SHADE

Spacial HEO Autonomous Detector & Evaluator

Team
Robert Redfern, Quinton Dombrowski, Benjamin Vidaurre, Elliott Tung, Katherine Nyland, Marlin Jacobson, Jacob Weiner, Davis Peirce, John Hugo & Vinay Simlot

Sponsor
The Aerospace Corporation

Advisor
Dr. Zachary Sunberg

Project Description

The Need

Risks posed by Earth-orbiting objects is increasing

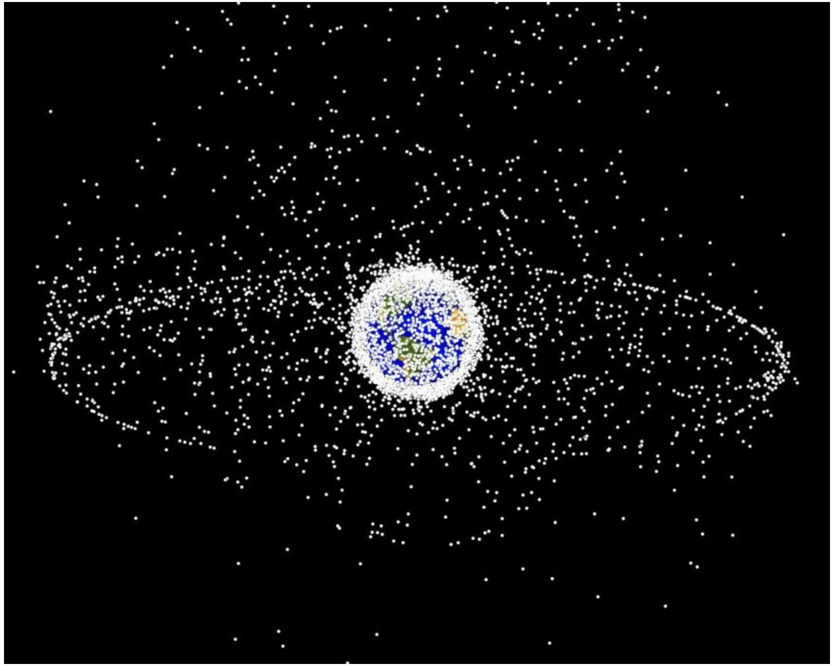
- With cheaper launches and limited capability for space junk removal, object density increases

Large Space Situational Awareness systems are highly capable and very expensive

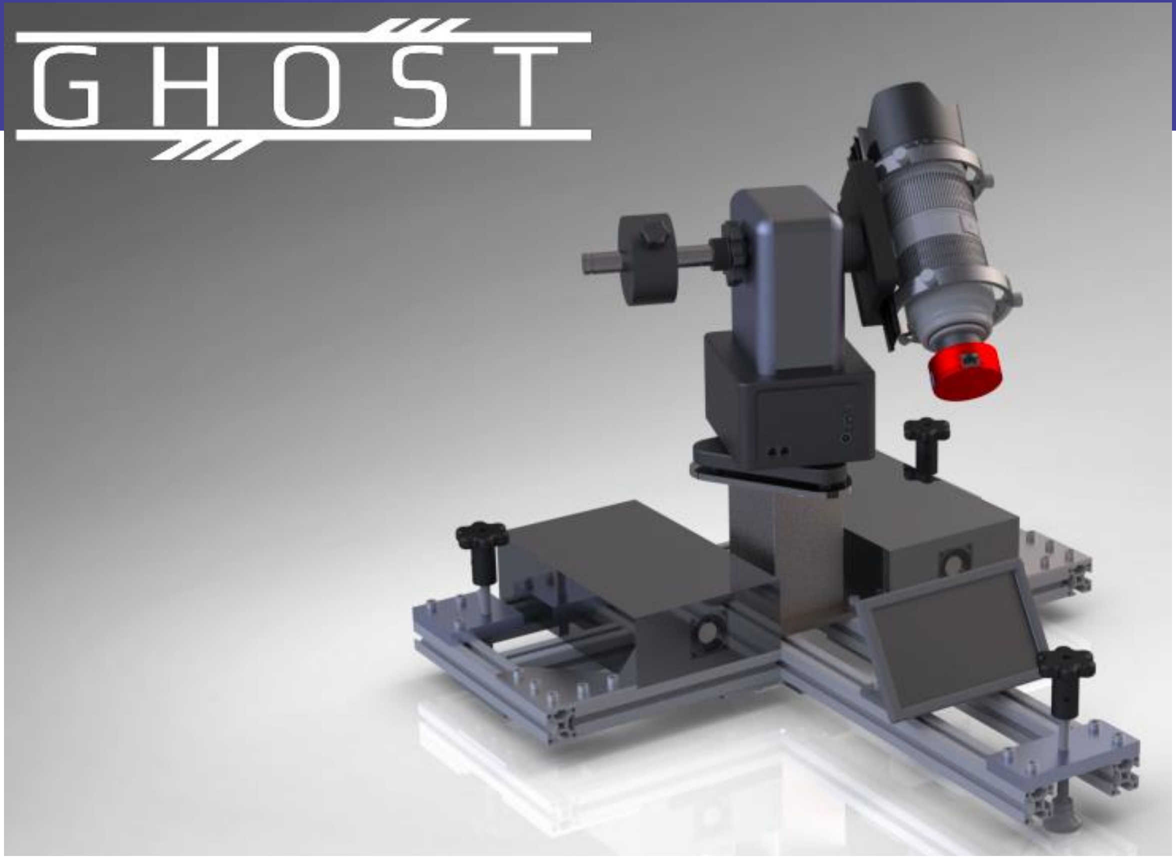
- Track ~ 25k objects greater than 10cm, ~500k between 1-10cm

Need to reduce the volume of ‘trivial’ tracking requests

- Inexpensive smaller systems will free up operational bandwidth for more capable systems



Courtesy: NASA Orbital Debris Program



2018-2019

Ground-Based **H**ardware for **O**rbital **S**pace **T**esting

Designed to meet need for a low-cost, high-production optical tracking platform

Created to track circular LEO and MEO objects

Key elements: Autonomous imaging platform actuation and processing for orbit determination, scheduling observation windows

WRAITH 2019-2020

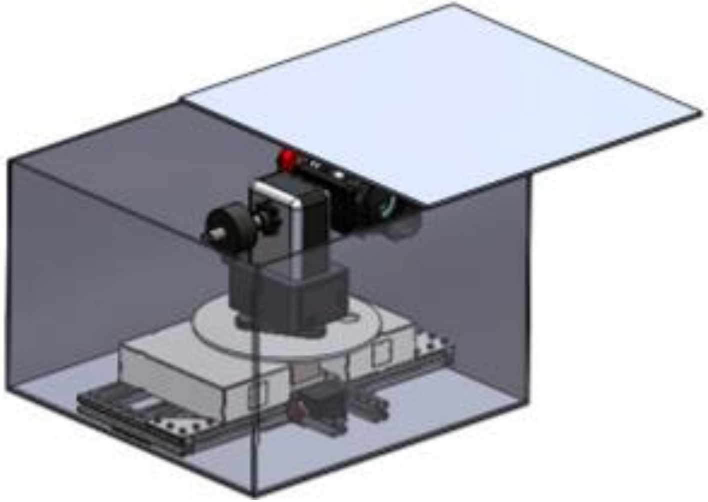
Weather **R**esistant **A**utonomous **I**maging for **T**racking **H**EOs

Added HEO tracking capabilities to GHOST

Modified to facilitate autonomous overnight observation over a 12 hour deployment

Integration and testing cut short in March 2020 due to COVID-19 pandemic

Key elements: Active and Passive weather protection measures, weather detection suite, live scheduler to reschedule missed observations



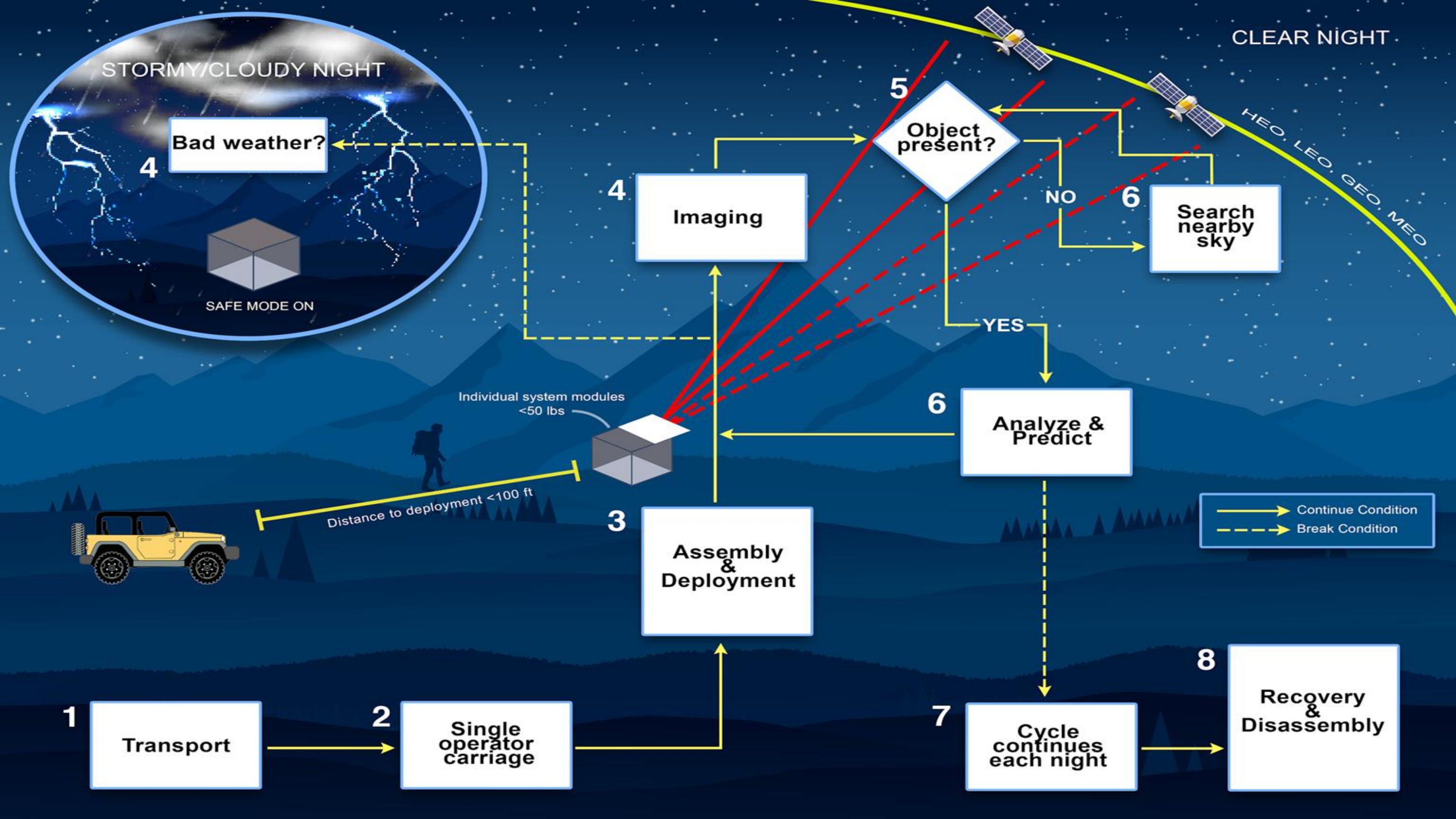
SHADE Mission Statement

To provide an easily accessible, multi-night orbit tracker, specializing in the evaluation of highly elliptical orbits. SHADE will be a low-cost, capable tracking system able to withstand adverse weather conditions.

Critical Objectives

Extend deployment duration up to five nights
Modularize system for single person deployment
Minimize required operator training & involvement
Complete WRAITH development and integration

CONOPS



STORMY/CLOUDY NIGHT
4
Bad weather?
SAFE MODE ON
CLEAR NIGHT
HEO, LEO, GEO, MEO
5
Object present?
NO
6
Search nearby sky
4
Imaging
YES
6
Analyze & Predict
Individual system modules <50 lbs
Distance to deployment <100 ft
3
Assembly & Deployment
Continue Condition
Break Condition
1
Transport
2
Single operator carriage
7
Cycle continues each night
8
Recovery & Disassembly

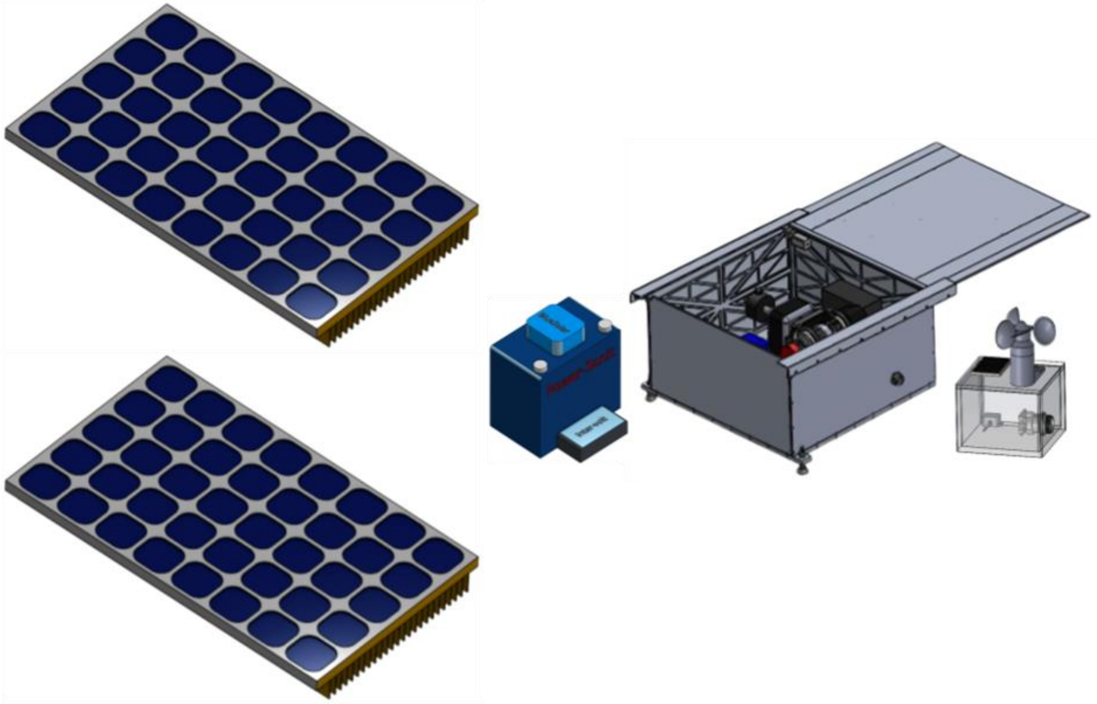
SHADE Functional Requirements

1) The system shall schedule predicted locations and visibility windows for objects in LEO, MEO, GEO, and HEO orbits.
2) The system shall function autonomously in standard operating conditions with no human intervention for at least two nights.
3) The system shall autonomously enter and exit a safe mode to protect itself from adverse weather.
4) The system shall autonomously point to and track objects in LEO, MEO, GEO, and HEO.
5) The system shall image objects with apparent magnitude of less than 10.
6) The system shall create and save an orbit estimate for each object imaged within five minutes of the end of the associated visibility window.
7) The system shall be deployed in 30 minutes and recovered in 30 minutes by one operator.
8) The system shall be capable of making observations on multiple nights during a single deployment.

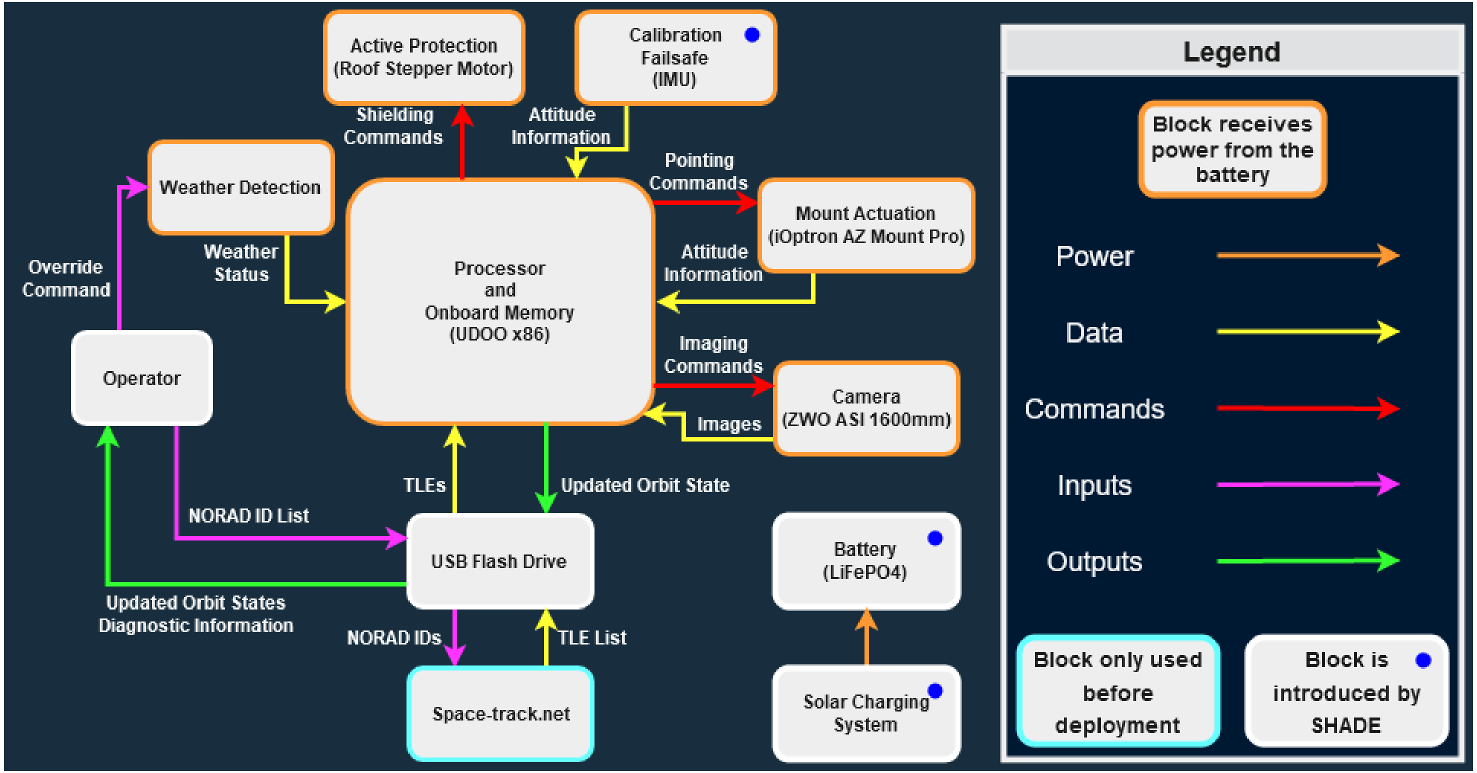
New to SHADE project

Baseline Design

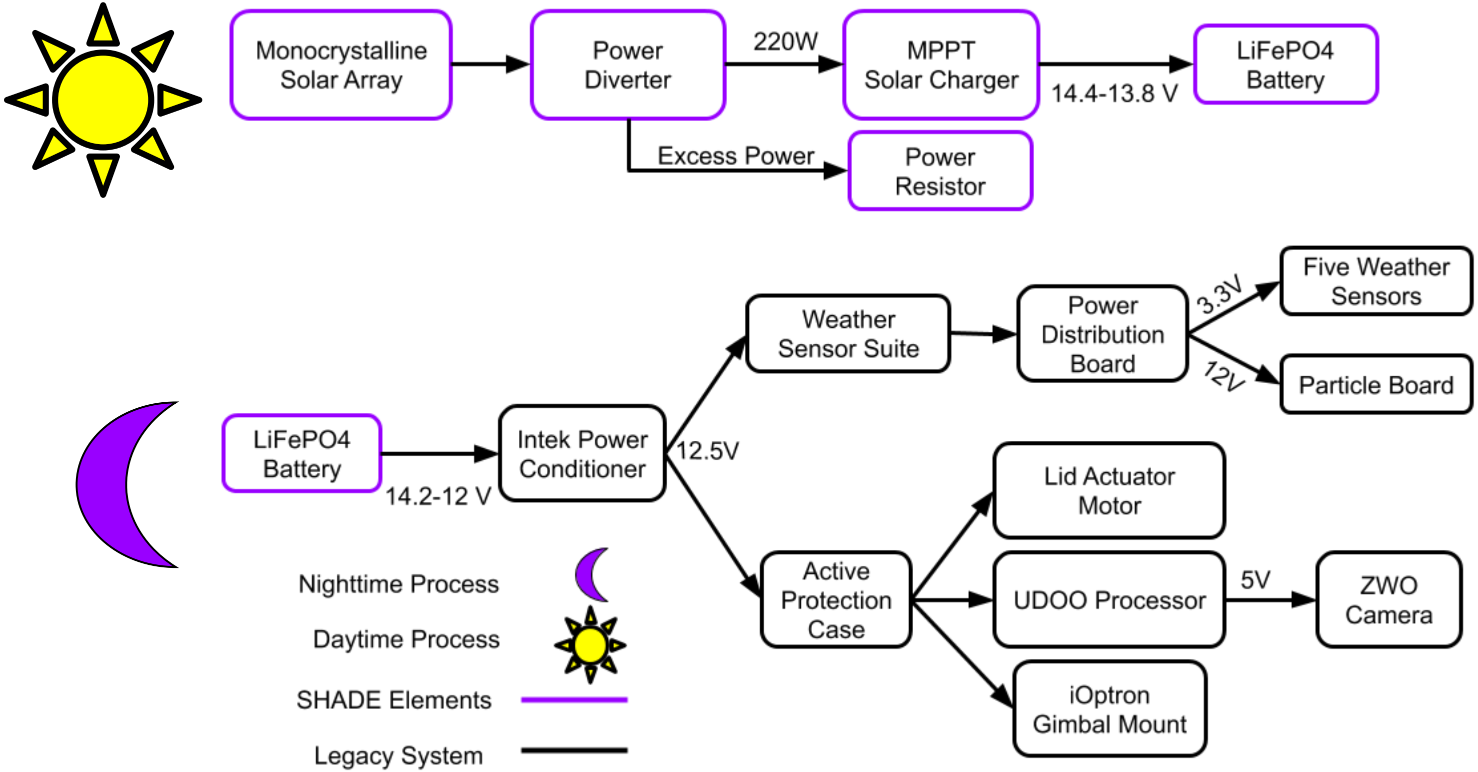
SHADE System



Overall Functional Block Diagram



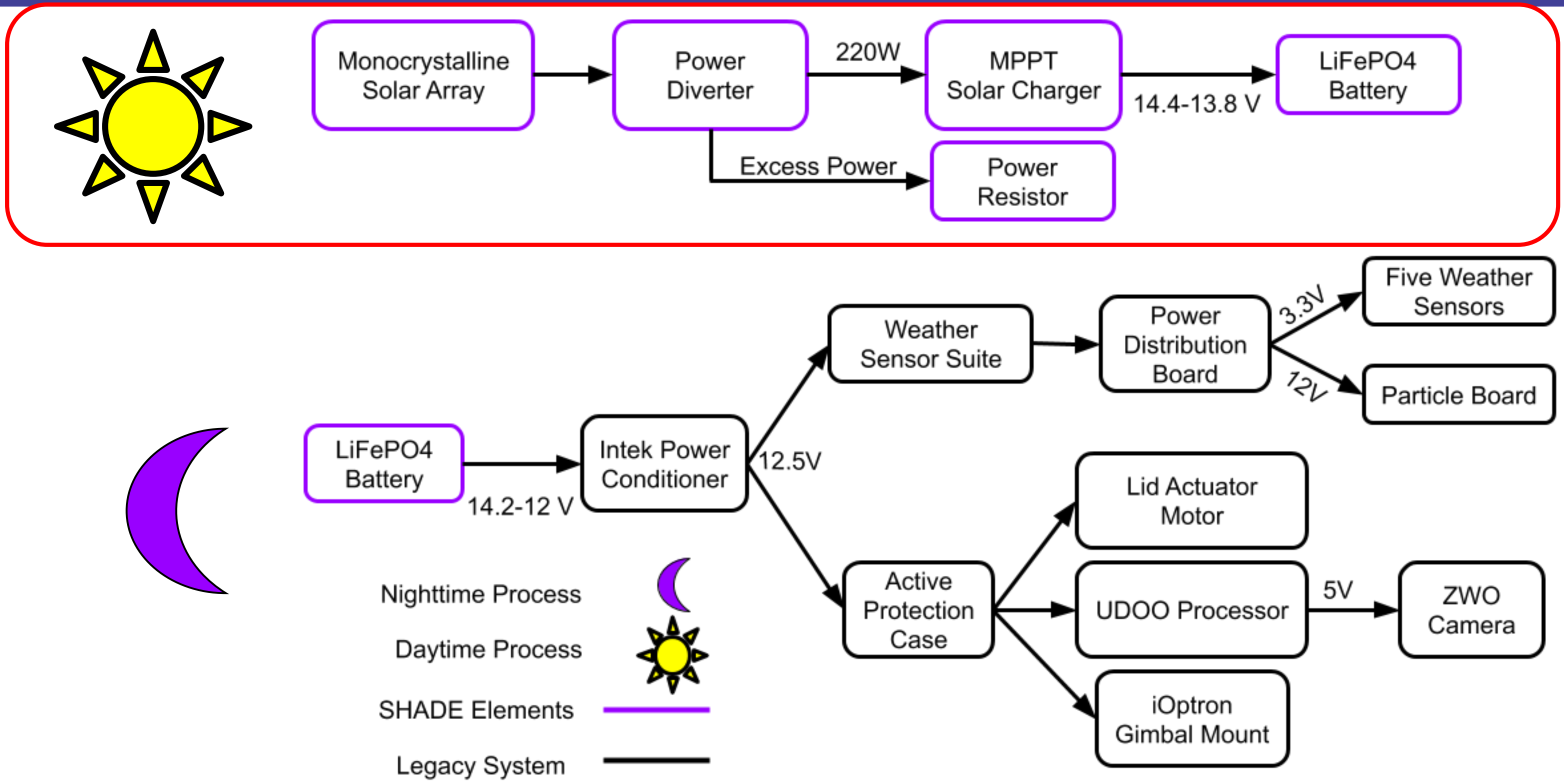
Power System Functional Block Diagram



Baseline Feasibility

Power System

Power System Functional Block Diagram



Battery & Charger

One 75Ah LiFePO4 will replace three SLA Batteries from WRAITH

- Reduced from 40 to 20.5 lbs
- Cycle life increased by 10x
- Cost per cycle lowered from $1.54 to $0.38
- Charges faster than SLA

Power Budget			
Component	Max. Draw (A)	Max. Duty Cycle	Max. Actual Draw (A)
Acutation Mount	2	0.4	0.8
MicroProcessor	0.5	0.6	0.3
Main Processor	3	0.95	2.85
Camera	1	0.3	0.3
GPS	0.02	1	0.02
Motor/Controller	2.00E+00	0.1	2.00E-01
Lightning	3.50E-04	1	3.50E-04
Temp/RH/Baro	6.50E-04	0.2	1.30E-04
Precipitation	0.1	1	0.1
IR Therm	0.0025	1	0.0025
Anemometer	0.02	1	0.02
Motor	2	0.1	0.2
	x12 Hours		x12 Hours
Total Draw	103.7 Ah		55.12 Ah

Maximum power point charging is more efficient than pulse width modulation (<98%)

- Charges at max battery charge point (15A/14.2V)
- 220W of maximum power
- Battery Voltage must remain above 11.1V

Monocrystalline Solar Array

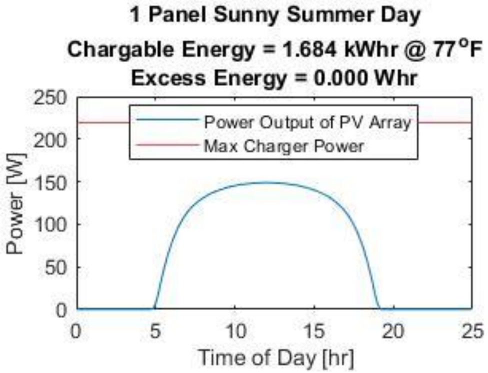
<u>Monocrystalline Cells</u>

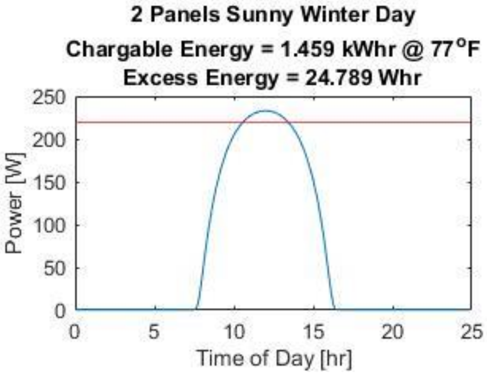
- Most efficient cell type at 23.1%
- Sturdy structure to mount cooling modifications

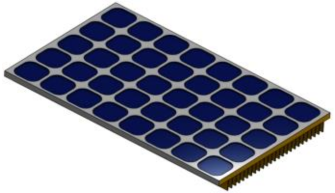
Required charge = 1.1kWhr (100% discharge)

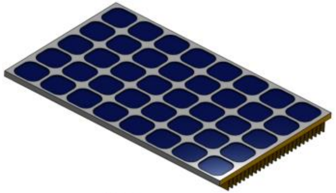
<u>Scalable 40 Cell Panels (8x5)</u>

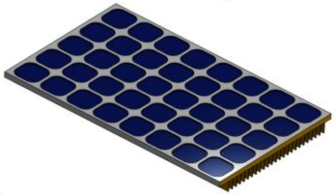
- Additional Panels will be connected in parallel
- Provide enough power on cloudy days
- Allow for deployment at other latitudes











Thermal Regulation

Rising Solar Panel Temperature reduced panel efficiency

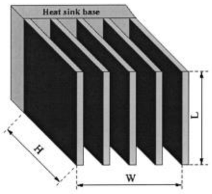
-0.161%/°F

Temperature assuming 1000 W/m^2 of sunlight and black body

148.5°F -- 11.5% decrease in efficiency

Photovoltaic Cooling Technologies

Water circulation, heat sink, phase change materials, forced air



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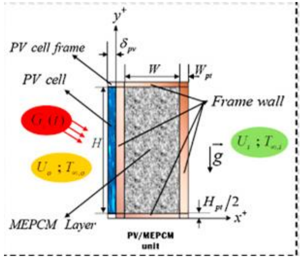
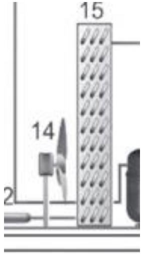




Thermal Regulation

Aluminum Conduction

$$\dot{q}_{fin} = 1.25\, L\, \theta_B \sqrt[3]{h_{fin} H t k_{fin}}$$

$$h_{fin} = {}^{tk_{fin}}\!/_{0.993H^2}$$

$$\dot{q}_{fin} = 31.497\, W/fin$$

$$\dot{Q}_{fin} = 3.15\, kW$$

Model via Cohen et.al

Forced Convection

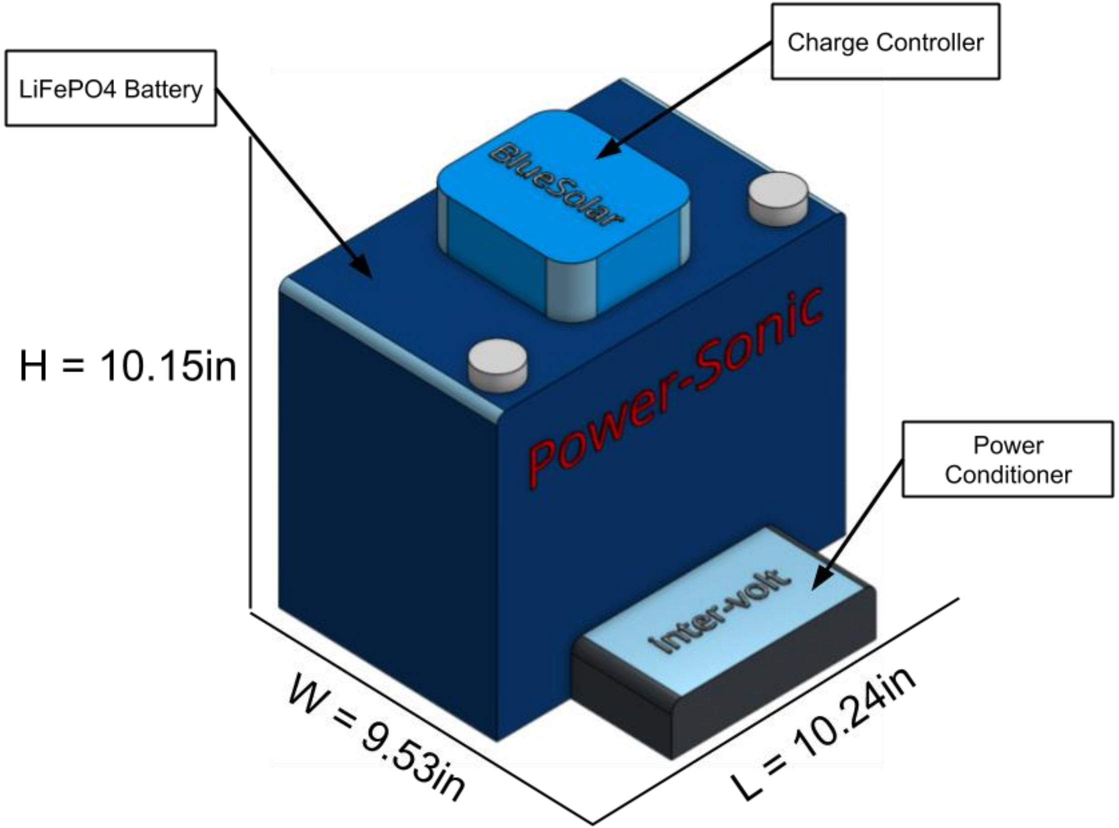
$$\dot{q}_{conv} = h(T_{panel} - T_{amb})$$

$$\dot{q}_{conv} = 87.1\, W/m^2$$

$$\dot{Q}_{conv} = 2.18\, kW$$

Averaging fan speeds between 2,3,4,5 m/s via Ceylan et.al

Power Module Size



Modularity

Requirements Overview

Requirement	Description
FR 2	**The system shall function autonomously in standard operating conditions with no human intervention for at least two nights.**
DR 2.1	The system shall operate in conditions defined by the Standard Operating Conditions defined in Appendix VI.A with no impact to orbit determination capabilities.
FR 3	**The system shall autonomously enter and exit a safe mode to protect itself from adverse weather, as defined by conditions worse than the Standard Operating Conditions defined in Appendix VI.A.**
DR 3.1	The system shall employ active weather shielding to protect the observation platform from adverse weather. [Met by WRAITH design, active protection verified in unit test]
FR 7	**The system shall be deployed and recovered within 30 minutes by one operator. [WRAITH verified that the individual environmental sensors are capable of starting up and outputting accurate data in less than 30 minutes]**
DR 7.1	The individual system modules shall weigh less than 22.68 kilograms (50 lbs).

Requirements Overview (cont.)

Requirement	Description
DR 7.1.1	The system modules, when located inside their travel casing, shall withstand impulses up to 7 g in any given direction.
DR 7.1.2	The system modules, when located inside their travel casing, shall withstand cyclical vibrations ranging between ±2g at a frequency of 1 Hz.
DR 7.1.3	The system shall utilize passive protection to protect sensitive components not requiring elemental exposure to function from adverse weather. [Met by WRAITH design, passive protection untested].
DR 7.2	SHADE shall be set up and taken down in accordance to the process document titled: SHADE System Operation Manual.
FR 8	**The system shall be capable of making observations on multiple nights during a single deployment.**
DR 8.1	SHADE shall be resilient to diurnal temperature fluctuations over the range of temperatures described by the Standard Operating Conditions in Appendix VI.A.
DR 8.1.2	While not in use, the internal temperature of the *MOST SENSITIVE ENCLOSURE* shall be maintained between [TBD Range].

Modules

#1 *Actuation Mount & Telephoto Lens/Camera:*

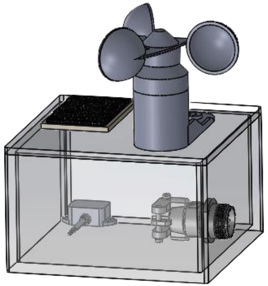
Dimensions: 11 x 15 x 10.5 in

Weight: 18 lb

#2 *Environmental Suite:*

Dimensions: 8 x 11 x 11 in

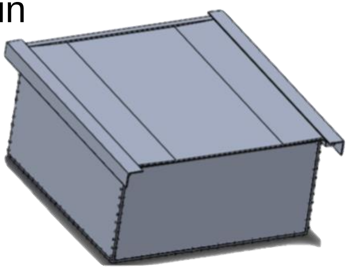
Weight: 5 lb



#3 *Processor & Weather Protection Box:*

Dimensions: 23 x 23 x 12 in

Weight: 15 lb

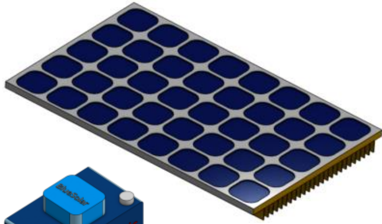


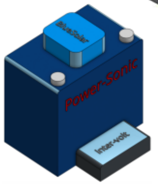
#4 *Solar Panel & Battery:*

Dimensions:

Weight:

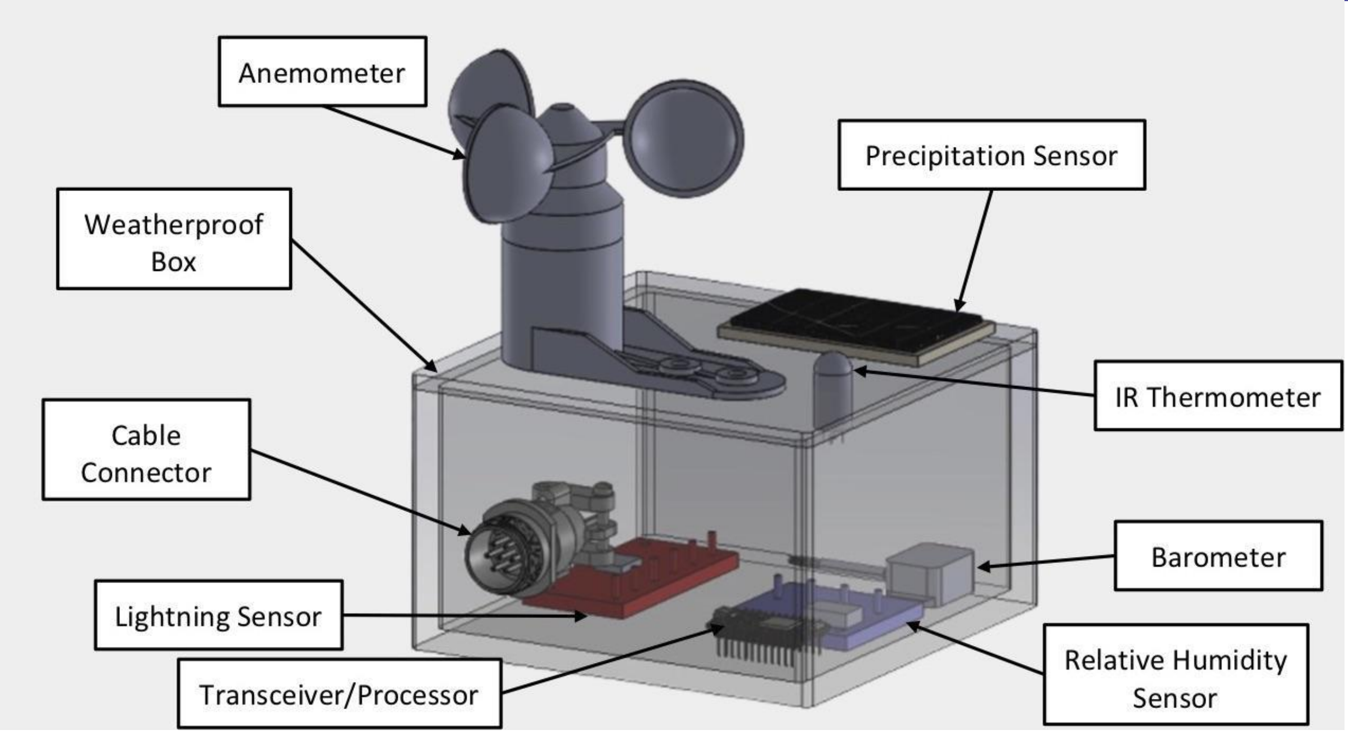
- 2 Solar Panels: 20 lb / panel
- Solar Charger: 1.1 lb
- Battery: 20.5 lb
- Power Conditioner:~ 1 lb





Weather Detection

Weather Detection - Design



Weather Detection Logic

Single Sensor Safe Mode Trigger:

Lightning detected at any distance

OR

Precipitation detected

OR

Wind speeds detected > 8 m/s

1 Hz

Multiple Sensor Safe Mode Trigger:

Pressure drops by > 3 mb

AND

RH detected above 70%

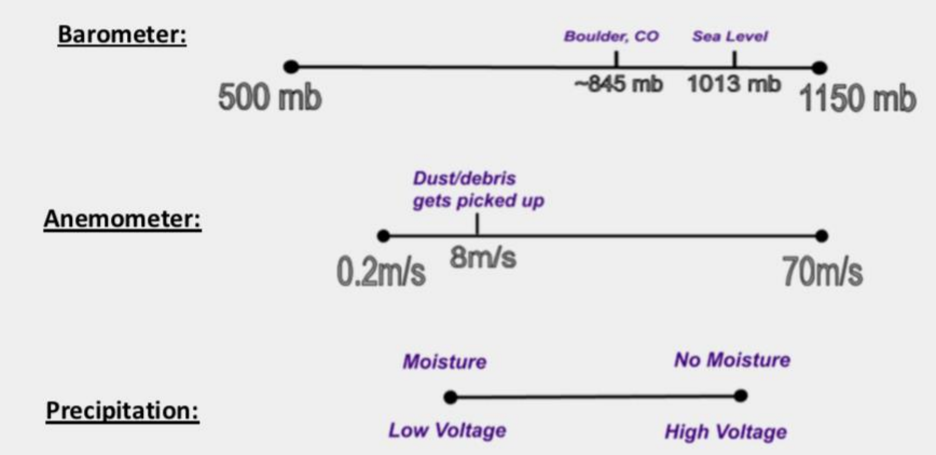
AND

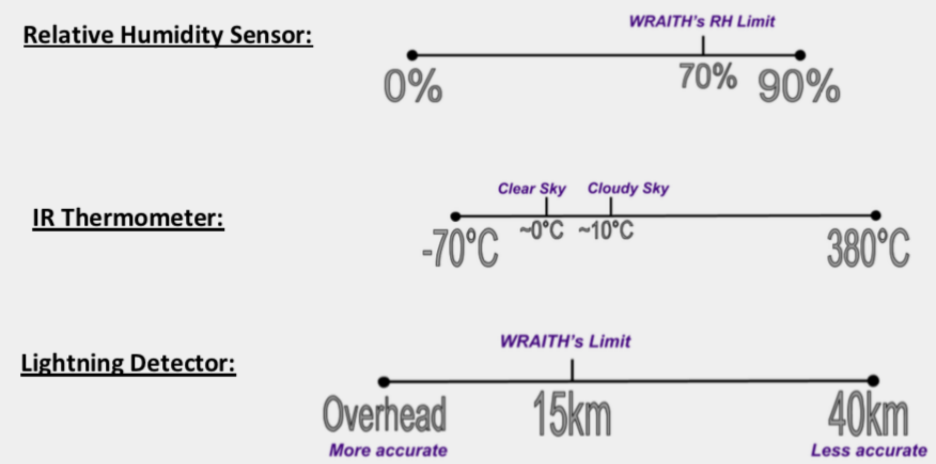
IR temperature higher than 10℃

Remote Operator Safe Mode Trigger:

Shutdown command received over cellular

Environmental Systems - Feasibility

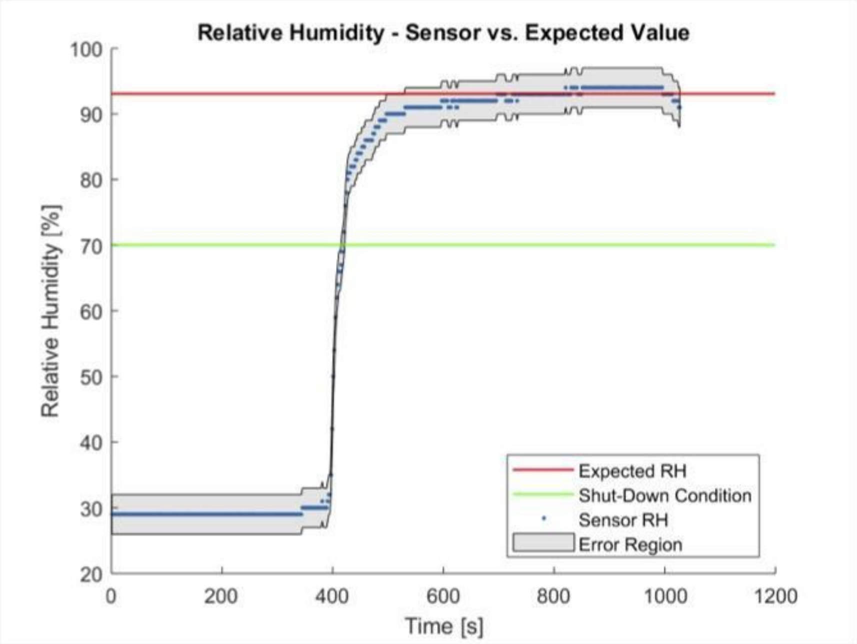




Completed Environmental Sensor Tests

All sensors have been **tested individually** and compared to known data provided by NWS

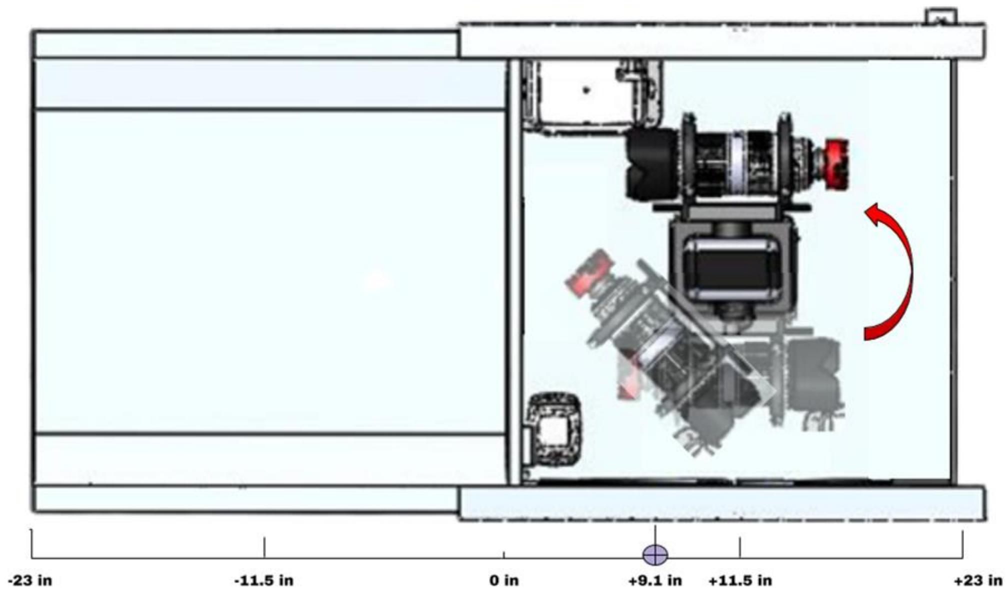
All sensors (except the anemometer) have been **tested together** with the completed environmental code

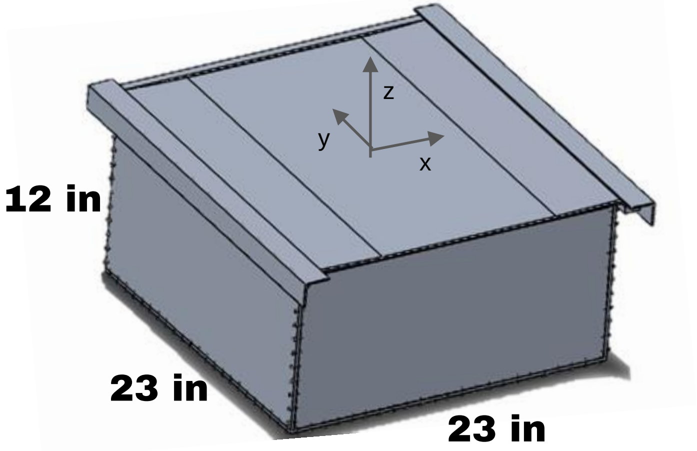


Satisfies Functional Requirement 7 since sensors reach equilibrium in <u>less than 30 minutes</u>

Active Protection

Active Protection Geometric Overview





- Floor dimensions enable camera and iOption mount to fully rotate about the box's center.

- Wall height ensures usable field of view (+/- 150 deg from Z center in X and Y directions) for camera during object tracking.

Active Protection Material Overview

Polycarbonate

Benefits

1. Highly durable
2. Easily machinable
3. Large temperature range
4. Low thermal conductivity

Notable Properties

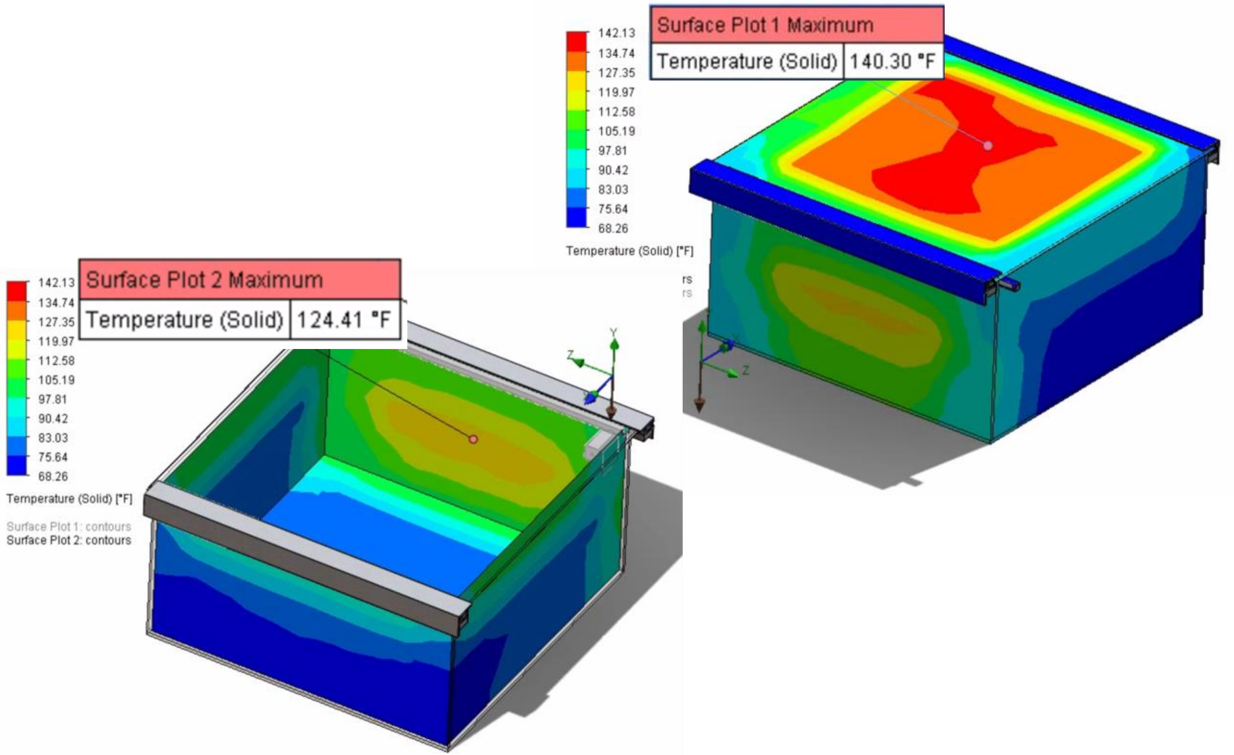
1. Density: 1.2 g/cm^3
   a. **SHADE will be half of WRAITH system weight.**
2. Thermal Conductivity: 0.113 BTU/hr ft F
   a. **Protects internal hardware from high temperatures.**
3. Emissivity: 0.95
   a. **Allows polycarbonate to remain within temperature range in sun.**

Active Protection Material Verification

- **Thermal analysis performed to verify internal temperatures of box do not exceed hardware limits.**

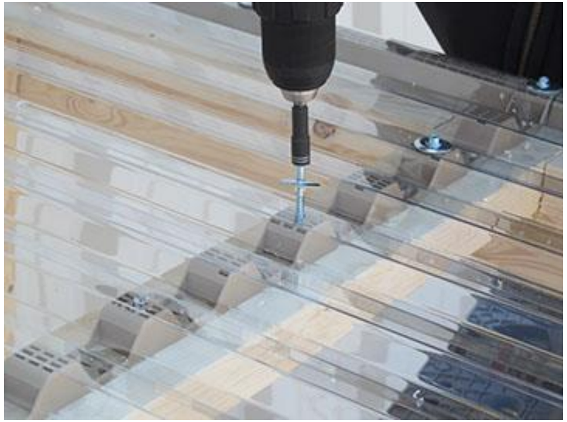
- Set Up: (Date = 3/11, Time = 12:00-15:00)
    a. External convection
    b. External and internal radiation
    c. Ambient & initial temperatures of 68F.
    d. Solar flux in Denver.

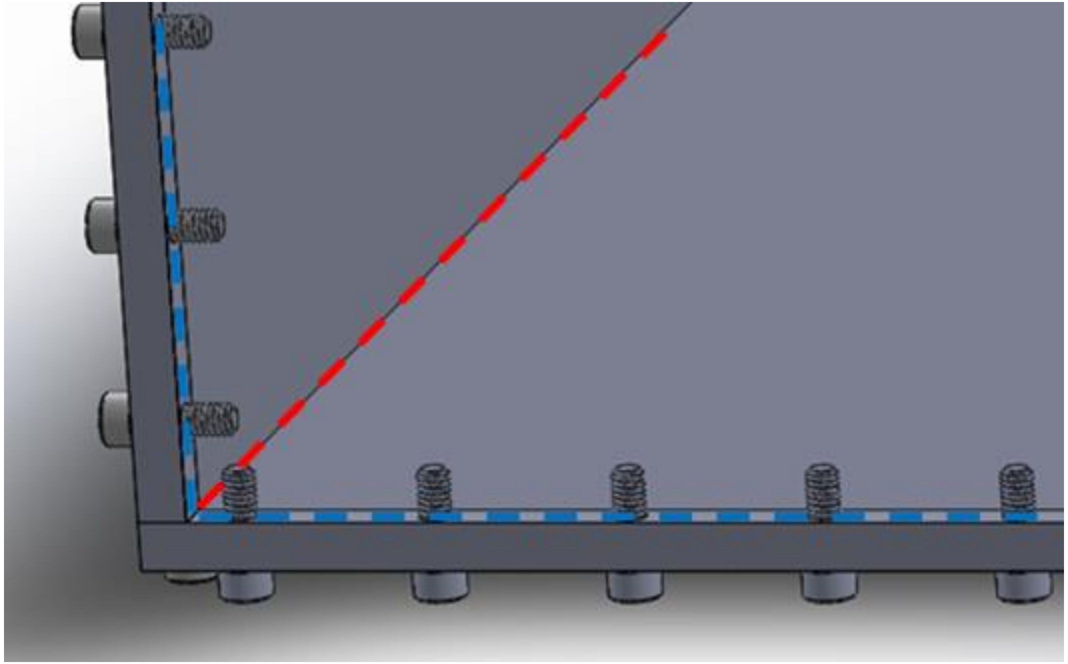
Temperatures do not exceed material limits. Internal hardware is safe from heating.



Active Protection Assembly

- For Polycarbonate panel exterior, utilize screws with washers to fasten panels together





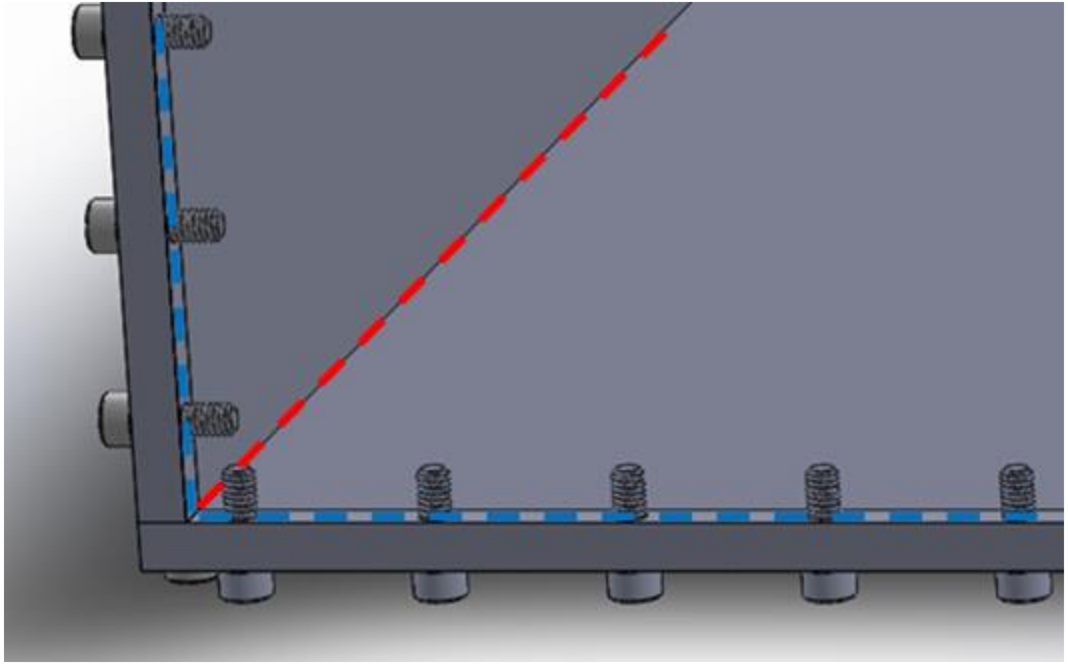
Edge Seal Design

Edge Sealant Options:

- Engine Block Liquid Gasket
- Gasket Tape
- Loctite Liquid Gasket

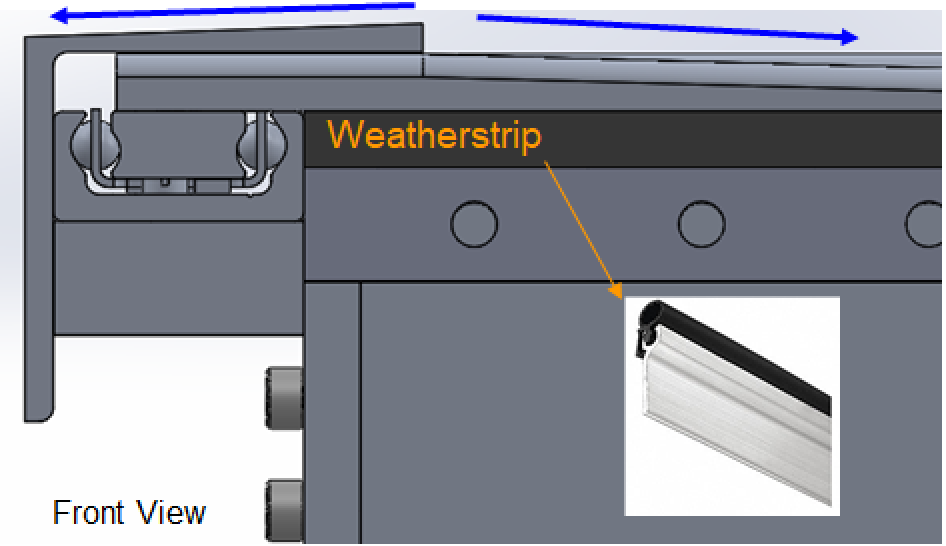
Interior Sealant Options

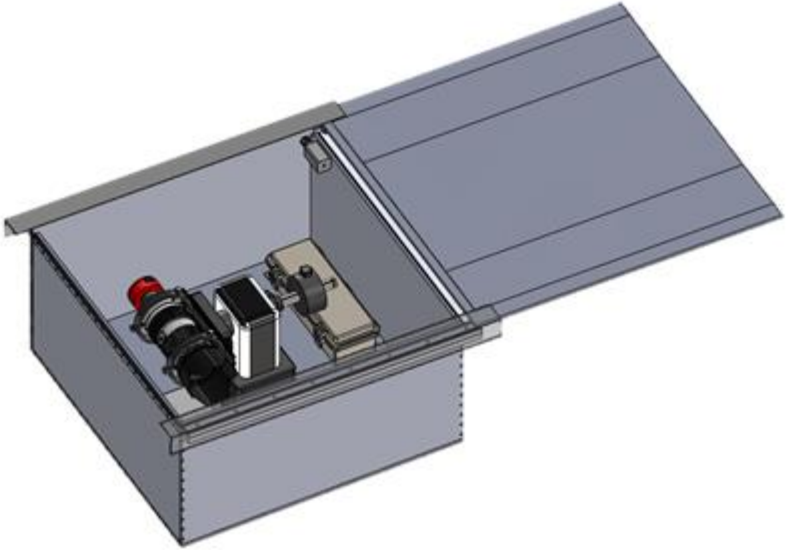
- Silicone Caulk



Actuating Roof Design

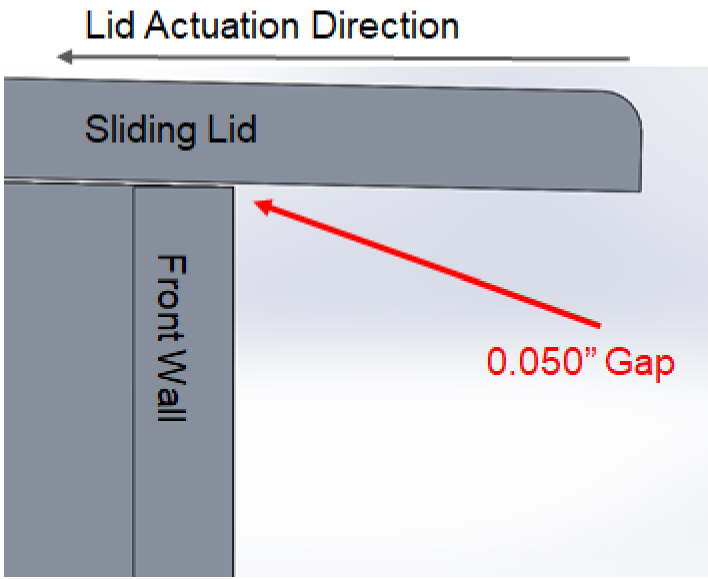
- Ensure water moves away from sliders
- Utilize weatherstripping/thresholds where appropriate

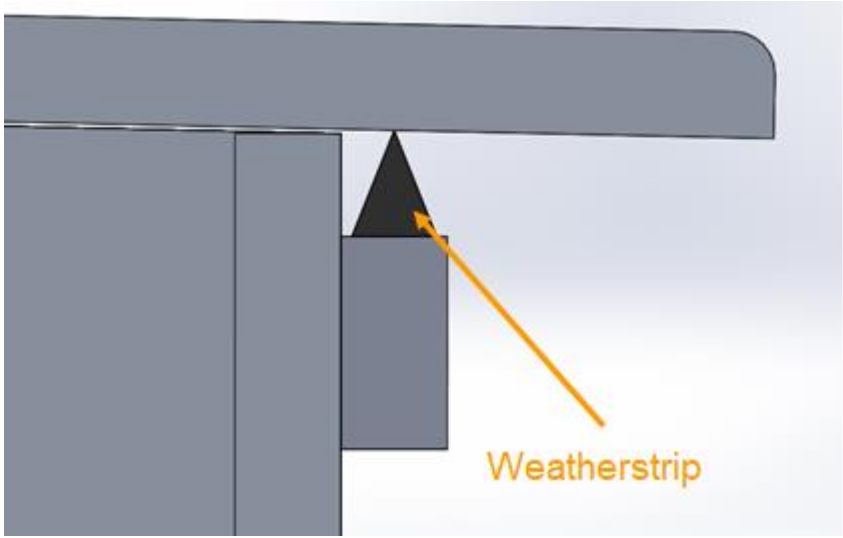




Actuating Roof Design

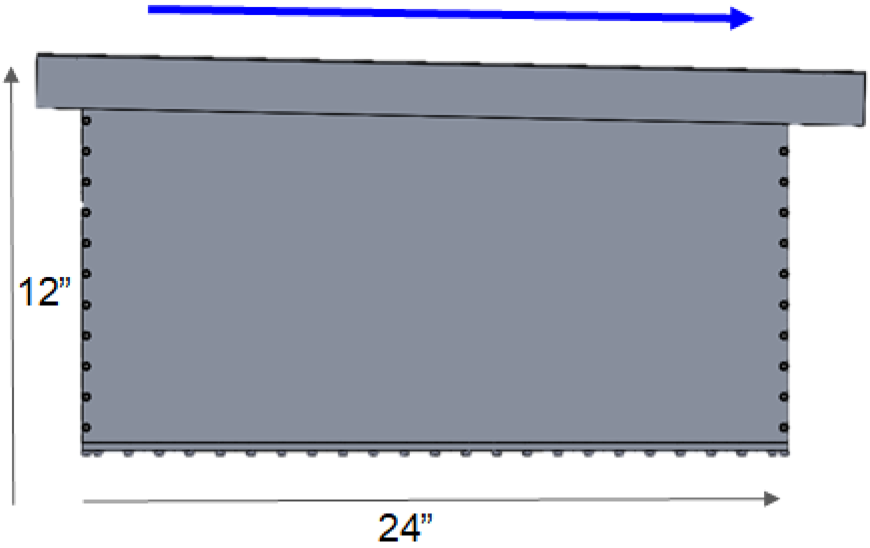
- Maintain tight tolerances (Gaps < 0.050'')
- Utilize weatherstripping/thresholds where appropriate

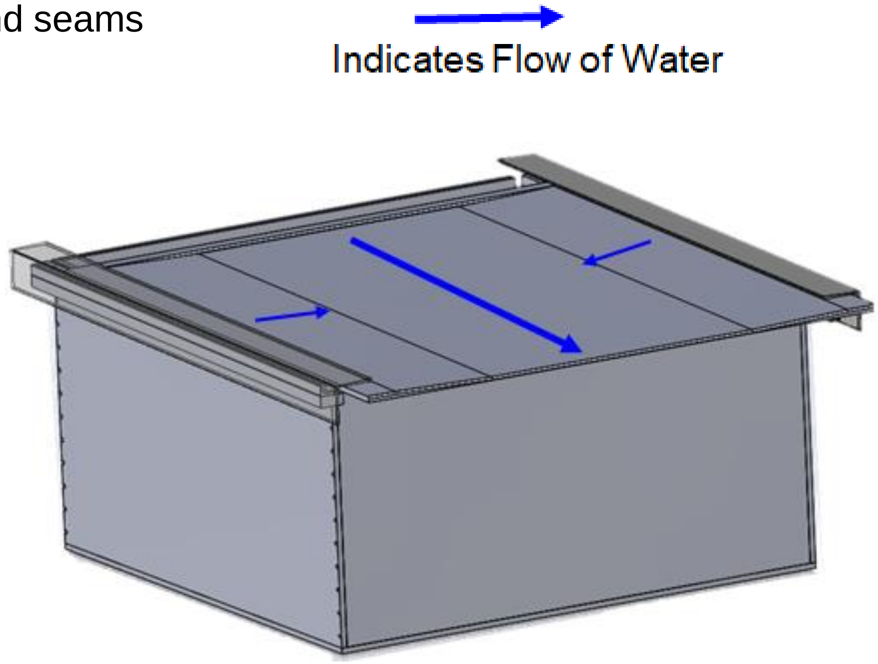




Actuating Roof Design (Water Pooling)

- All slopes are greater than ¼" of drop per horizontal foot
- Roof is contoured to move water away from sliders and seams
- Box will be leveled with adjustable feet





Hardware Tipping Prevention Model

Determine max allowable moment at fulcrum before box tips over

$$cg_{total} = \frac{W_{lid}d_{lid} + W_{Box}d_{box} + W_{hardware}d_{hardware}}{W_{lid} + W_{box} + W_{hardware}}$$ **= 9.095 in**

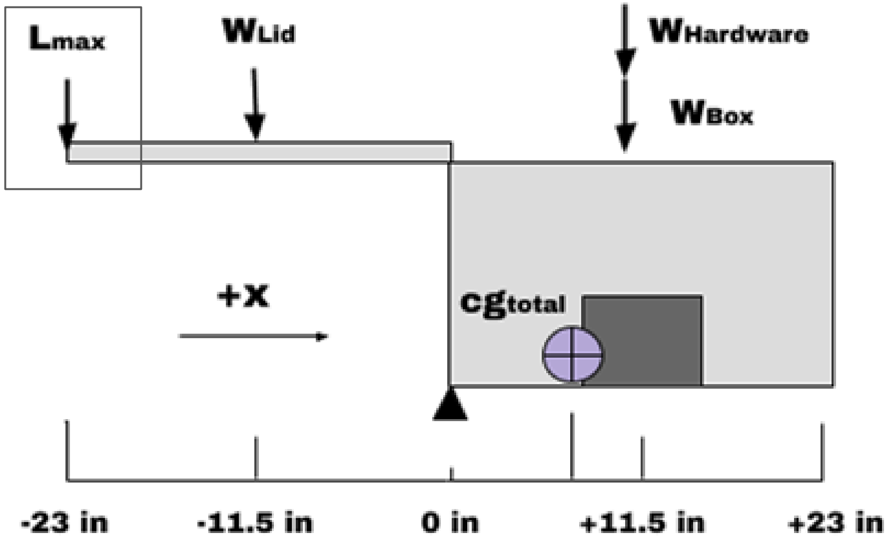
$$\Sigma M_{fulcrum} = L_{max,tip}d_{max,tip} - W_{total}cg_{total} = 0$$

$$\boxed{L_{max,\ tip} = \frac{W_{total}cg_{total}}{d_{max,tip}}}$$ **= 13.05 lbf**

$$M_{max\ allowable,\ tip} = W_{lid}d_{lid} + L_{max,tip}d_{max,tip}$$ **= 28.32 lbf ft**

$$M_{fulcrum,\ due\ to\ lid} = W_{lid}d_{lid}$$ **= 3.31 lbf ft**

$$\boxed{FOS_{lid,\ tip} = \frac{M_{max\ allowable}}{M_{due\ to\ lid}}}$$ **= 8.5**

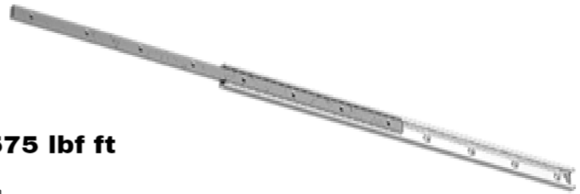


The active protection **system will not tip over** due to the weight of the lid or small animals.

Hardware Failure Prevention Model

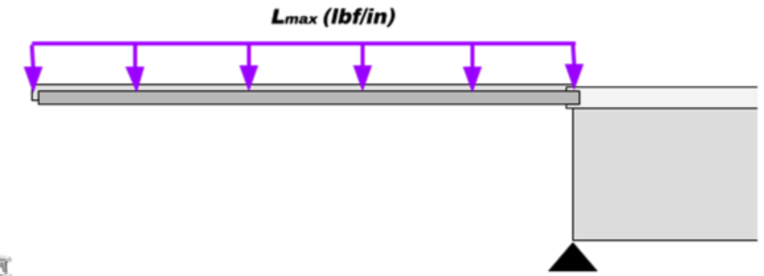
Determine max allowable moment at fulcrum before slider roof track breaks

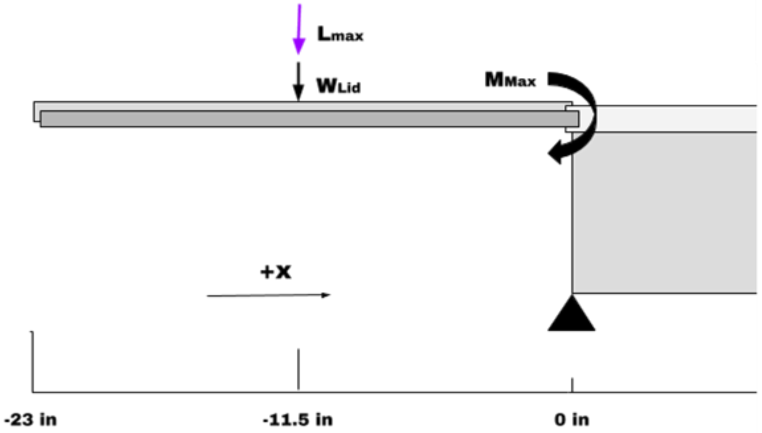
$L_{max\ allowable,\ slider}$ = **600 lbf**



$M_{max\ allowable,\ slider} = L_{max,slider} d_{slider}$ = **575 lbf ft**

$FOS_{lid,\ slider} = \frac{M_{max\ allowable}}{M_{due\ to\ lid}}$ = **173.9**





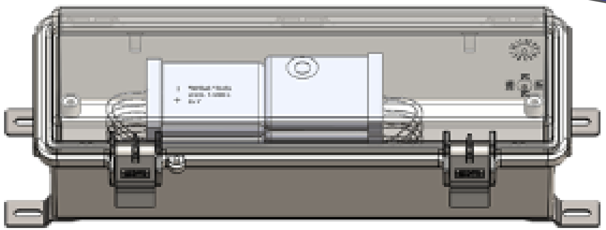
The **slider tracks will not break** due to the weight of the lid.

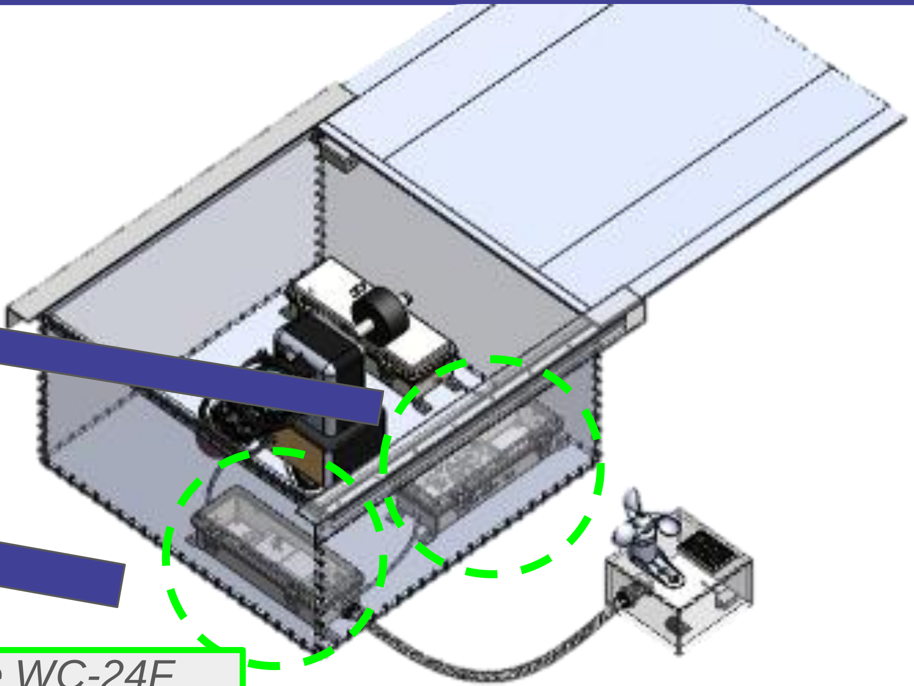
If weight is applied to the lid, the **system will tip over before breaking**.

Passive Protection

Passive Weather Protection Design

Polycase waterproof outdoor boxes for UDOO processor and distribution board

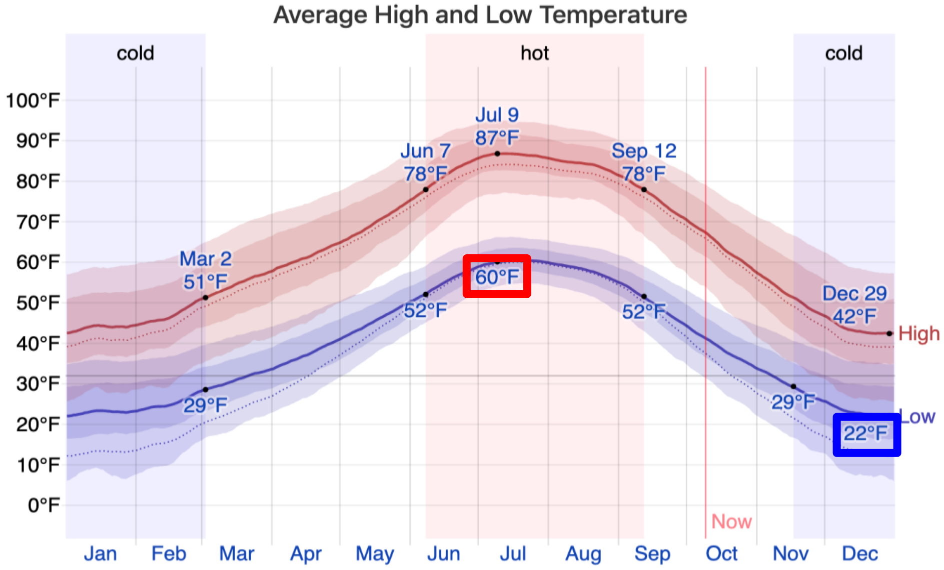




Thermal Protection

Standard Operating Conditions (Level 1)

Temperature: 22°F - 60°F (-5°C - 16°C)



Cold Case Risk

UDOO x86 Processor

iOptron AZ Altazimuth Mount

ZWO ASI 1600MM Camera

Hot Case Risk

none

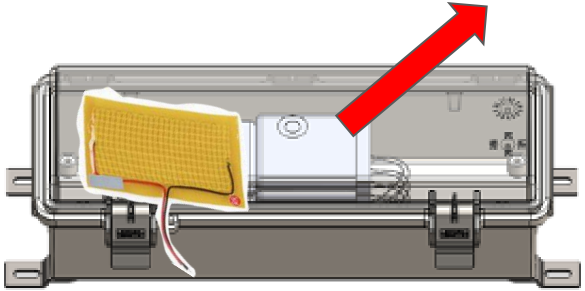
Cold Case Risk

UDOO Minimum Operating Temperature: 32℉ (0℃)

Minimum Temperature With Heater on Polycase: 17.87℉ (-7.85℃)

iOptron Minimum Operating Temperature: 14℉ (-10℃)

ZWO Camera Minimum Operating Temperature: 22℉ (-5℃)



***Feasibility Check*: Current Operating Temps Are Within SOC (FR 2)**

Software

Novel Software Requirements Overview

Requirement	Description
FR 7	**The system shall be deployed and recovered within 30 minutes by one operator.**
DR 7.3	SHADE shall be able to startup and perform all tasks with no user input beyond supplying a target list file via external USB drive.
DR 7.4	During setup, SHADE shall execute an automatic attitude determination routine.
FR 8	**The system shall be capable of making observations on multiple nights during a single deployment.**
DR 8.3	The scheduler shall predict location of an object at an arbitrary time up to five nights in the future.
DR 8.4	When creating the initial schedule, the scheduler shall be able to consider the total mission duration when prioritizing observation windows.

Core Software Components

Startup Procedure
(Novel, FR 7)

- Minimizes necessary operator expertise
- Fewer setup tasks for operator to perform
- Faster setup time
- Generally improved interface

Automatic Calibration
(Modification, FR 7+8)

- Part of automatic setup
- Allows for recalibration (a necessity of long deployments)

Scheduler
(Modification, FR 8)

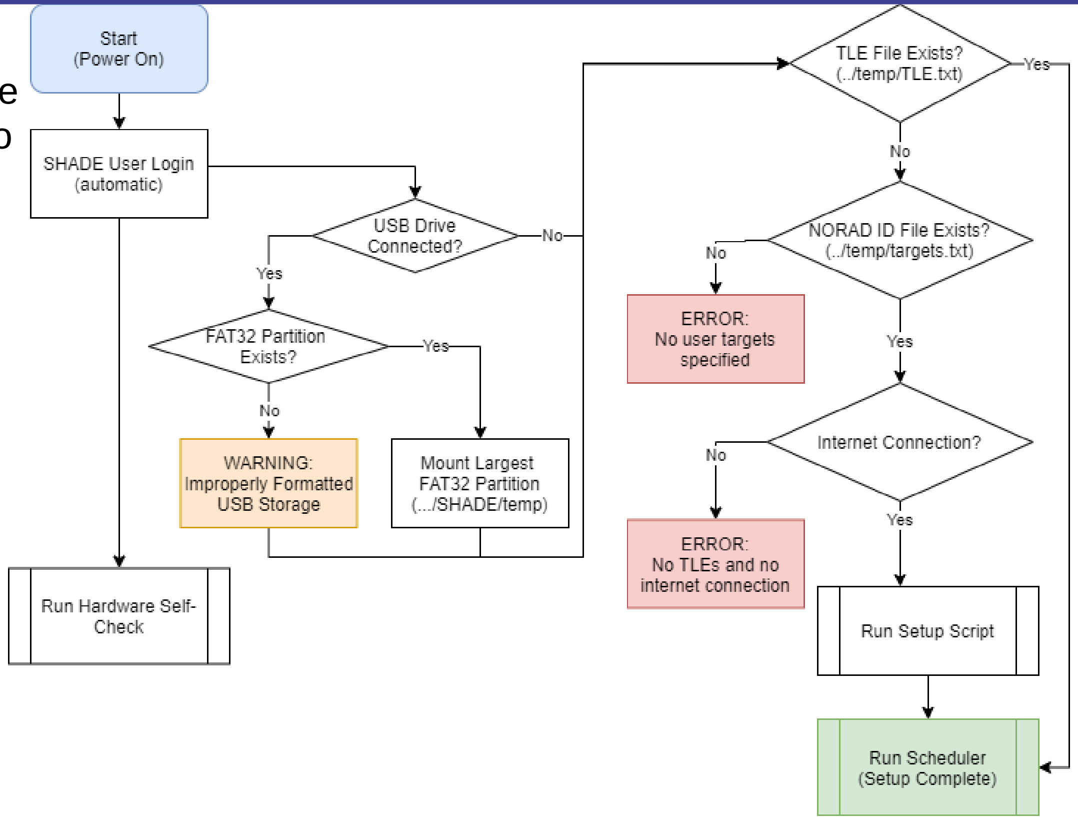
- Multi-day deployments demand changes to observation priority
- Potential for prediction quality to decay

Startup Procedure

Before Deployment (on PC/Laptop)
- Write target NORAD IDs file on USB Drive
- Run single script (stored on USB Drive) to fetch TLEs from online database

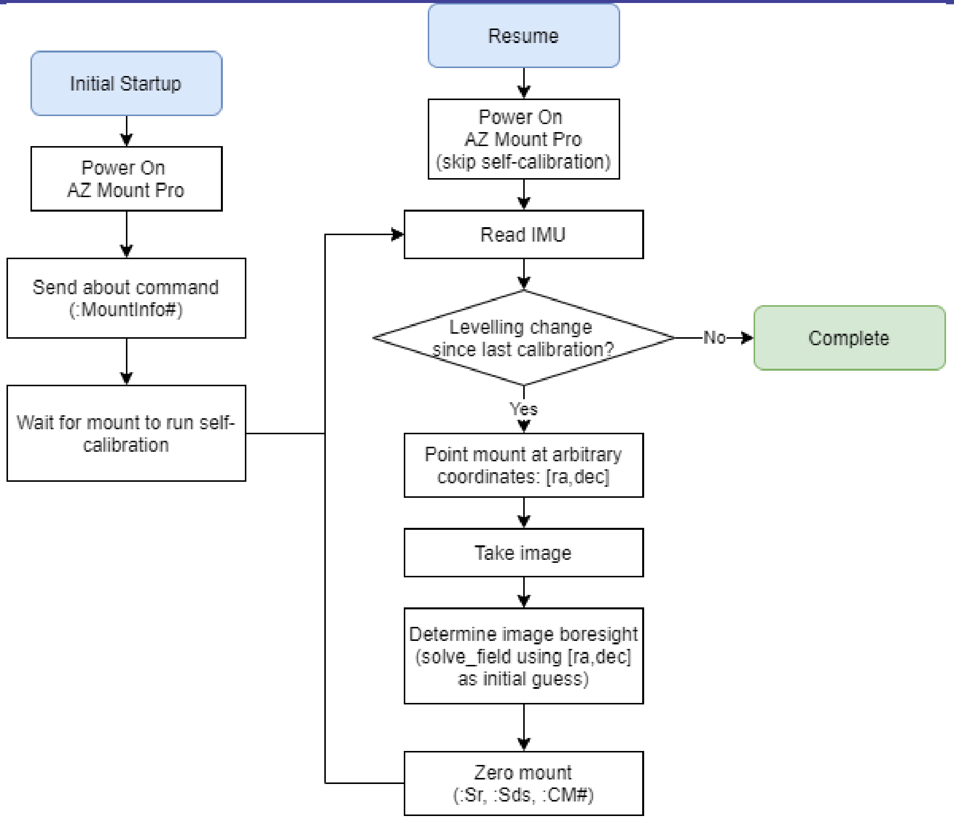
At Deployment
- Plug in USB Drive
- Attach Monitor via HDMI
- Power on system
- Observe console output for errors, and confirm system operability

After Deployment
- USB Drive contains all results
  - Observation results (Orbits)
  - Images used
  - Debug Images
  - Logs



Automated Calibration

- AZ Mount Pro performs low-accuracy self calibration (uses magnetometer)
- Calibration refined using process at right (using image and star map software)
- Calibration can be checked by reading IMU
  - Uses gravity vector to detect disturbances that require recalibration



Scheduler Improvements

Power Consumption (FR 8): Have system enter low-power state between observations (especially day time)

Calibration (FR 7,8): Include time to run recalibration if necessary

Multi-Day Deployments (FR 8): Adjust priorities to account for observations made in preceding days

Observation Quality (FR 1,4,8): Prioritize objects with less stable orbits/less accurate propagation

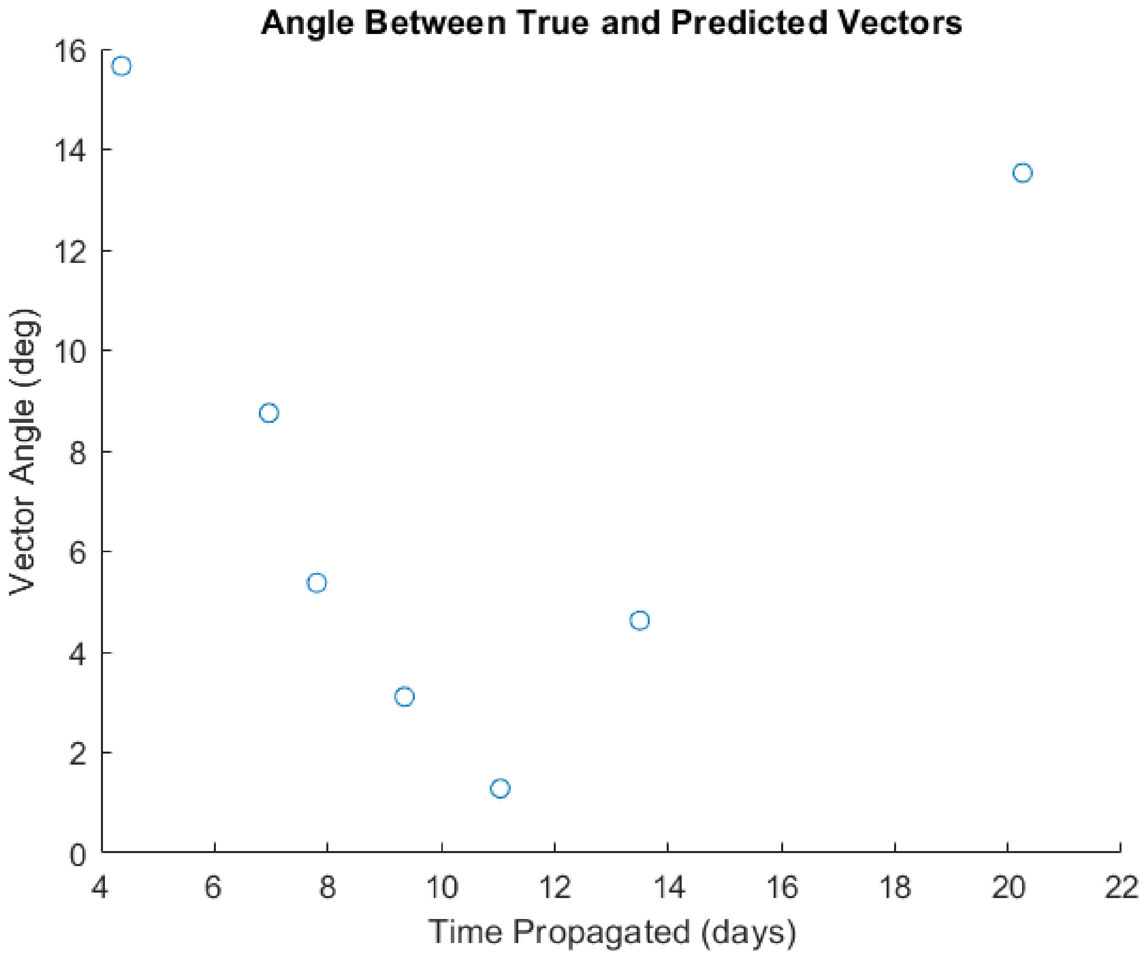
Orbit Propagation Model - SGP4

Motivation for Verification: WRAITH found the following using STK

- TLEs become too old
  - Eccentricity ~.1: 3 days
  - Eccentricity ~.3: 5 days
  - Eccentricity ~.7: 10 days

Test Case: NOAA-6 between 1/03/1980 and 1/23/1980

Results are in True Equator Mean Equinox (TEME) Coordinate System


Angle Between True and Predicted Vectors
Vector Angle (deg)
0
2
4
6
8
10
12
14
16
4
6
8
10
12
14
16
18
20
22
Time Propagated (days)

Testing Status & Summary

Inherited Component Testing Status

A. Power

B. GHOST Scheduler

C. WRAITH Scheduler

D. Imaging

E. Active Protection

F. Weather Detection

		Criticality				
		Non-Path	Slight Path	Moderate Path	Main Path	Critical Path
Amount of Prior Testing	No Documented Tests				C	
	Component Test		F			
	Unit Test					E
	Integration Test					A B D
	System Test					

Baseline Legacy Component Test Prioritisation

Ranked Testing Priority:

1. Power, Scheduling (GHOST), Imaging
2. Active Protection
3. Scheduling (WRAITH)
4. Weather Detection

General Methodology:

- Verify proper integration to the power system
- Verify proper I/O communication between the components and the processor
- Verify individual component functionality

Example Testing Flow - WRAITH Scheduler

Component Testing

- Intra-program communication
- Proper input handling and output production

Unit Testing

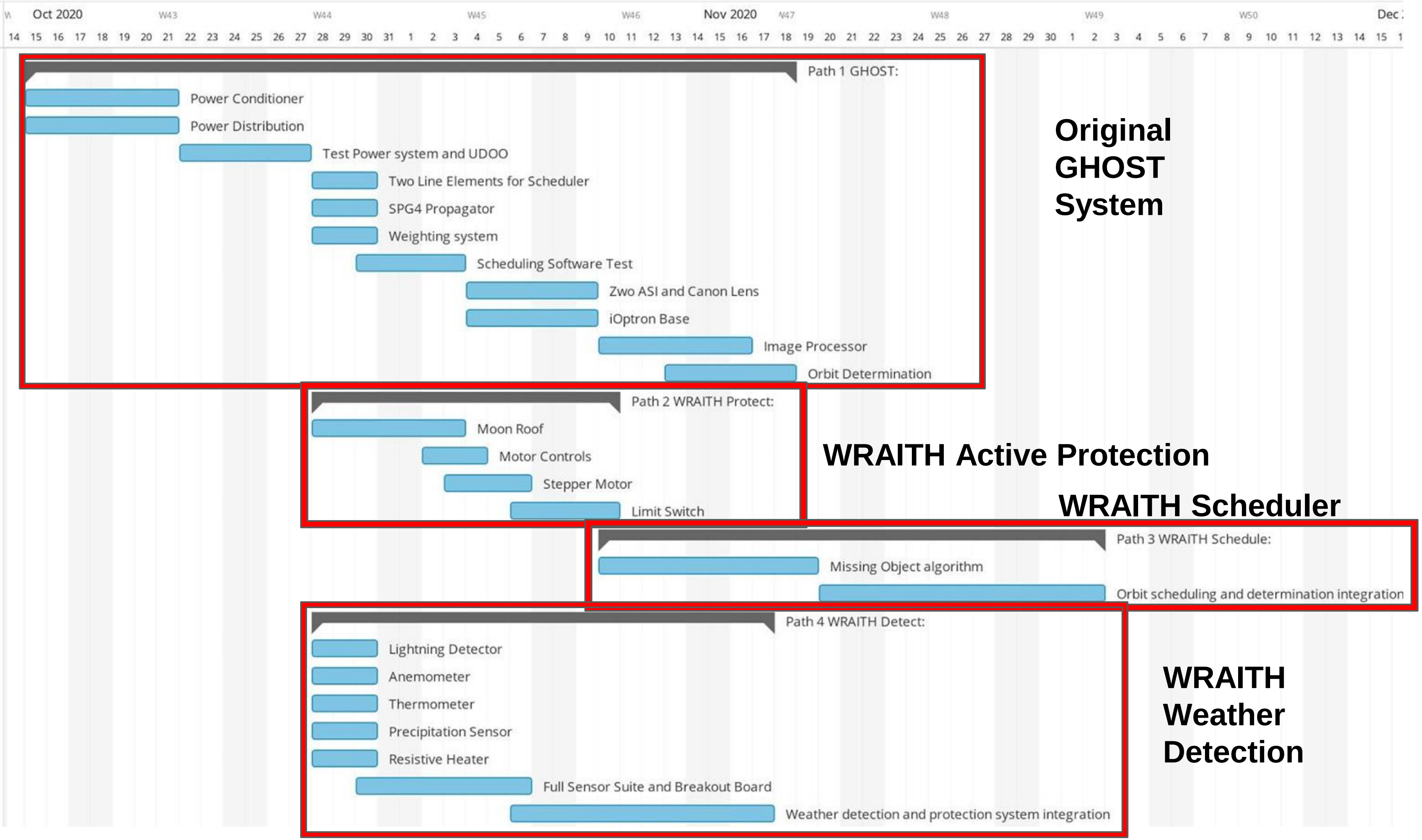
- Produces initial schedule when given list of TLEs
- Modifies existing schedule when given a missed observation

Integration Testing

- Verify software functionality on the processor
- Test communication with the imaging and weather subsystems

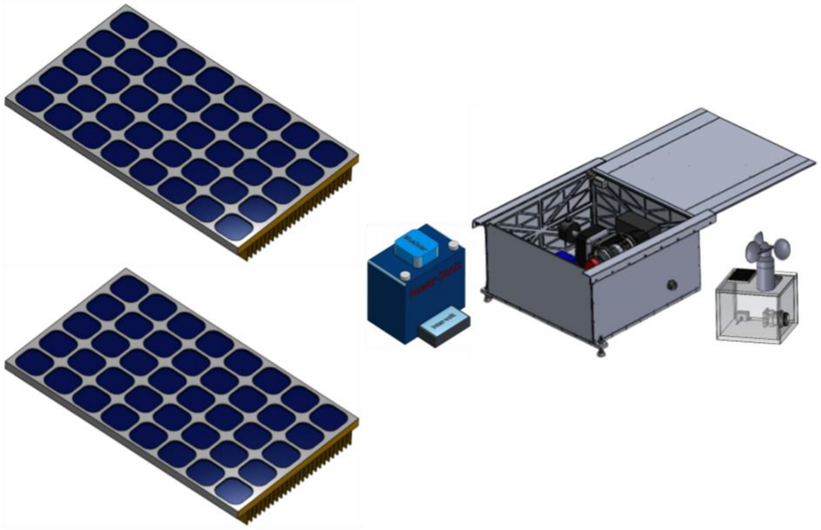
System Testing

Deploy GHOST system running the WRAITH scheduler to test field performance


Oct 2020
W43
W44
W45
W46
Nov 2020
W47
W48
W49
W50
Path 1 GHOST:
Power Conditioner
Power Distribution
Test Power system and UDOO
Two Line Elements for Scheduler
SPG4 Propagator
Weighting system
Scheduling Software Test
Zwo ASI and Canon Lens
iOptron Base
Image Processor
Orbit Determination
Original GHOST System
Path 2 WRAITH Protect:
Moon Roof
Motor Controls
Stepper Motor
Limit Switch
WRAITH Active Protection
WRAITH Scheduler
Path 3 WRAITH Schedule:
Missing Object algorithm
Orbit scheduling and determination integration
Path 4 WRAITH Detect:
Lightning Detector
Anemometer
Thermometer
Precipitation Sensor
Resistive Heater
Full Sensor Suite and Breakout Board
Weather detection and protection system integration
WRAITH Weather Detection

Summary

To provide an easily accessible, multi-night orbit tracker, specializing in the evaluation of highly elliptical orbits. SHADE will be a low-cost, capable tracking system able to withstand adverse weather conditions.



Design
- Add power regeneration
- Divide system into portable modules
  - 35-50 lbs each
- Limit operator interaction
  - Automate software processes
    - Calibration, set up

Test and validate legacy hardware
  - Determine additional work required for WRAITH’s hardware to meet SHADE’s requirements
  - Budget for replacement modules

Questions

Additional Slides

Prior Test Breakdown

Fan Wind Speed

Data from Wind Speed Test

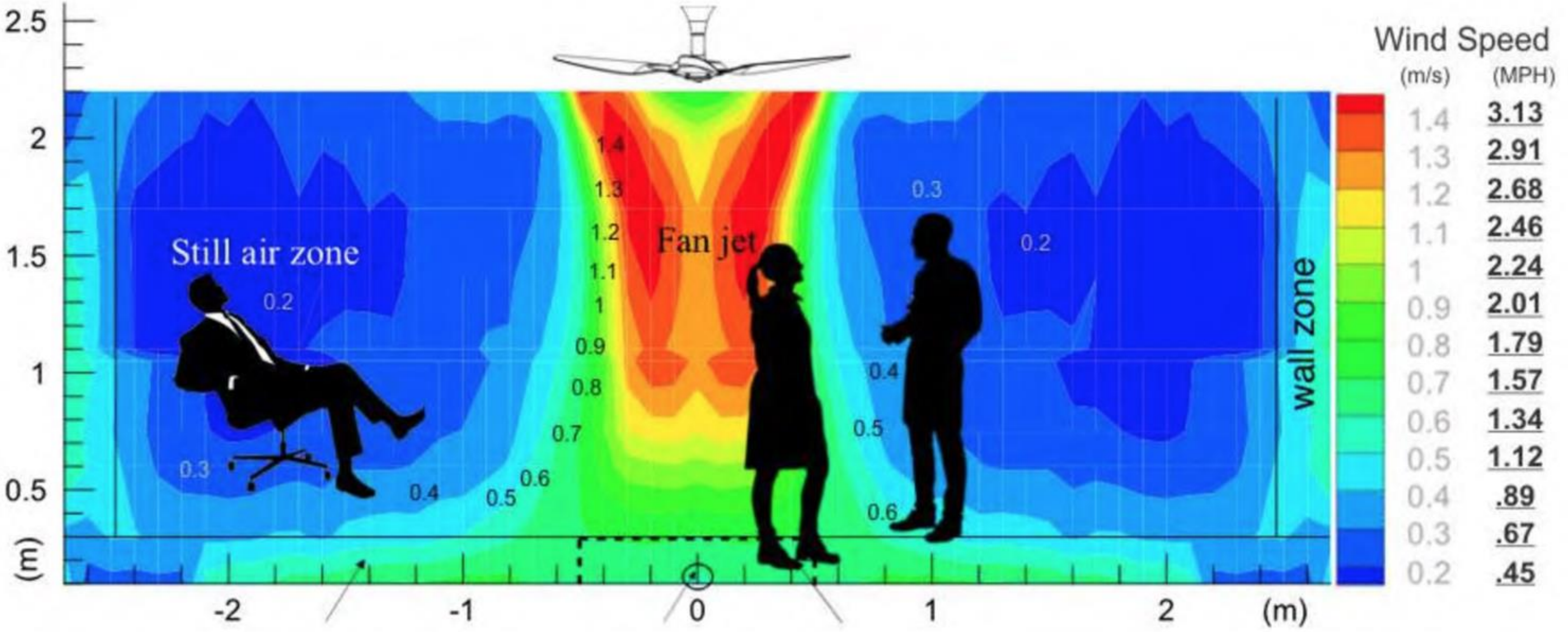
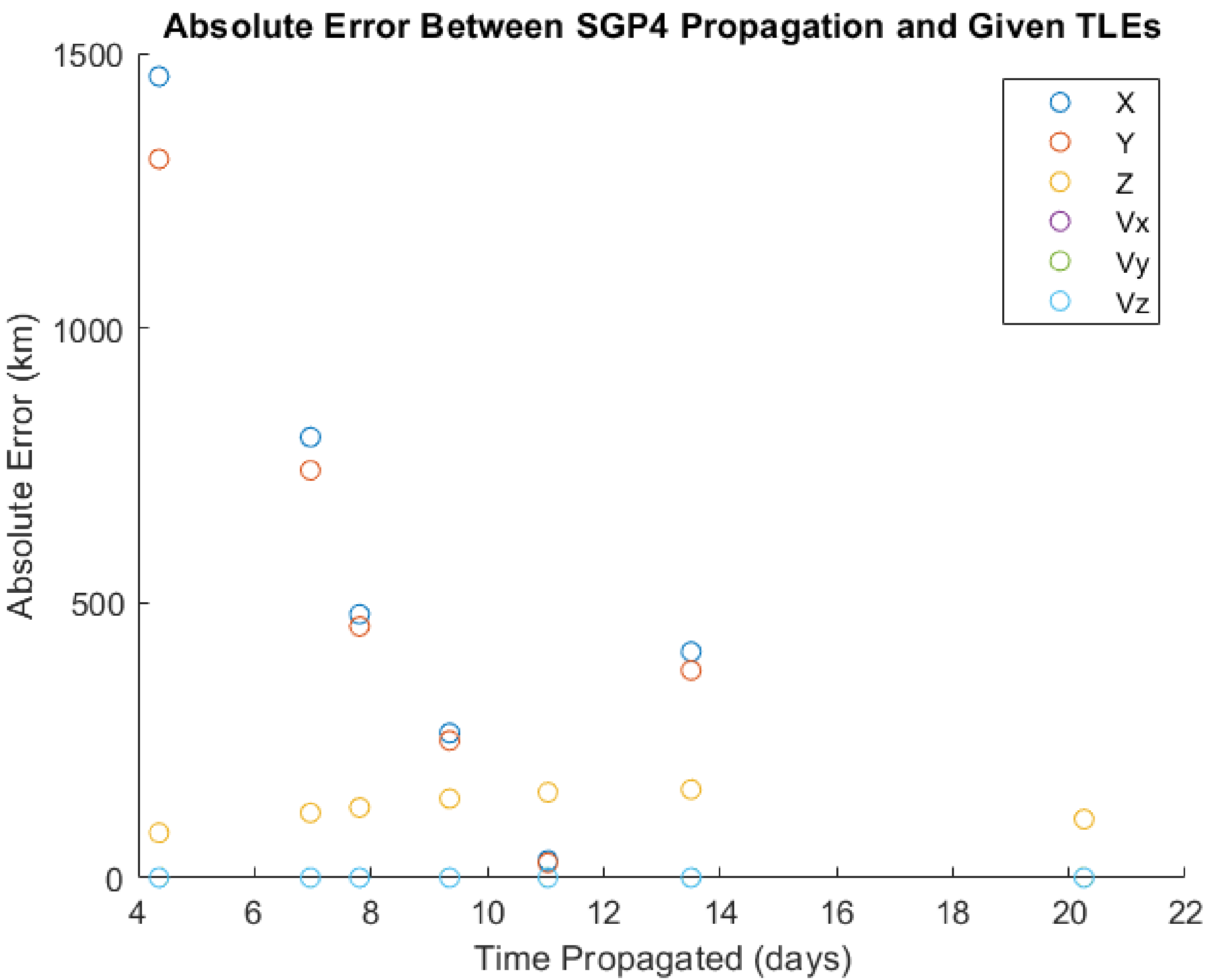


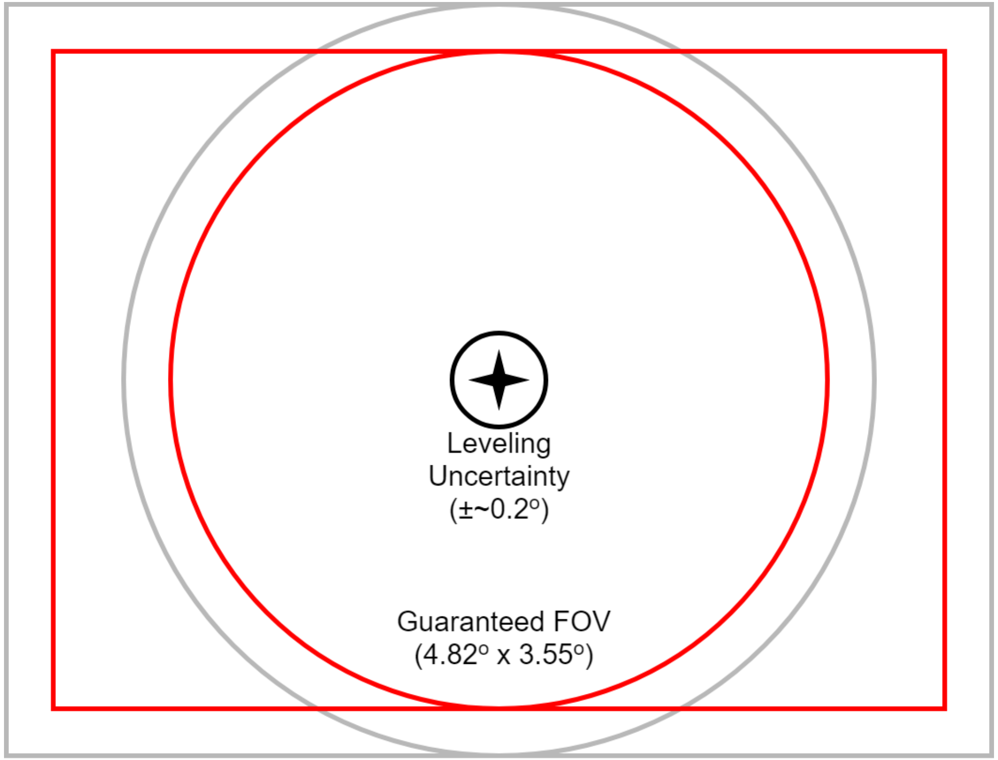
Fig. 2: Wind speed distribution of 60" Haiku fan on speed 4 in a room 18' x 18' x 8.3'


Absolute Error Between SGP4 Propagation and Given TLEs
Absolute Error (km)
Time Propagated (days)
0
500
1000
1500
4
6
8
10
12
14
16
18
20
22
X
Y
Z
Vx
Vy
Vz

IMU Calibration Failsafe

2-Axis accelerometer (ADXL203 as reference)

- Can be configured to provide varying resolution
- Levelling accuracy within ±0.2º is readily achievable
- Real camera FOV: 5.22º x 3.95º
- If failsafe is not triggered, can guarantee FOV of 4.82º x 3.55º



Camera FOV (5.22º x 3.95º)

Thermal Regulation

Heat Sinks

Copper fins attached to the bottom of the panel

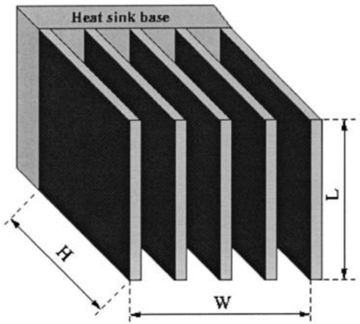
Fin thickness: 0.00197 in

Fin Separation: 0.354 in

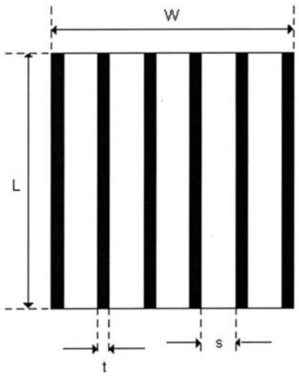
Fin Height: 1.97 in

Number of Fins: 100

Maximum Temperature of the Panel = 64.73 degrees Celsius (assuming blackbody)



(a)



(b)

MPTT Charging - BlueSolar 75|15

Maximum Power Point Charging - Energy transfer from the solar array to the battery

Higher efficiency than PWM - up to 98%

Optimized to charge battery at maximum power over time

Victron Energy BlueSolar MPPT 75|15 Charger

Dimensions: 4.42” x 3.94” x 1.57”

Will charges battery at 15A to 14.2V

Battery Voltage will remain above 11.1V

Open Circuit Voltage max: 75V

Current input max: 15A

Power input max: 220W

Solar Cell Specifications

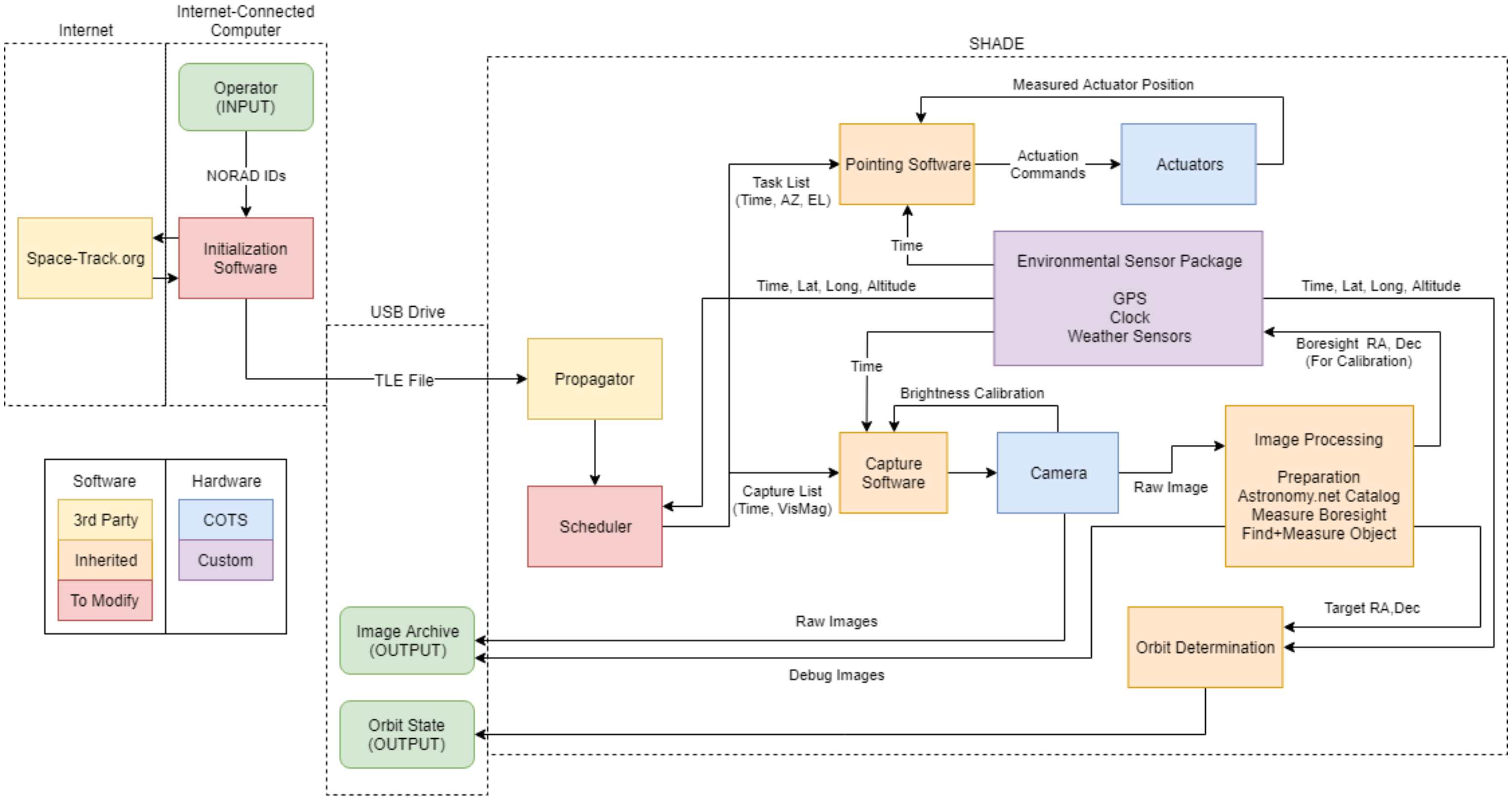
SunPower Maxeon Gen lll PV Cells*

- Vmpp = 0.612V @ -0.967V/^{o}F
- Impp = 5.79A @ 1.611mA/^{o}F
- Pmax = 3.54W @ -0.161%/^{o}F
- Voc = 0.713A
- Isc = 6.11A

*Values at 92.903W/ft^2 and 77^{o}F

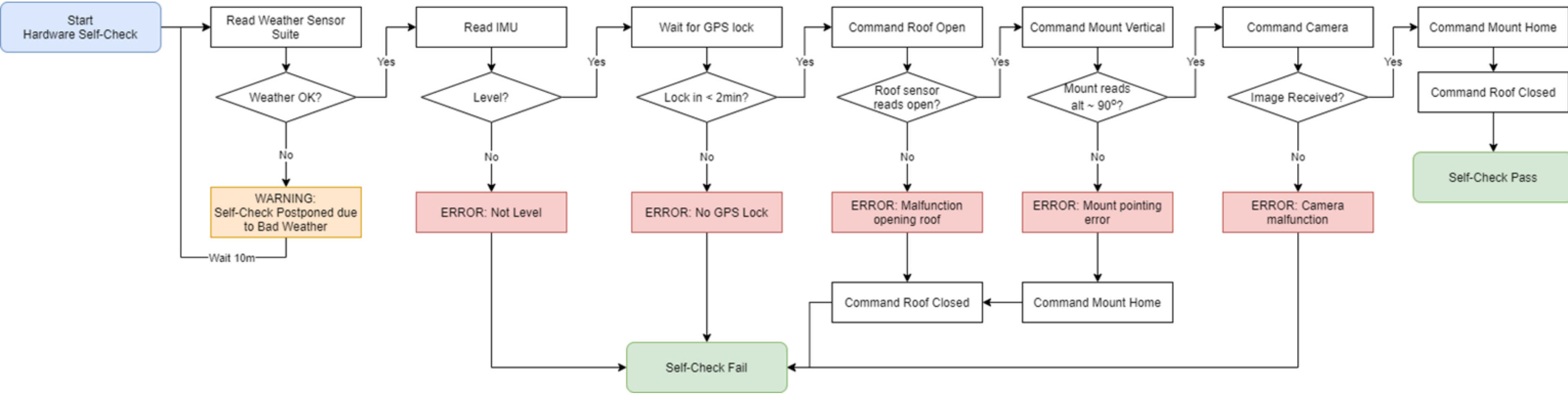
Each Panel is approximated as 45” x 22.5” x 3”

Modified Software FBD (Weather Sensor Not Included)



Misc. Software: Hardware Self-Check

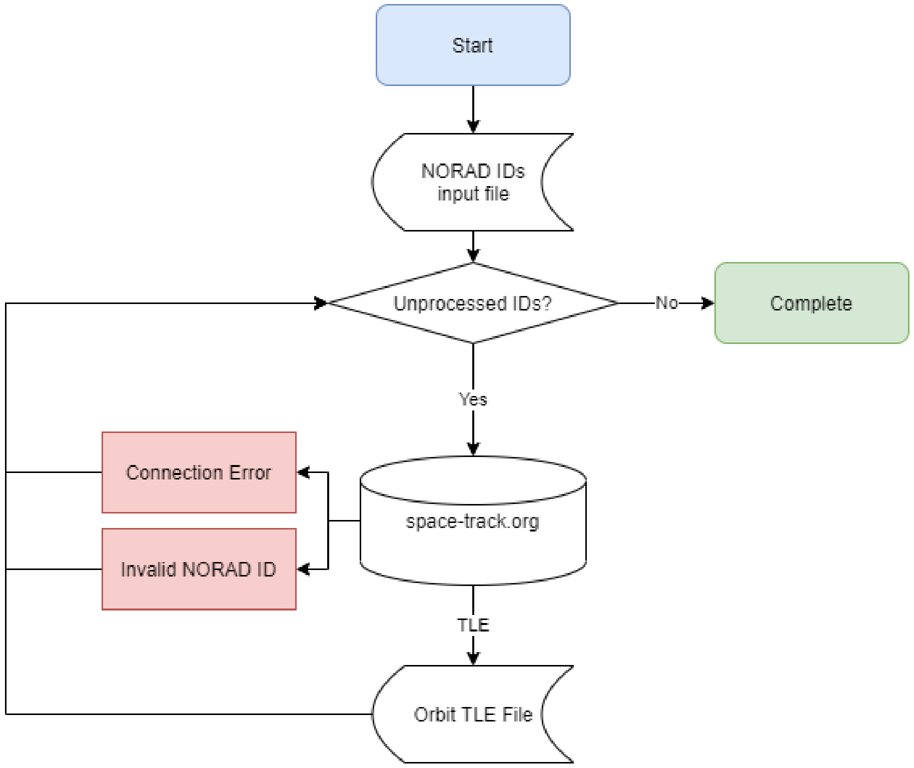
Designed to detect missing, disconnected, or otherwise non-functional components at deployment, when operator is present



Misc. Software: Operator Setup Script

Gets most recent orbit info (as TLEs) from space-track.org for each operator-specified target (in the form of a NORAD ID list)

- Stays on I/O USB
- Designed for use by operator on personal machine pre-deployment
- May be run automatically by SHADE at startup if internet connection is available
- Platform agnostic (may need BASH and .bat versions)



Legacy Components

A. Power
    a. Power conditioner, power distribution
B. GHOST Scheduler
    a. Space-track.org python package, SGP4 Propagator, weights, orbit determination
C. WRAITH Scheduler
    a. Space-track.org package, SGP4 propagator, weights, missing object algorithm, orbit determination
D. Imaging
    a. Magnetometer, iOptron base, Zwo ASI 1600 MM, Canon Telephoto EF 200 mm, image processor, orbit determination, UDOO x86 2.24 GHz board
E. Active Protection
    a. Moon roof, stepper motor, motor controller, limit switch
F. Weather Detection
    a. Lightning detector, Anemometer, Thermometer, Precipitation Sensor, Resistive Heater, breakout board

Legacy Test Status: Imaging System

Camera (Lens, Sensor, & Filter): Integrated system test performed by GHOST

Actuation Mount: Integrated system test performed by GHOST

Image Processing: Integrated system test performed by GHOST, modification to the integration was made by WRAITH but functionality was not modified

Legacy Test Status: Scheduling

Base Scheduler: Integrated system test performed by GHOST

Orbit Determination and Propagation: Integrated system test performed by GHOST

Live Scheduling: Designed by WRAITH, no documented testing

Missed Object Search: Designed by WRAITH, no documented testing

Legacy Test Status: Active Protection & Weather Detection

Active Protection:

Roof Actuation System: Integrated system test performed by WRAITH

Operator Override function: Designed by WRAITH, no documented testing

Weather Detection:

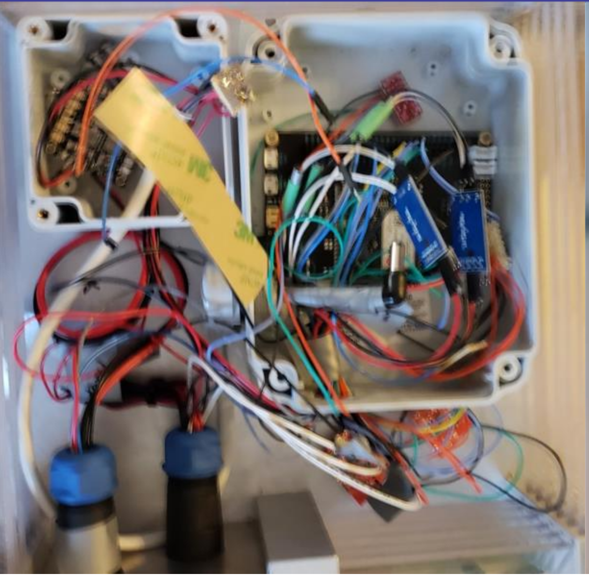
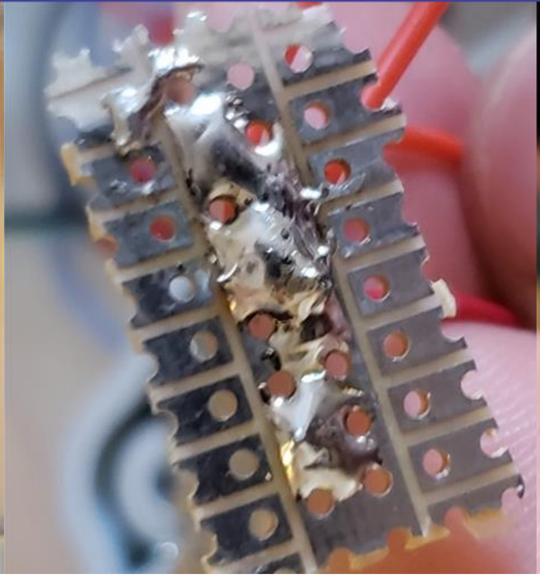
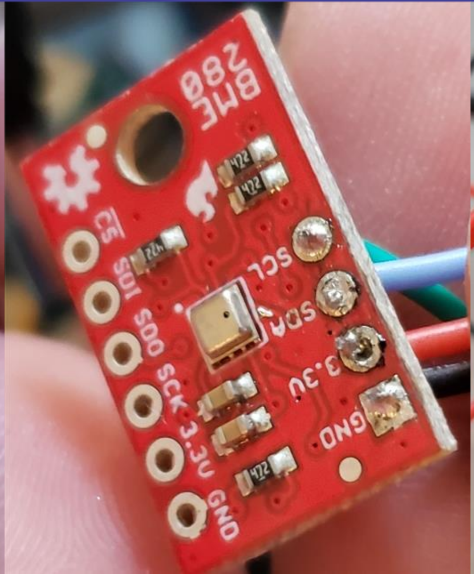
Each component was unit tested & integrated, full integration test incomplete

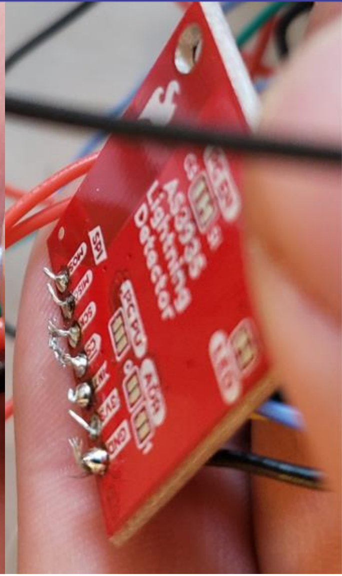
Legacy Test Status: Power System

Power conditioner: Integrated system test performed by GHOST, unit test performed by WRAITH

Power Distribution Board: Integrated system test performed by GHOST, unit test performed by WRAITH

Inherited Hardware



- Umbilical cable wiring
- Particle board
- Main Processor
- Lense focus

Active Protection Thermal Model Setup

- Set Up: (Date = 3/11, Time = 12:00 - 13:00)
  - Convection applied all external surfaces.
  - External and internal surfaces allowed to radiate to space and surfaces.
  - All solids/surfaces began at initial temperature of 68F.
  - Ambient temperature of 68F.
  - Solar flux dependent on location in Denver was applied to external surfaces.