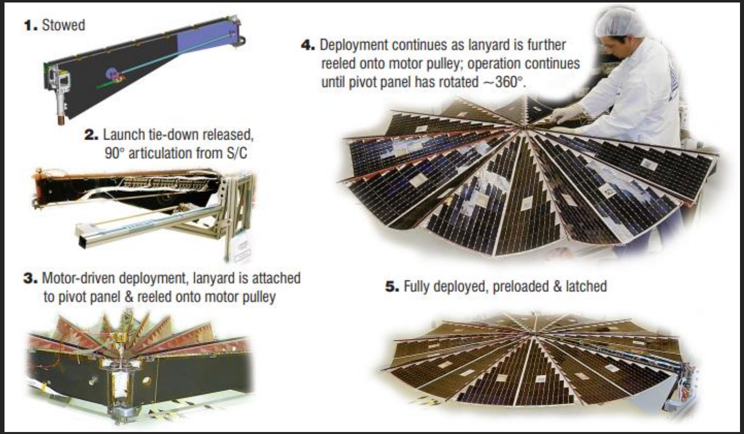




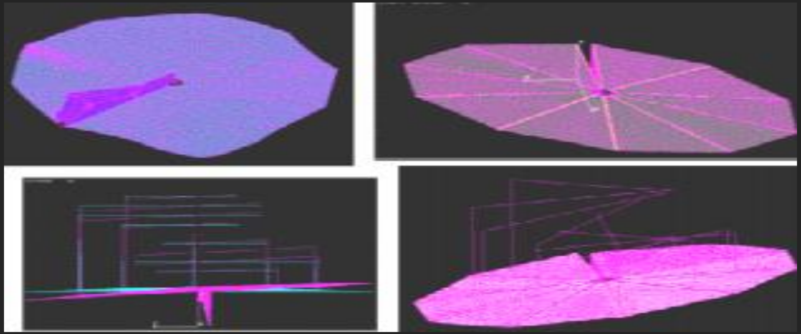
http://bigidea.nianet.org/wp-content/uploads/2018/03/2018-BIG-Idea-Final-Paper_Princeton-1.pdf

Solar Panel Structural Analysis

- Orbital ATK UltraFlex solar panel
  - Designed to be opened permanently
  - Closing potentially hazardous
    - No prior research on closing
      - Can it fold back correctly?
    - Structural wear of repeated use
- Solar panel can support itself (NASA FEA)



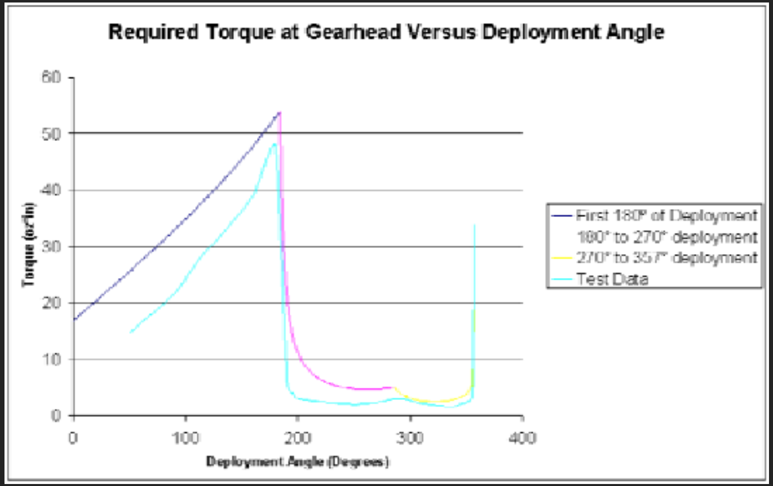
http://rascal.nianet.org/wp-content/uploads/2015/07/Ultraflex-Solar-Array.pdf



2005 IEEE Aerospace Conference _Big Sky_ Paper- NGU ST8.pdf

Solar Panel Deployment

- Investigating the use of a stepper motor
  - Cheaper than Servos
  - Can rotate a full 360 degrees
    - Reduces the use of a Gear Box
- Future Testing
  - Assemble a simple deployment mechanism.
  - Apply a strict folding mechanism.
  - Track possible pinch points



Torque requirements (oz-in) for panel deployment using single deployment system - JPL

FLIGHT SYSTEMS

AVIONICS

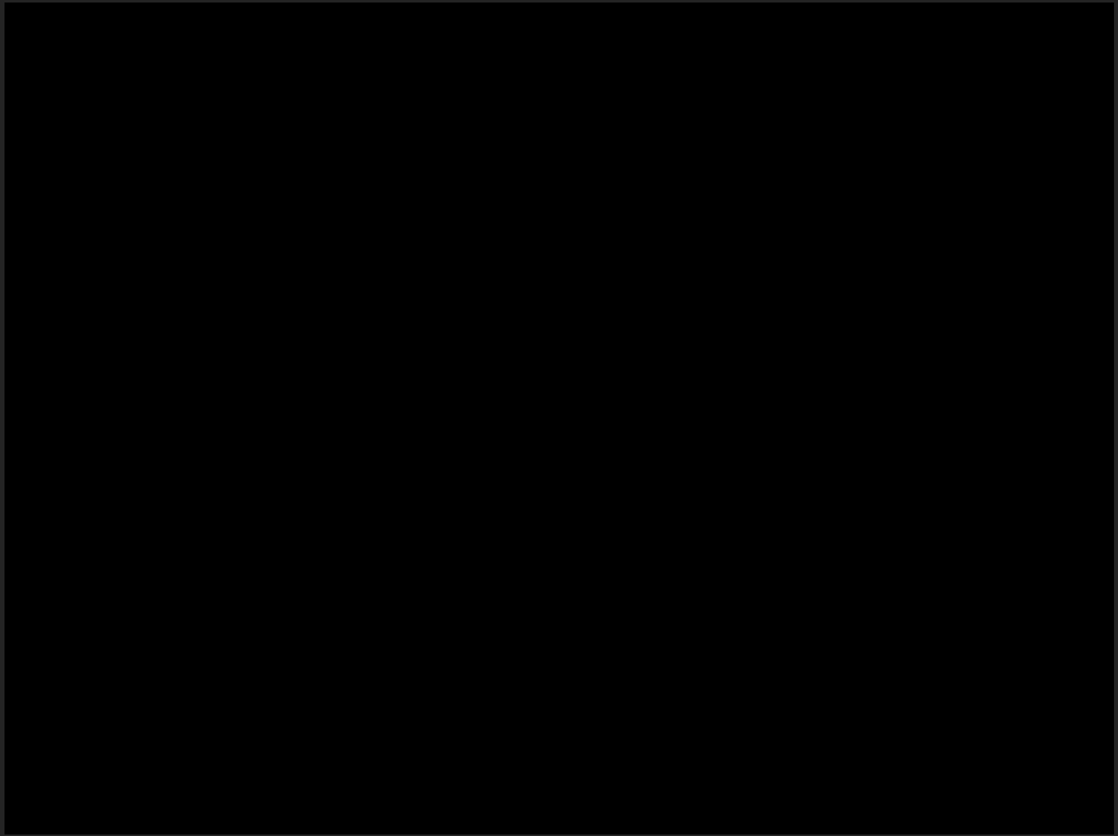
Drone Avionics

- Pixhawk is the current testing flight controller, which will be analogous to the intended flight controller for the mission.
- Separate from that is the flight computer, a lightweight computer system responsible for processing flight input as well as taking commands from the mission computer.
- Flight controller manages voltage delivered to each of the 4 motors in flight.

Preliminary Flight Algorithms

- Old Method - Crazyflie
- Pros:
  - Easy to use with scripting
  - Buy package with everything needed
- Cons:
  - Not portable between drones
  - Proprietary software

CrazyFlie Demo



Current Flight Algorithms

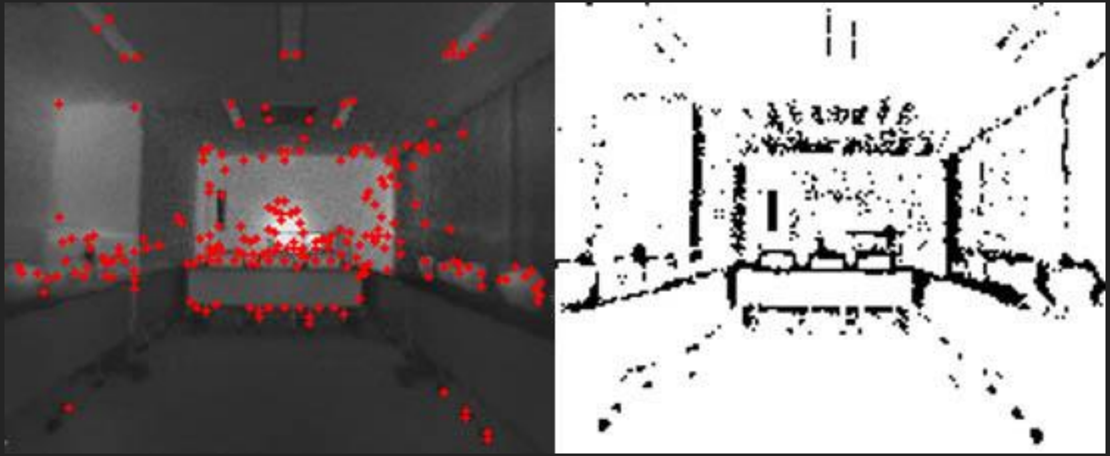
- New method used - Ardupilot
  - Provides scalability and portability for the drone system
  - Simple, easy interface to run autonomous scripts in Mission Planner
- Documentation for Windows machines is written for ease-of-transfer between semesters

Localization Techniques

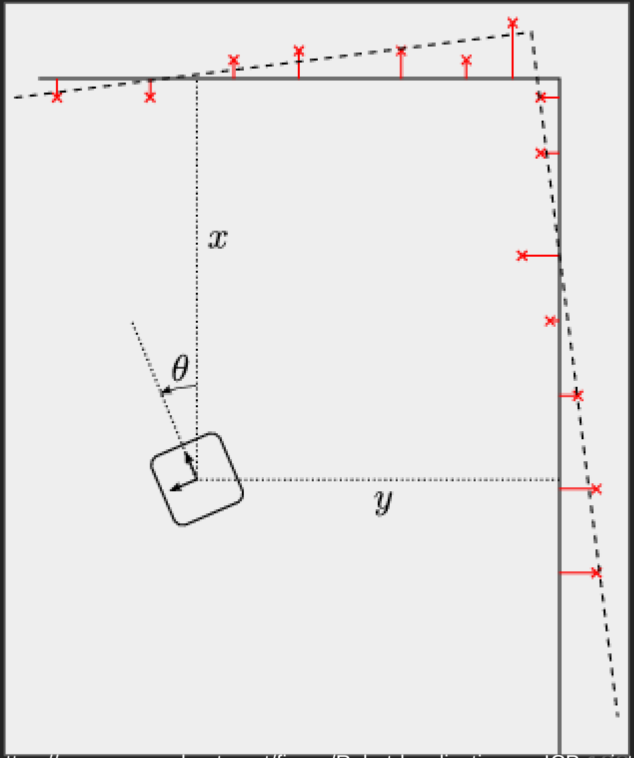
- Two techniques chosen
  - Main Technique
    - Point Set Registration - Iterative Closest Point (ICP)
      - Known starting location
        - Use Radar Trilateration when available to reset starting point.
      - Least Squared Rigid Approximation for localization during flight
  - Backup Technique
    - Monte Carlo Localization
      - Unknown starting location
      - Location converges via recursive Bayesian Estimation
- Both Techniques require basic reference map for lidar comparison

Localization Techniques

Iterative Closest Point [FS 4]



https://www.fujipress.jp/jrm/rb/robot003000010065/

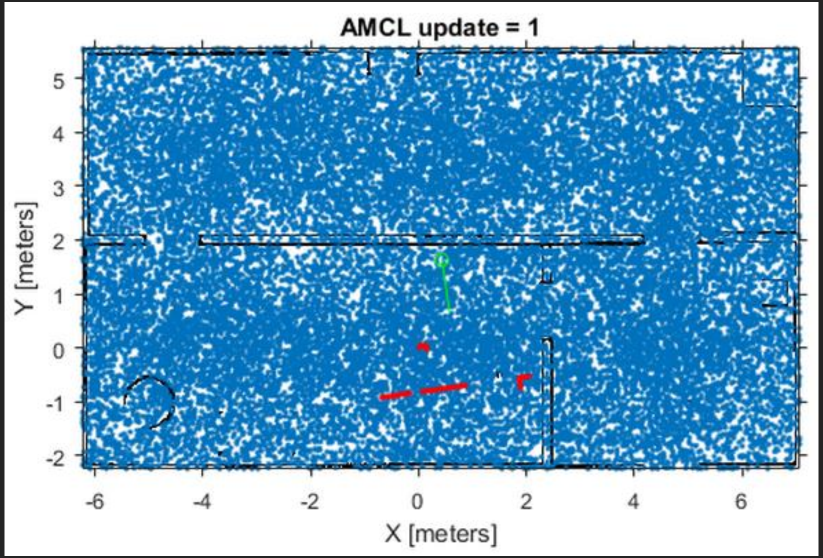


https://www.researchgate.net/figure/Robot-localization-an-ICP-point-to-line-method-is-used-to-compute-the-transformation_fig2_280852833

Localization Techniques

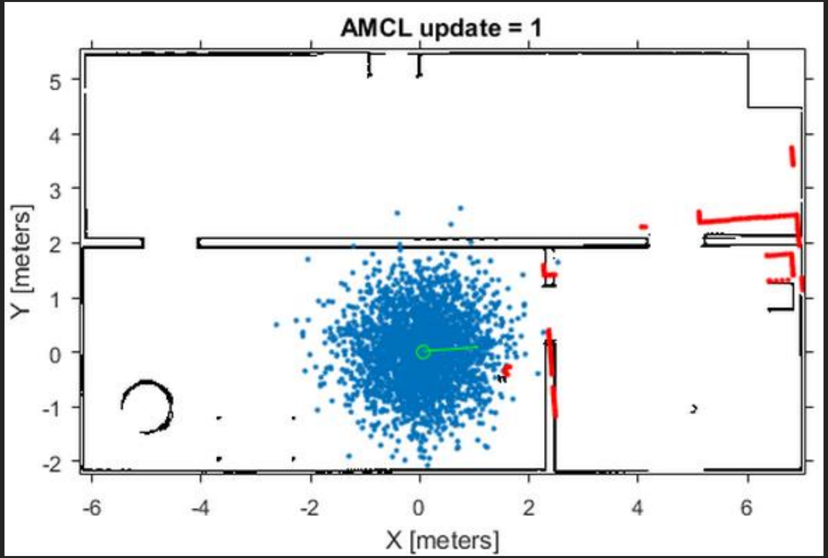
Monte Carlo [FS 5]

Initial Measurement



https://www.mathworks.com/help/robotics/ug/monte-carlo-localization-algorithm.html

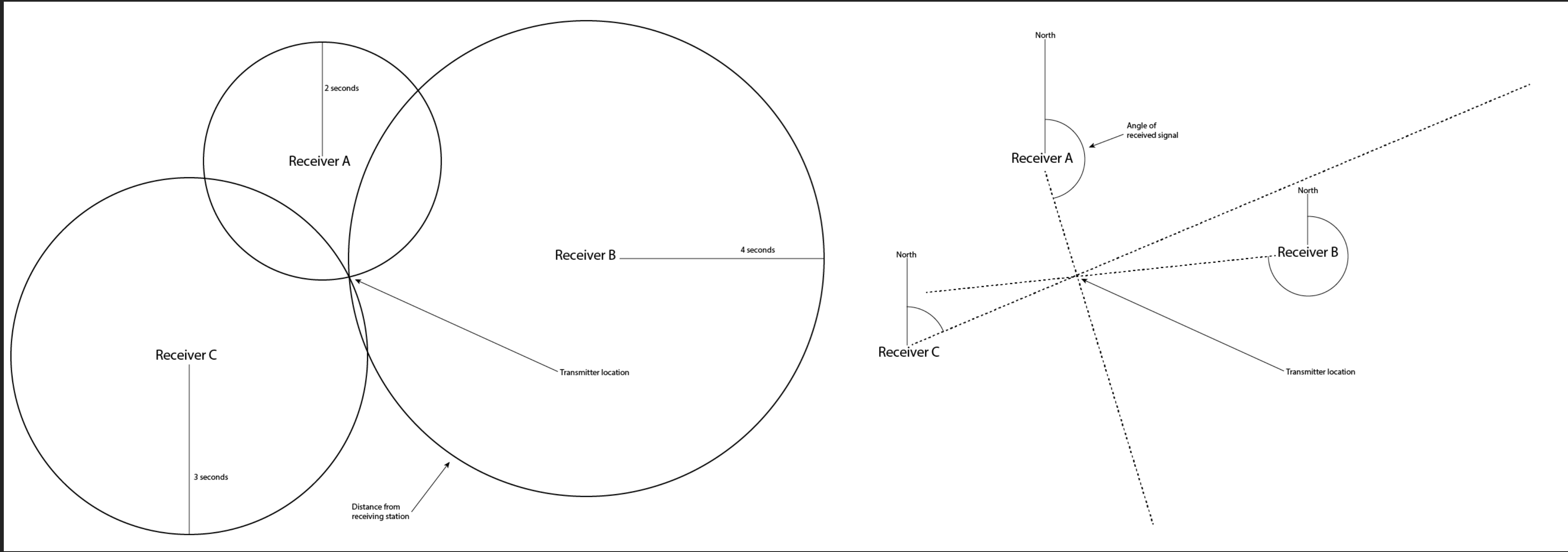
Second Measurement



https://www.mathworks.com/help/robotics/ug/monte-carlo-localization-algorithm.html

Localization Techniques

Radio Transliteration [FS 6]



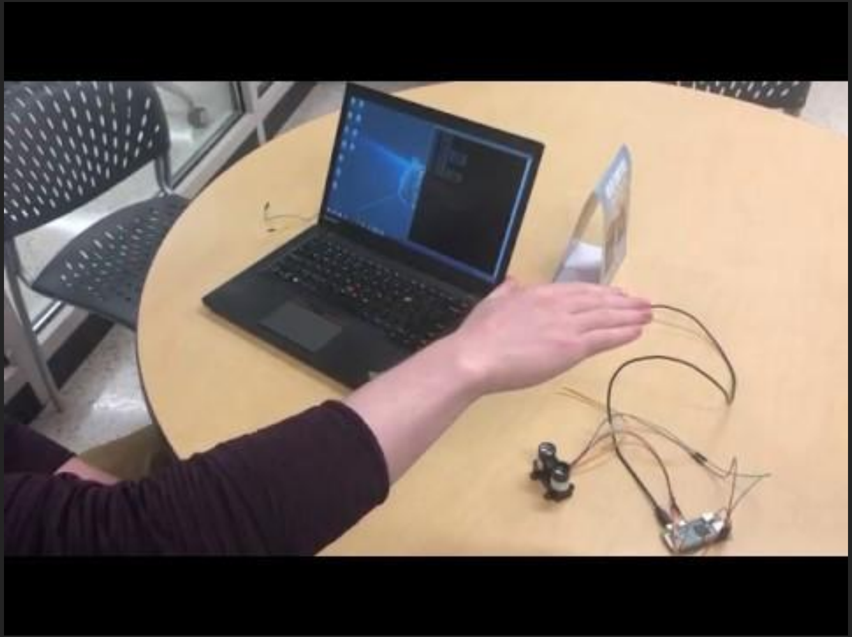
https://hackaday.io/project/25995-bloodhound-autonomous-radiolocation-drone/log/63866-radio-direction-finding-techniques

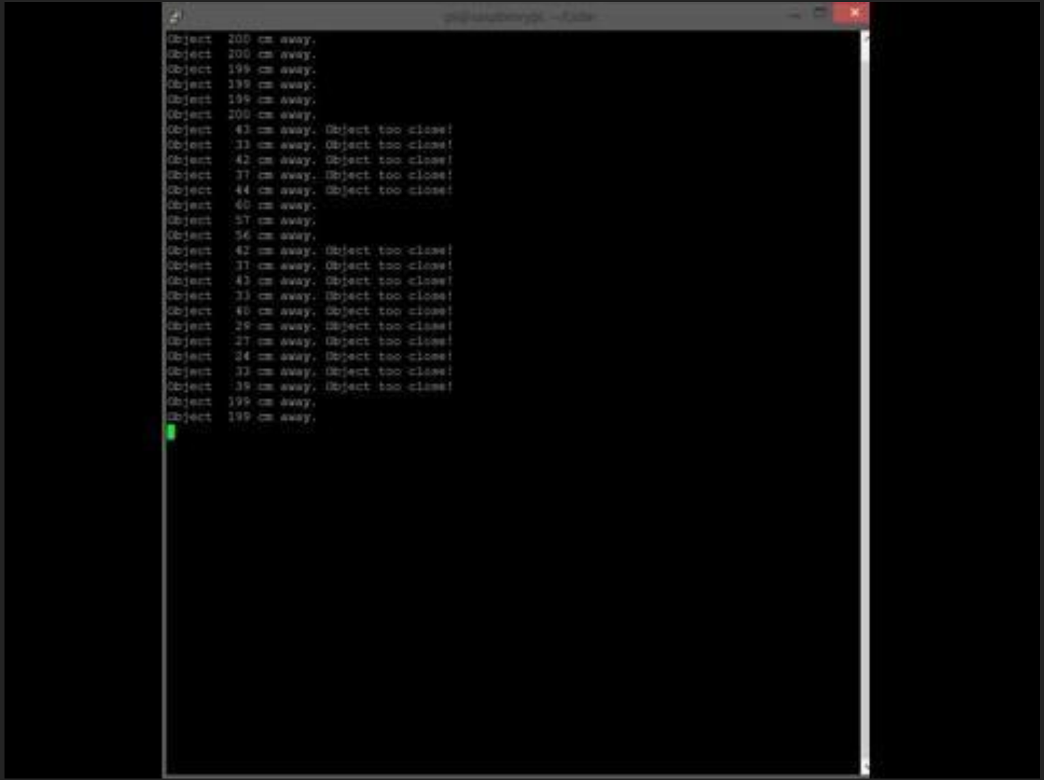
LIDAR

- LIDAR-Lite v3
    - Specifications
        - Range: 0-40m Laser Emitter
        - Accuracy: +/- 2.5cm at distances greater than 1m
        - Power: 4.75–5V DC; 6V Max
        - 20 x 48 x 40 mm (0.8 x 1.9 x 1.6 inches)
- Used as altimeter, located in Chassis
- Used in Mars 2020 Mission

https://www.sparkfun.com/products/14032

LIDAR Test



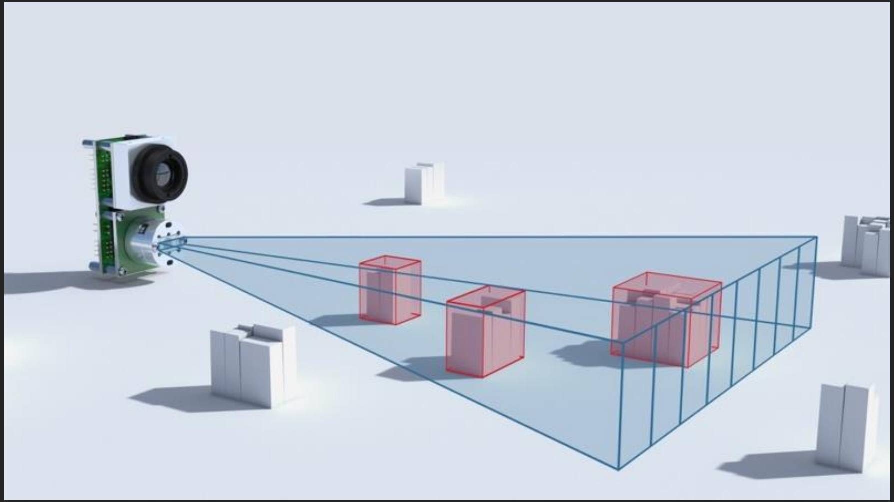

Object 200 cm away.
Object 200 cm away.
Object 199 cm away.
Object 199 cm away.
Object 199 cm away.
Object 200 cm away.
Object 43 cm away. Object too close!
Object 33 cm away. Object too close!
Object 42 cm away. Object too close!
Object 37 cm away. Object too close!
Object 44 cm away. Object too close!
Object 60 cm away.
Object 57 cm away.
Object 56 cm away.
Object 42 cm away. Object too close!
Object 37 cm away. Object too close!
Object 43 cm away. Object too close!
Object 33 cm away. Object too close!
Object 40 cm away. Object too close!
Object 29 cm away. Object too close!
Object 27 cm away. Object too close!
Object 24 cm away. Object too close!
Object 33 cm away. Object too close!
Object 39 cm away. Object too close!
Object 199 cm away.
Object 199 cm away.

LIDAR

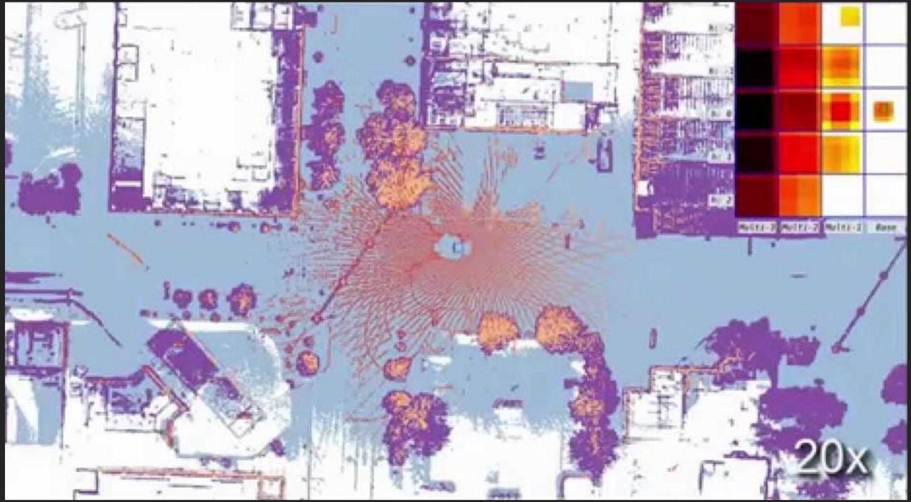
- LeddarTech Vu8 Lidar Sensor for Localization
  - Specifications
    - 215m range
    - 8 lidar beams for 2D map
      - 20, 48, and 100 degree beam width options
    - 75 grams
  - High Noise tolerance
  - Solid State
    - Ideal for martian environment where no maintenance can be performed
- Mounted on gimbal
  - Default, downward facing for localization and autonomous landing
  - Can be used for object detection by facing forward when approaching cliffside

https://leddartech.com/lidar/leddarvu/

LIDAR



https://www.spar3d.com/news/lidar/vu8-475-solid-state-lidar-adapts-needs/



https://www.spar3d.com/news/lidar/vu8-475-solid-state-lidar-adapts-needs/

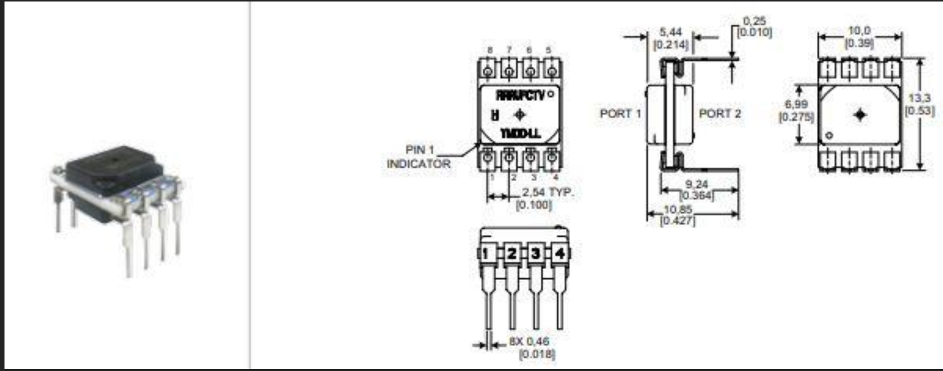
Sensor Selection

PURDUE AERONAUTICS & ASTRONAUTICS

Pressure transducer

SSCDRNN100PGAA5-ND

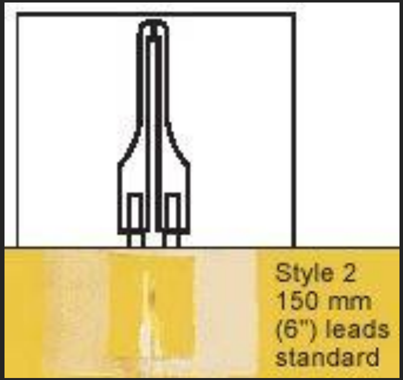
- 0 Pa ~ 689476 Pa
- 0.0276 W (maximum)
- 2% Error



Thermocouple

CO2 - K

- -270°C ~ 540°C
- Might have lower accuracy due to low pressures
- 6’’ lead wires



FLIGHT SYSTEMS

BATTERIES

Battery Choice and Specifications

- Lithium-Polymer Pouch Cell
  - Pouch cells provide high energy density
    - 440 W-hr/L based on Samsung PGF3383F0 [FS 7]
    - 350 W-hr/kg based on extrapolation of Li-Po cells in near future
    - No gaps between cells in comparison to cylindrical cells

- Battery Size Based on PSE Mass Budget Code
  - Capacity: 48,000 mAh
  - Mass: 6 kg
  - Volume: 0.0047 m^3

Battery and ESC Thermal Control

- Heat Loss Calculation
  - Assuming laminar flow, uniform heat distribution and negligible conduction loss through legs
  - Maintain batteries at 20°C
  - Convection loss through CO_2 insulation.
  - Low emissivity surface coating (Gold)
  - Primarily interested in night time power consumption (Around -100°C)

  - Battery Convection loss: 4.3 W
  - Battery Radiative loss: 9.8 W
  - Total Loss through four ESCs (Convective and Radiative): 1.4 W

- Patch Heaters
  - Use patch heaters to match heat loss
  - Negligible efficiency power loss using patch heater (~99%) [FS 8]

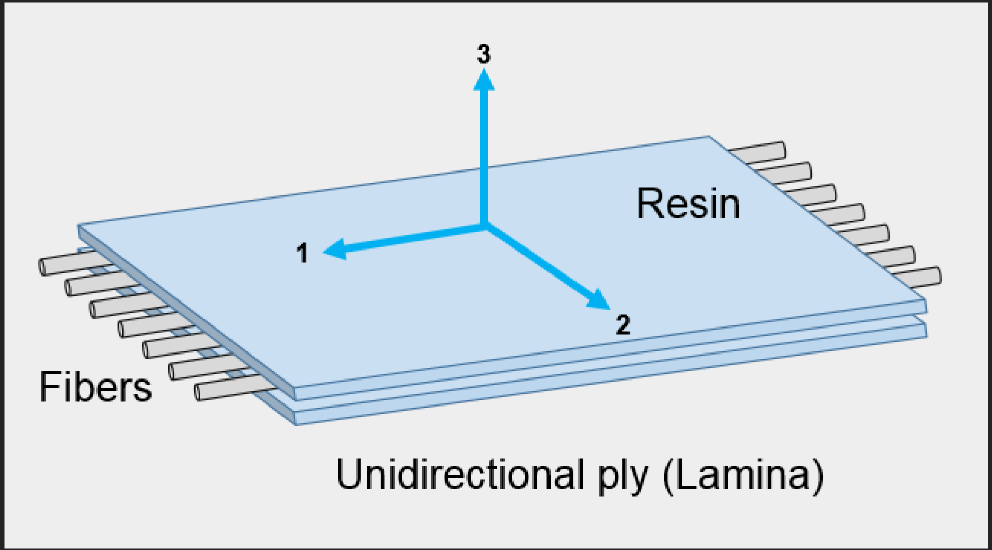
BONUS SLIDES

FLIGHT SYSTEMS

Material Properties

Material Selection: High modulus carbon fiber M60J

M60J Composite Properties		
Modulus E11 (0°)	365	GPa
Modulus E22 (90°)	6.20	GPa
Shear Modulus G12	3.70	GPa
Compressive Modulus	320	GPa



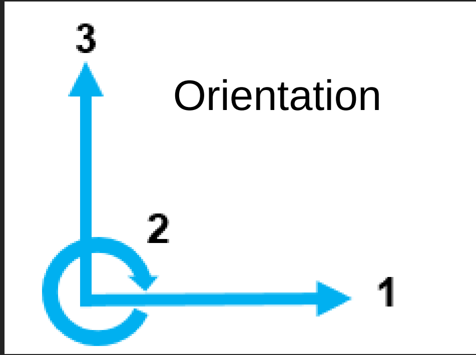
Material Model

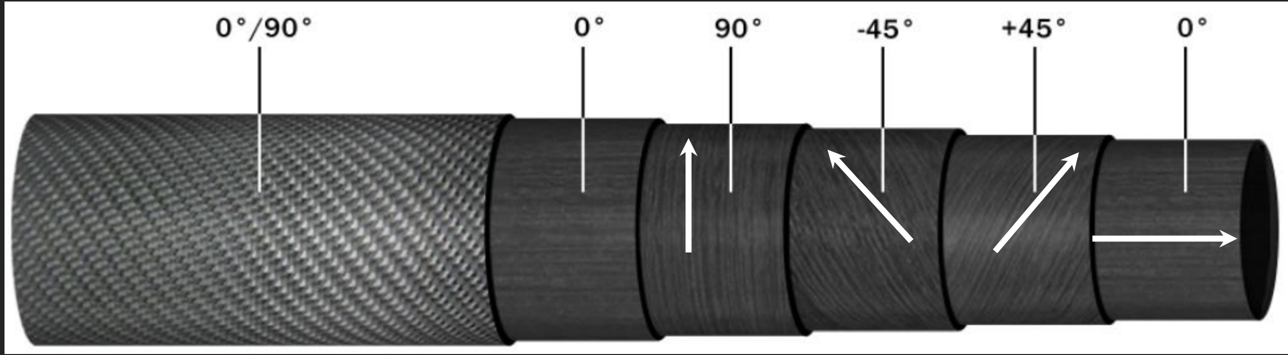
Laminate (multiple lamina) Model Assumptions

- Quasi-Isotropic and layup
    - Provides strength in all directions
- No temperature effects on properties
- Developed from classical laminate plate theory

Laminate Properties (For Abaqus)		
E11 = E22 =E33	126.79	GPa
G12 = G13	3.70	GPa
G23	47.83	GPa

Carbon fiber manufacturing concept





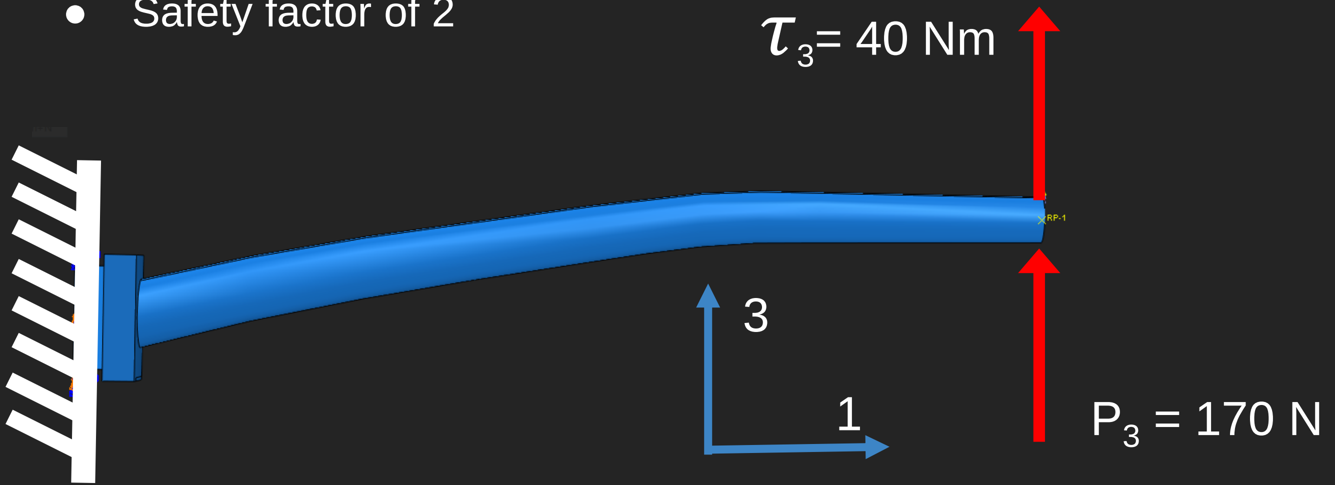
Arm Loading Analysis

Load Assumptions

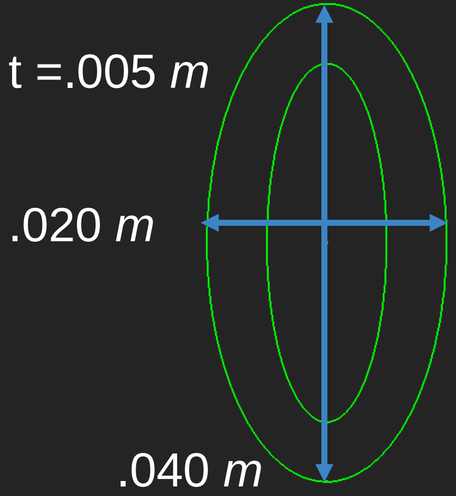
- Mass = 60 kg
- Equal weight distribution between 4 arms
- Max motor torque 20 N/m
- Max acceleration of 1.5 g
- Safety factor of 2

Hand calculation deflection

$$\delta = \frac{PL^3}{3EI} = .47 \text{ cm}$$

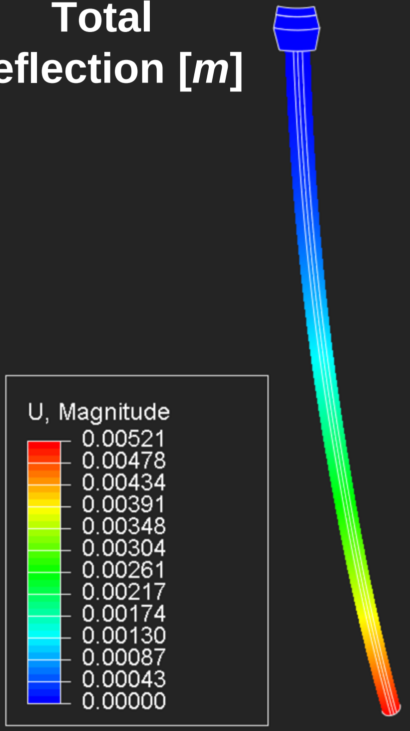


Cross Section

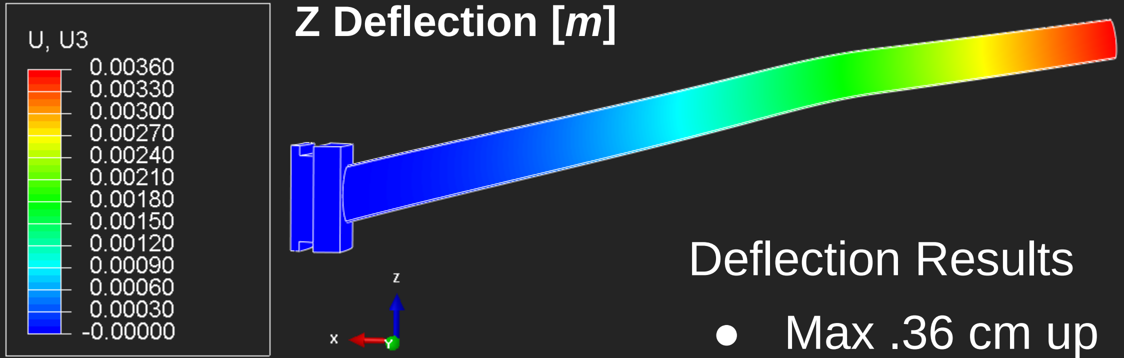


Arm Deflection Results

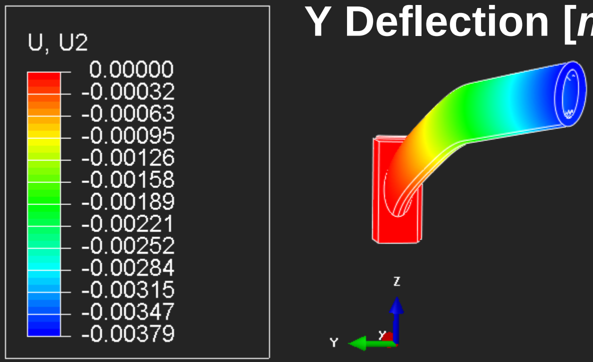
Total Deflection [*m*]



Z Deflection [*m*]



Y Deflection [*m*]



Deflection Results

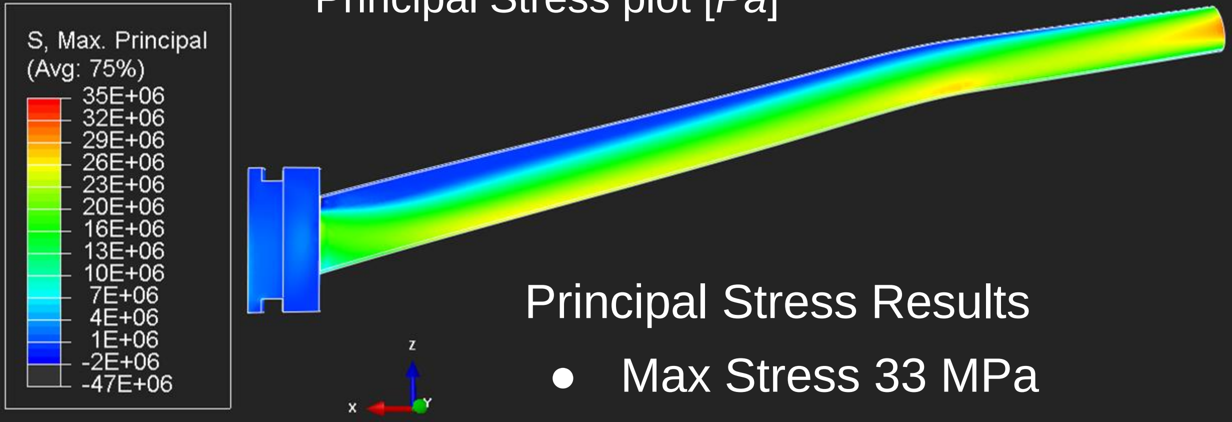
- Max .36 cm up
- Max .38 cm aft
- Similar to predicted .47 cm

Design meets proposed deflection requirement of .5 cm

Note* deformations are scaled

Arm Principal Stress Plots

Principal Stress plot [*Pa*]

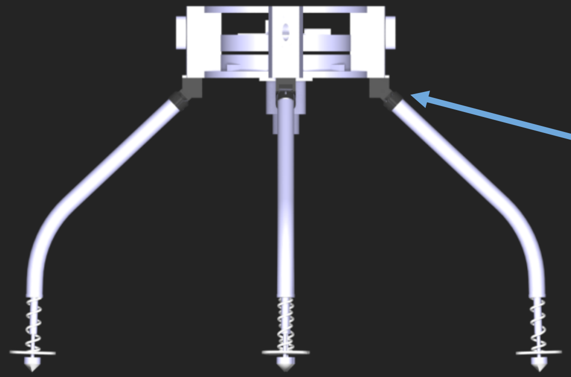


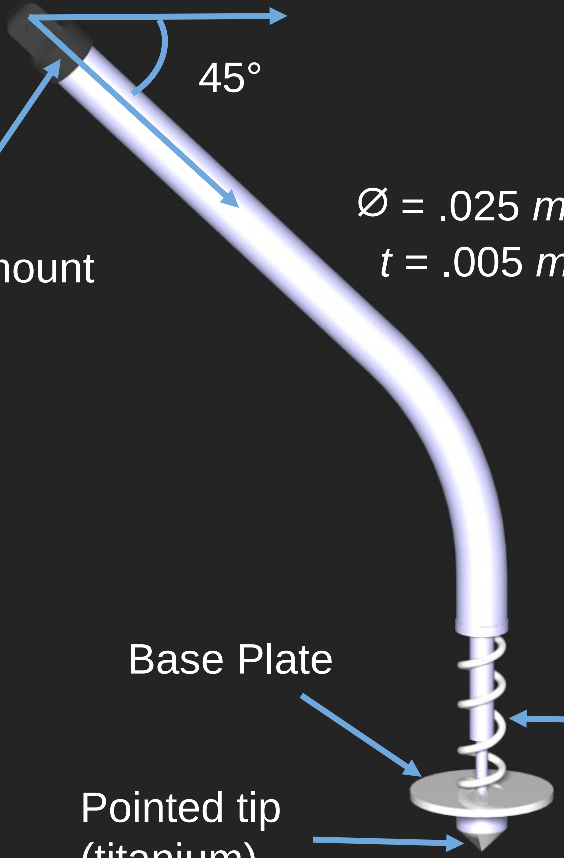
Principal Stress Results

- Max Stress 33 MPa
- Significantly lower than laminate strength ≈ 2 GPa
- Dominant concern is deflection over failure

Small stresses will limit the effects of delamination / crack propagation

Landing Gear Design





Current Design

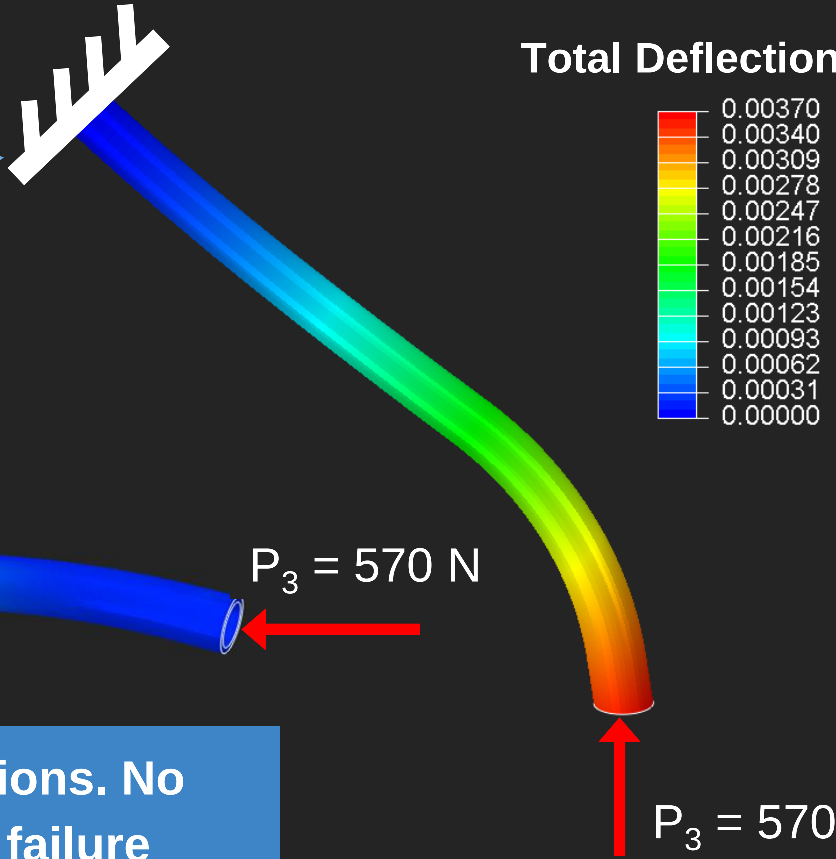
- Added plate for sand landing
  - Future sand tests to validate
- Spring tip damping / stabilization
- One-time deployment
  - Transported in horizontal position for volume saving

Landing Gear Analysis

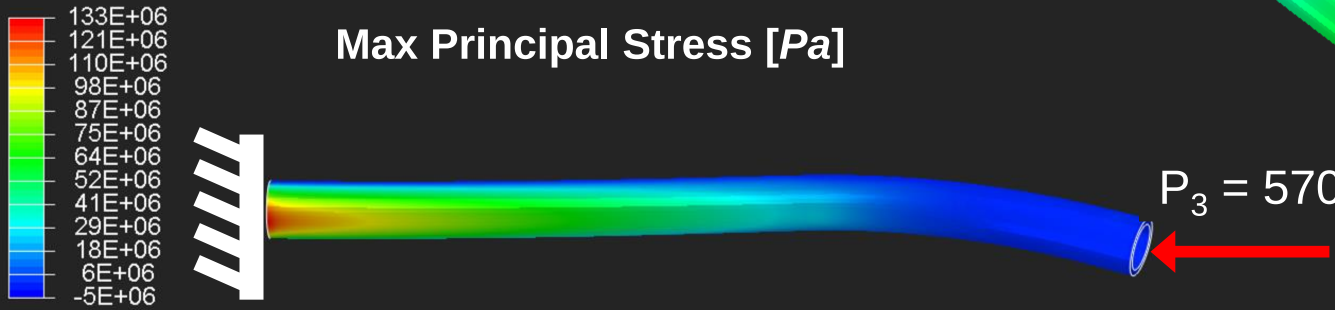
Model Assumptions

- 60 kg mass supported on one leg
- 1.3 g impact on one leg
- Fixed mount to Chassis
- Factor of safety of 2

Total Deflection [*m*]



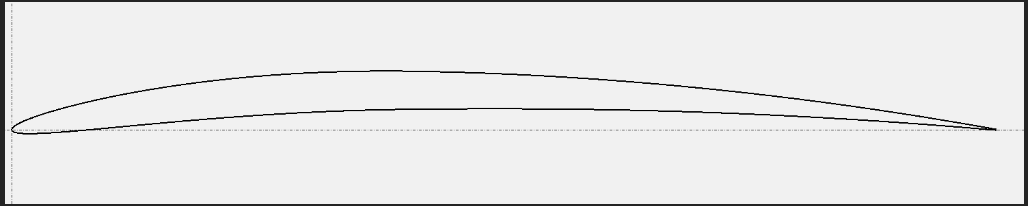
Max Principal Stress [*Pa*]



Small stresses and deflections. No buckling or compressive failure

Blade Design

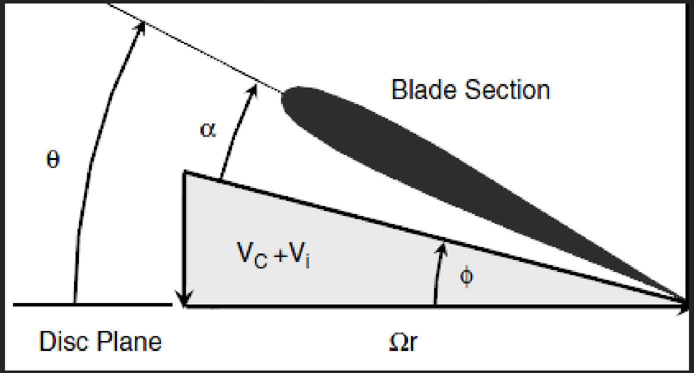
- Objective: Design a rotor blade that can provide enough thrust for the vehicle to hover
- Airfoil: NACA 4404
  - High L/D at low Reynolds Number (< 50,000)
  - “Cambered flat plate” shape similar to JPL helicopter airfoil
  - Higher Mach numbers do not affect performance as much as thicker airfoils
- Assumptions
  - Uniform inflow across rotor blade
  - Mach at blade tip set to 0.8 max
  - Vehicle Mass: 60 kg
  - Blade Material: Carbon Fiber



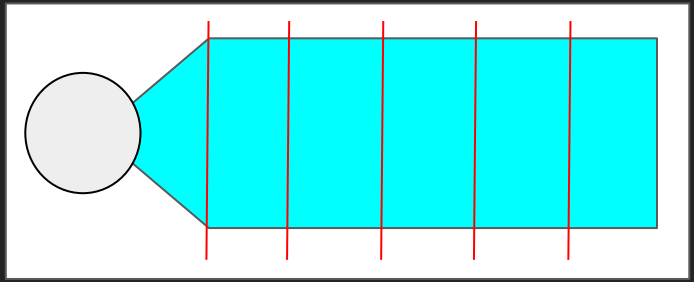
NACA 4404 Airfoil

Blade Design

- Approach
  - Determine inflow into rotor using vehicle mass and blade radius
  - Split the blade up into sections of constant chord along the radius
  - Determine relative velocity and angle of attack at each section
  - Compute forces on each section and sum for total forces of blade



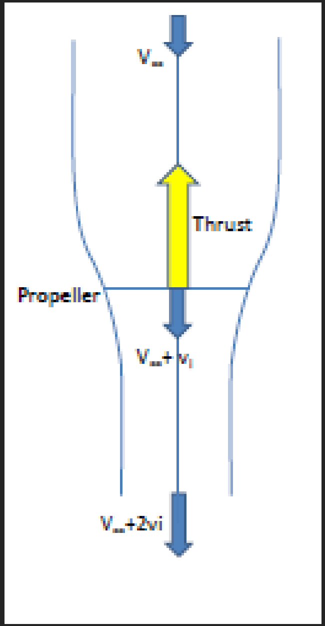
Basic Helicopter Aerodynamics, Seddon



Power Consumption

- Power calculated in each flight regime based on Momentum Theory
- Assumptions
  - Uniform inflow velocity across the rotor
  - Airflow enters rotor normal to rotation plane
  - Flight speeds are constant
- Power calculated by adding power to induce velocity (P_i) and power to overcome drag (P) [FS 9]
  - $P_i = |T|*v_i$
  - $P_p = C_D*solidity*\rho*V^3*A/8$

$$v_i = \sqrt{\frac{T}{2\rho A_D}}$$



Future Motor Tests

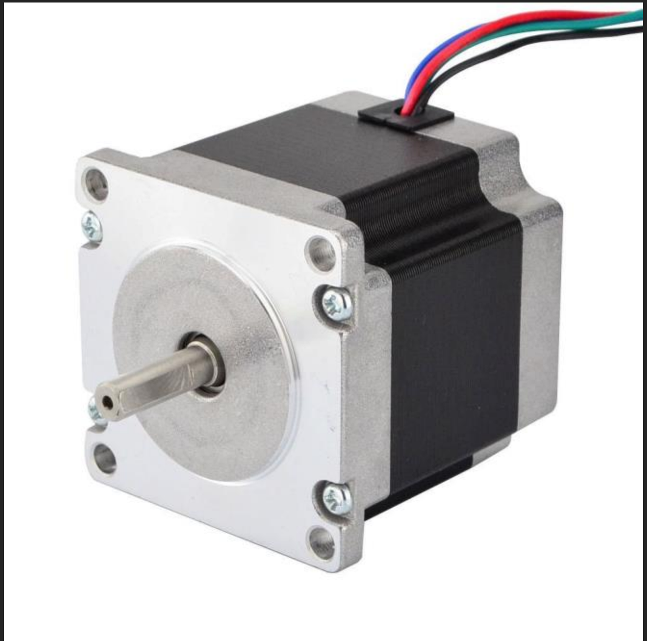
- Statorade Tests
  - Need to verify performance of statorade in Martian atmosphere using vacuum chamber
    - Spin up motor with statorade and gather torque and temperature data
    - Cool motor and statorade system to “nighttime” Martian temperatures and spin up the motor again
- Calculate heat transfer from statorade tests
- Use this to determine how much phase-change wax must be applied to get appropriate heat dissipation
- Rerun vacuum chamber tests with complete motor thermal system and compare data

Potential Stepper Motor Selection:

Nema 23 CNC Stepper Motor

- Meets torque requirements
- Size is compatible with solar panel system

Motor Specs	
Torque	1.26 Nm (178.5 oz-in)
Size	5.7 x 5.7 x 5.6 cm
Current	2.8 A
Step Angle	1.8 Degrees (200 Steps/rev)



https://www.amazon.com/Stepper-Motor-Bipolar-269oz-Router/dp/B00PNEPI0A

Battery and ESC Thermal Control

Heat Loss Calculation Details [FS 10]

Convection

$Re = \rho * v * L/\mu$

$Pr = \mu * c_p/k$

$Nu = 0.664*(Re)^{0.5}*(Pr)^{(1/3)}$

$h_{conv}=Nu*k/L$

$Q = h*A*\Delta T$

Conduction

$Q = k*A*\Delta T/t$

Radiation

$Q = \varepsilon*\sigma*A*\Delta T$

Flight Systems - References

[1] Mars Helicopter Technology Demonstrator

[2] http://manuals.hobbico.com/gpm/gpmg4800-4805-manual.pdf

[3] https://hobbyking.com/en_us/rotorstar-120a-hv-4-14s-brushless-speed-controller-opto.html

[4] http://ais.informatik.uni-freiburg.de/teaching/ss11/robotics/slides/17-icp.pdf

[5] https://ac.els-cdn.com/S0004370201000698/1-s2.0-S0004370201000698-main.pdf?_tid=462ce759 -6506-4fcf-96a9-884be25cdebf&acdnat=1542001200_c2db10d53a42520dfc514dd925731a2a

[6] https://en.wikipedia.org/wiki/Radiolocation

[7] http://www.samsungsdi.com/lithium-ion-battery/it-devices/tablet.html

Flight Systems - References

[8] https://www.energy.gov/energysaver/home-heating-systems/electric-resistance-heating

[9] Basic Helicopter Aerodynamics, Seddon, Newman

[10] https://www.ndt.net/article/aero2013/content/papers/61_Guemes.pdf

[11] https://pdfs.semanticscholar.org/4495/8108803f40b846517b35a8e5e0629e53380b.pdf

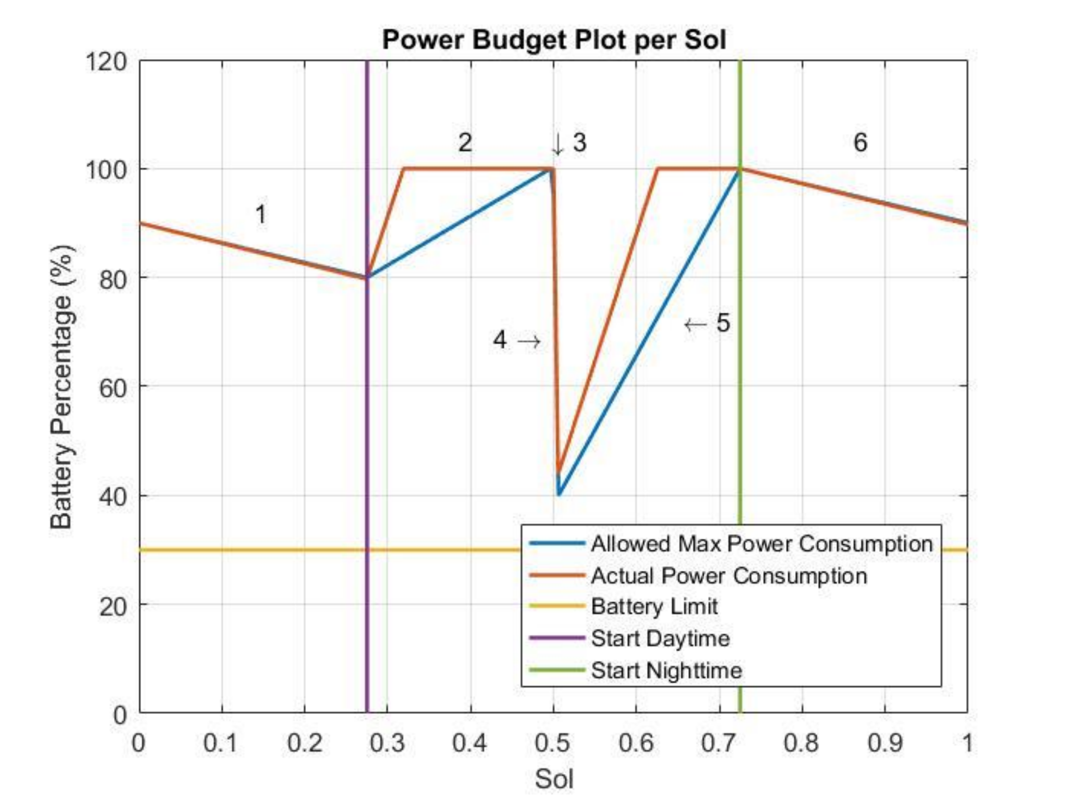
SPECTRE

POWER BUDGETING

Power Budget

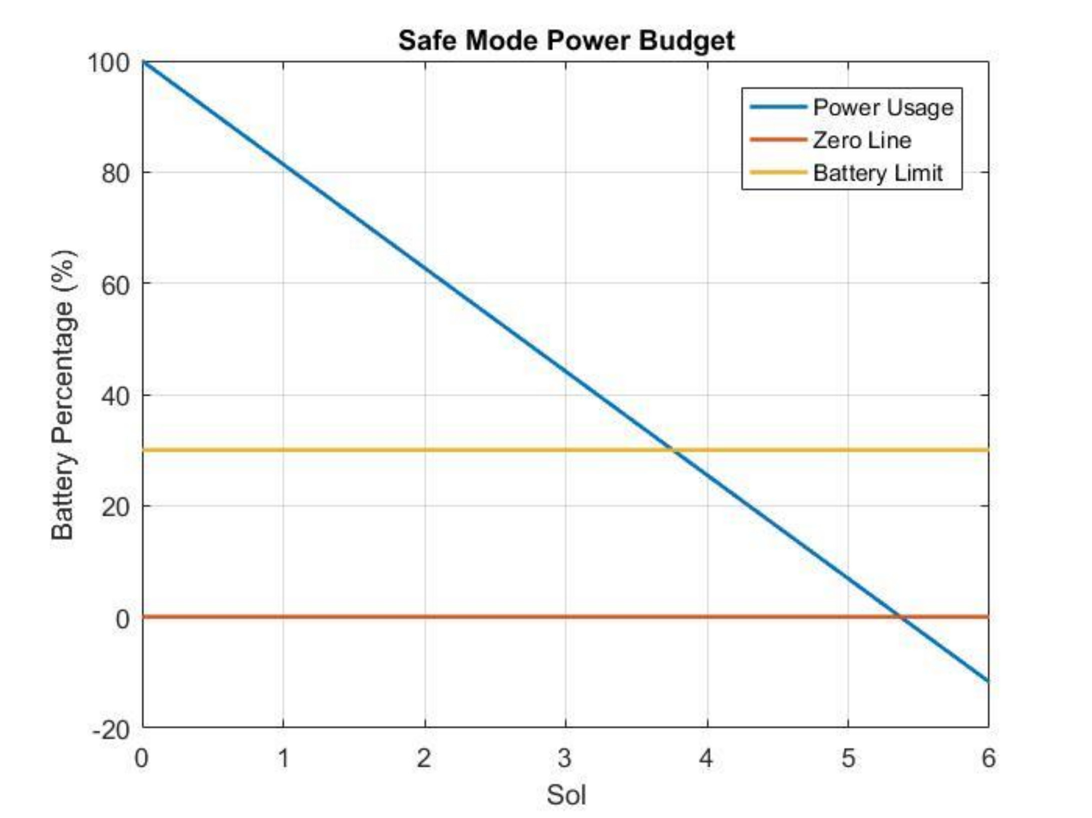
Power Mode	Percent Change Budgeted	Total Energy Change (kJ/cycle)
Charging/Transmission	+200%	+14500
Pre-Flight	-5%	-10.6
Flight	-55%	-4140
Night	-20%	-762
Safe	-100%	-1380

Power Budget



1. Night Mode
2. Charge Mode
3. Pre-Flight Mode
4. Flight Mode
5. Charge Mode
6. Night Mode

Emergency hibernation



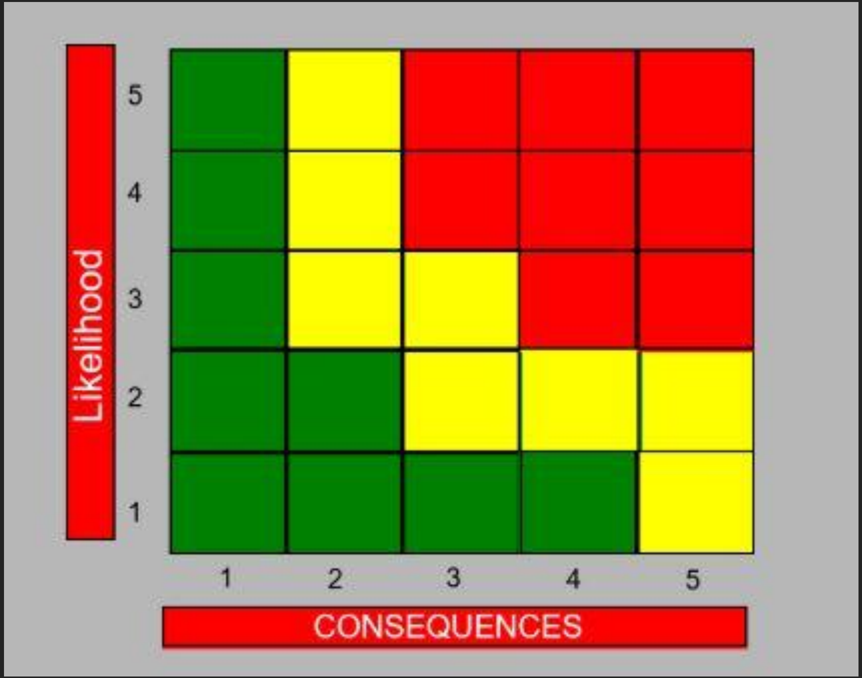
SPECTRE

RISK ASSESSMENT

Risk Assessment

Likelihood	Rank	Description
Very Low	1	P < 1%
Low	2	1% > P > 10%
Moderate	3	10% > P > 50%
High	4	50% > P > 80%
Very Likely	5	P > 80%

Consequences	Rank	Description
Minimal Impact	1	Example: minor delay in obtaining non-critical data
Minor Impact	2	Loss of non-critical data, delay in critical events
Moderate Impact	3	Loss of science objective, failure to meet full mission success criteria
Major Impact	4	Loss of instrument, loss of critical mission data set, failure to meet minimum mission success criteria
Mission Catastrophic	5	Loss of mission, mission cancellation, failure to achieve any mission objectives



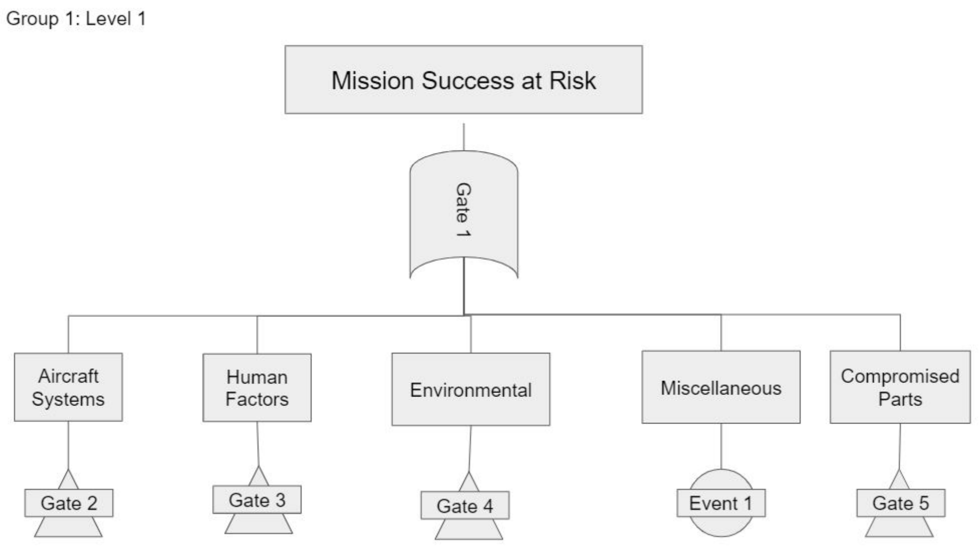
Risk Tabulation

- Lists all potential risky events and rank accordingly
- Contributed by different members across different teams

Group	Event	What caused this event?	Likelihood	Consequence(s)	Risk Rating	Contributer	Suggested Action
Flight-Power	2.1.1 Power Plant Failure	Charging circuit failure	1	4		Derek Vaughan	
Flight-Power	2.1.1 Power Plant Failure	Failure to deploy solar panels	2	3		Derek Vaughan	
Flight-Power	2.1.2 Battery Failure	Overdraw due to unexpected loads and overheat	2	5		Derek Vaughan	
Flight-Power	2.1.2 Battery Failure	Overdischarge, exceeding planned battery capacity usage	2	3		Derek Vaughan	
Flight-Power	2.1.2 Battery Failure	Imbalanced charge due to partial charging circuit failure	1	4		Derek Vaughan	

Fault Tree

- Top level of Powerpoint
- Made with Powerpoint
- Bottom up approach

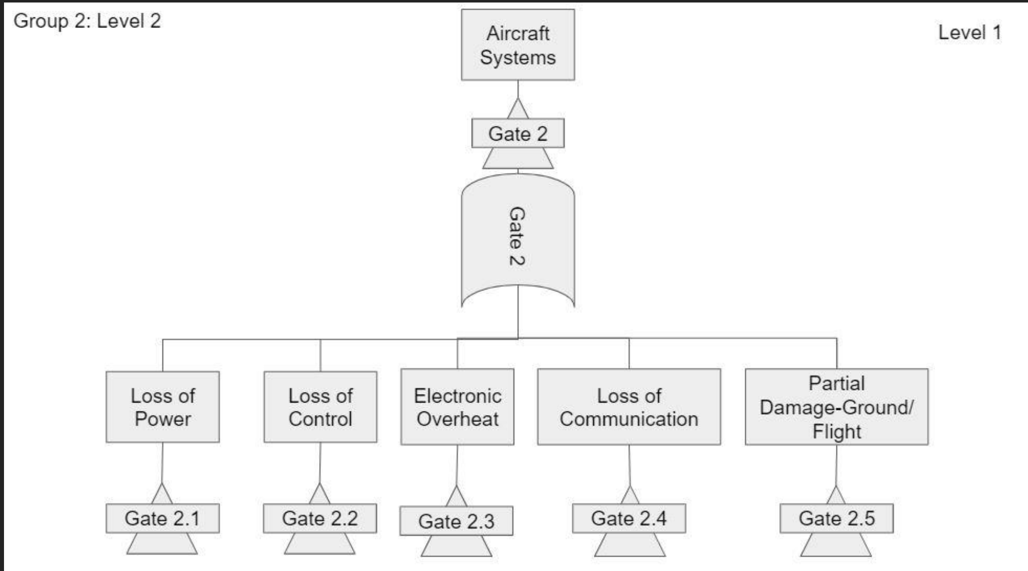


Fault Branches

Example branch: Aircraft Systems

- Includes the parts and mechanisms behind drone flight

- Example events:
  2.2.4.2.1 - Unexpected system reset
  2.2.3.1 Software failure on UAV
  2.2.4.1.2 Other hardware failure



Events

- Basic Event pages found in the powerpoint
- Naming convention follows the gates you click
- Event name, risk rating, possible causes
- 140 events

Events 2.1 - Loss of Power

Event 2.1.1 - Power plant failure

- **What caused this event? (Risk Rating)**
    - Dust coverage preventing adequate charge (Yellow)
    - Charging circuit failure (Green)
    - Failure to deploy solar panels (Yellow)

Event 2.1.2 - Battery failure

- **What caused this event? (Risk Rating)**
    - Overdraw due to unexpected loads and overheat (Yellow)
    - Overdischarge, exceeding planned battery capacity usage (Yellow)
    - Imbalanced charge due to partial charging circuit failure (Green)

Bonus Slides

Risk Assessment

PSE Risk Assessment

- The purpose of the fault tree analysis was to provide an initial risk assessment.
- Create a foundation for future project members

RFA #20

Submitted by: Kyle Shiller

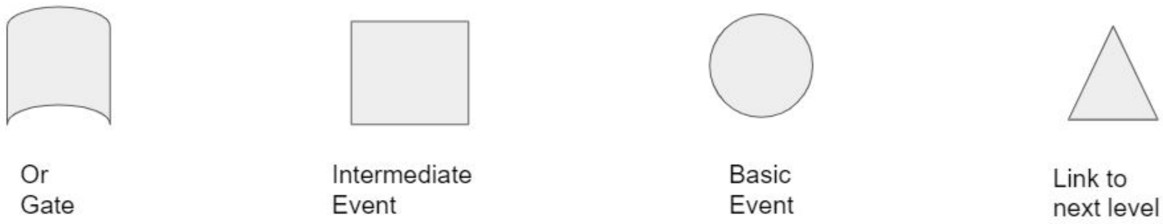
Issue or Concern: Fault Tree Evaluation

Recommended Action: Research and create a fault tree analysis that addresses the risk associated with this project

Action Assigned To: Systems Engineering

PSE Risk Assessment

Index of Fault Tree Elements



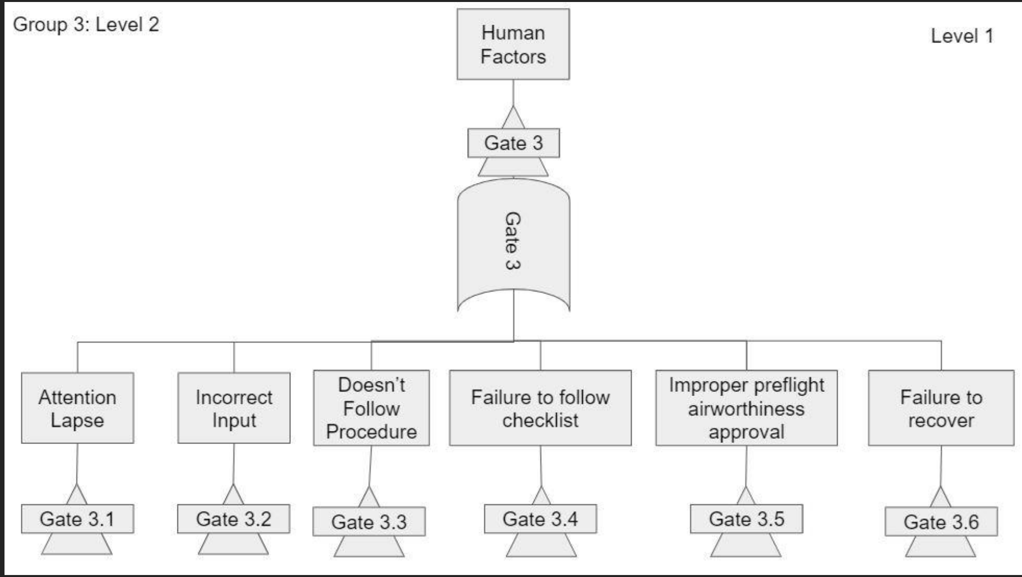
influenced from following thesis:
https://etd.ohiolink.edu/!etd.send_file?accession=ohiou1492778505498031&disposition=inline

PSE Risk Assessment

Human Factors

- Includes everything to do with the humans involved in the program

- Example events:
  3.4.1 - Skipped steps on following the checklist
  2.2.3.1 Software/sensor error leading to incorrect airworthiness approval

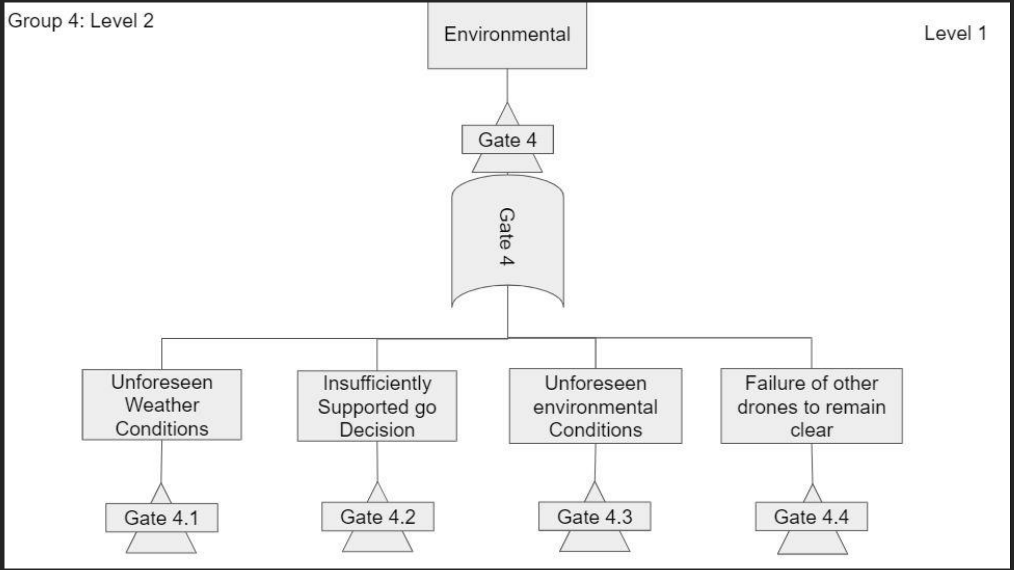


PSE Risk Assessment

Environmental

- Focuses on the relationship between the drones and external factors

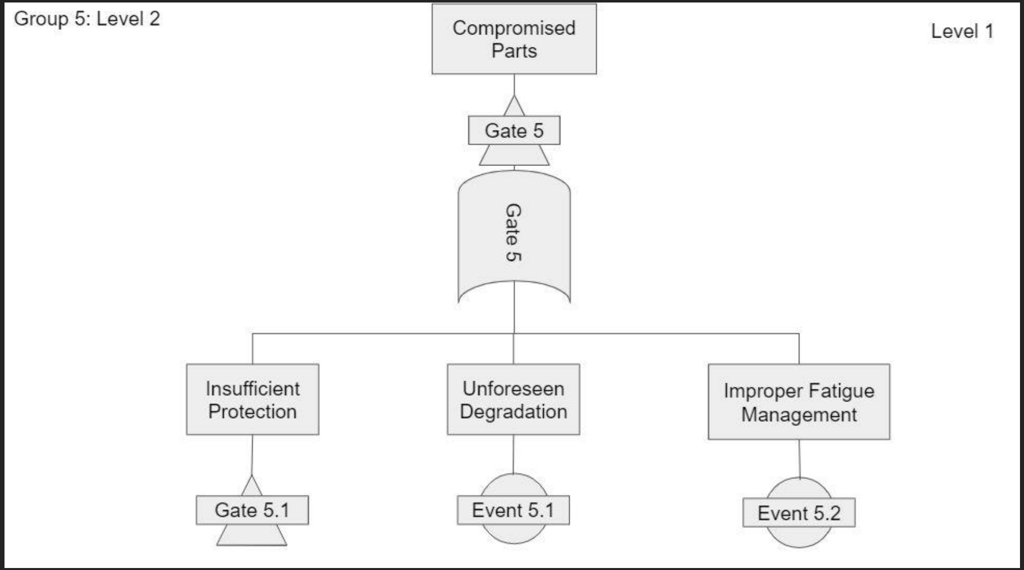
- Example events:
  4.2.1.1 Bad Information of weather conditions
  4.2.1.2 Unrealistic expectation of aircraft performance capability



PSE Risk Assessment

Compromised Parts

- Focuses on risk due to parts failing
- Lists everything related to parts failing not listed before or not related to other parent gates
- Example events:
  5.1.1 Loss of protection before reaching mission site
  5.2.2 Improper fatigue management



SPECTRE

MISSION COST ESTIMATION

Mission Cost Estimation

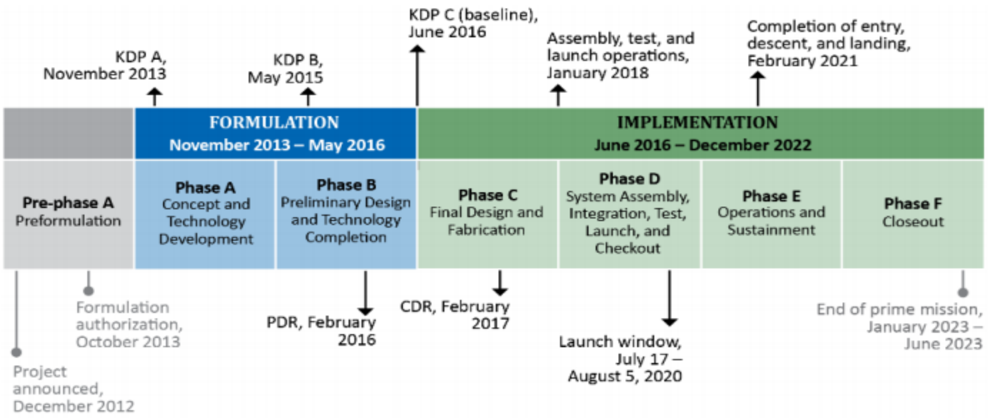
COST BY ANALOGY

- A high degree of heritage between Mars 2020 and Spectre
  - Drone/Helicopter
  - Hub/Rover
- Both improve and build upon existing technology from previous missions
  - Mars 2020 - Curiosity
  - Spectre - Mars 2020

Mars 2020 - Analogous Model

The following presents a detail on the Mars 2020 - analogous model

Figure 4: Mars 2020 Mission Timeline



Source: NASA.

Table 3: Project Estimate from Mission Concept Review to Agency Baseline Commitment (Real Year Dollars in Millions)

	Mission Concept Review	KDP-A	KDP-C
JPL obligations and bypass obligations[a]	$1,053	$1,053	$1,183[g]
Multi-Mission Radioisotope Thermoelectric Generator	66	66	70
Launch vehicle and Unallocated future expenses-Project[b]	671	671	576
Other NASA costs[c]	22	22	19
Phase E costs and Unallocated future expenses-Headquarters[d]		$329–543	456
Pre-phase A costs			23
HEOMD/STMD payload accommodations costs[e]			21
HEOMD/STMD payloads[f]			93
Total	**$1,811**	**$2,140–2,354**	**$2,442**

Source: NASA OIG analysis of Project documentation with nominal differences in dollar amounts presented due to rounding.

SPECTRE Mission Cost

The Mission cost for SPECTRE is illustrated below

Mars 2020 - analogous model

Mars 2020 Mission Cost Evolution

2012	2017	2018
NASA announces Mars 2020	**Pre-CDR Key Design Point-B**	**Spectre - conservative cost estimate**
Project Cost Estimation Range: $1.3 - $1.7 billion	$2.44 billion	$2- $2.5 billion

Speculated Mission Cost - Spectre

Upcoming Goals

Mission Systems: Complete communications transceiver test. The purpose of this test is for verification of estimated losses within the communications system.

Systems Engineering: Transfer all requirements to a text based SRD rather than a spreadsheet, examine interfaces between components to ensure compatibility, and then move primarily into a communications role to ensure that all system/interface requirements are met in future.

Flight Systems: All components' validation tests, and full system integration tests.

Payload Integration: Testing limits of mounting system, criteria for identifying stromatolites, classification of areas of interest (post mission phase), investigation of modified cameras and possible means of reducing payload mass.

AAE 450: Fall 2018 SPECTRE

THANK YOU FOR YOUR TIME