SHADE

Spacial HEO Autonomous Detector & Evaluator

Spring Final Review

Team

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Sponsor

The Aerospace Corporation

Advisor

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Project Objectives

Project Goal

★ Increasing amount of Earth-orbiting objects

★ Large SSA systems now have an overwhelming number of tracks

★ Need: Inexpensive tracking solution

★ Impact: Free up operational bandwidth for larger SSA systems

Courtesy: NASA Goddard Space Flight Center

<u>SHADE Mission Statement</u>

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**.

Project History

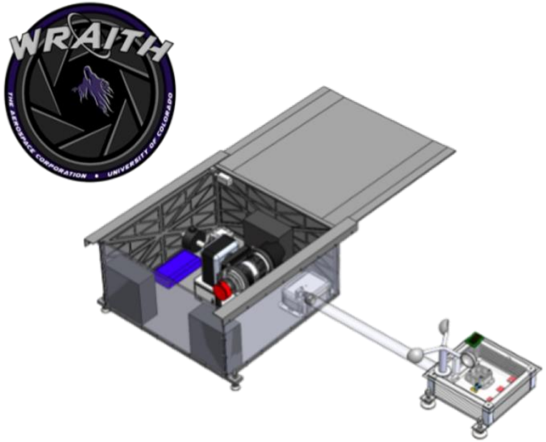
2018/19

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

Established foundation systems for autonomous imaging of circular LEO and MEO objects

Validated with ISS tracking test

2019/20



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

Added HEO tracking capabilities & weather protection

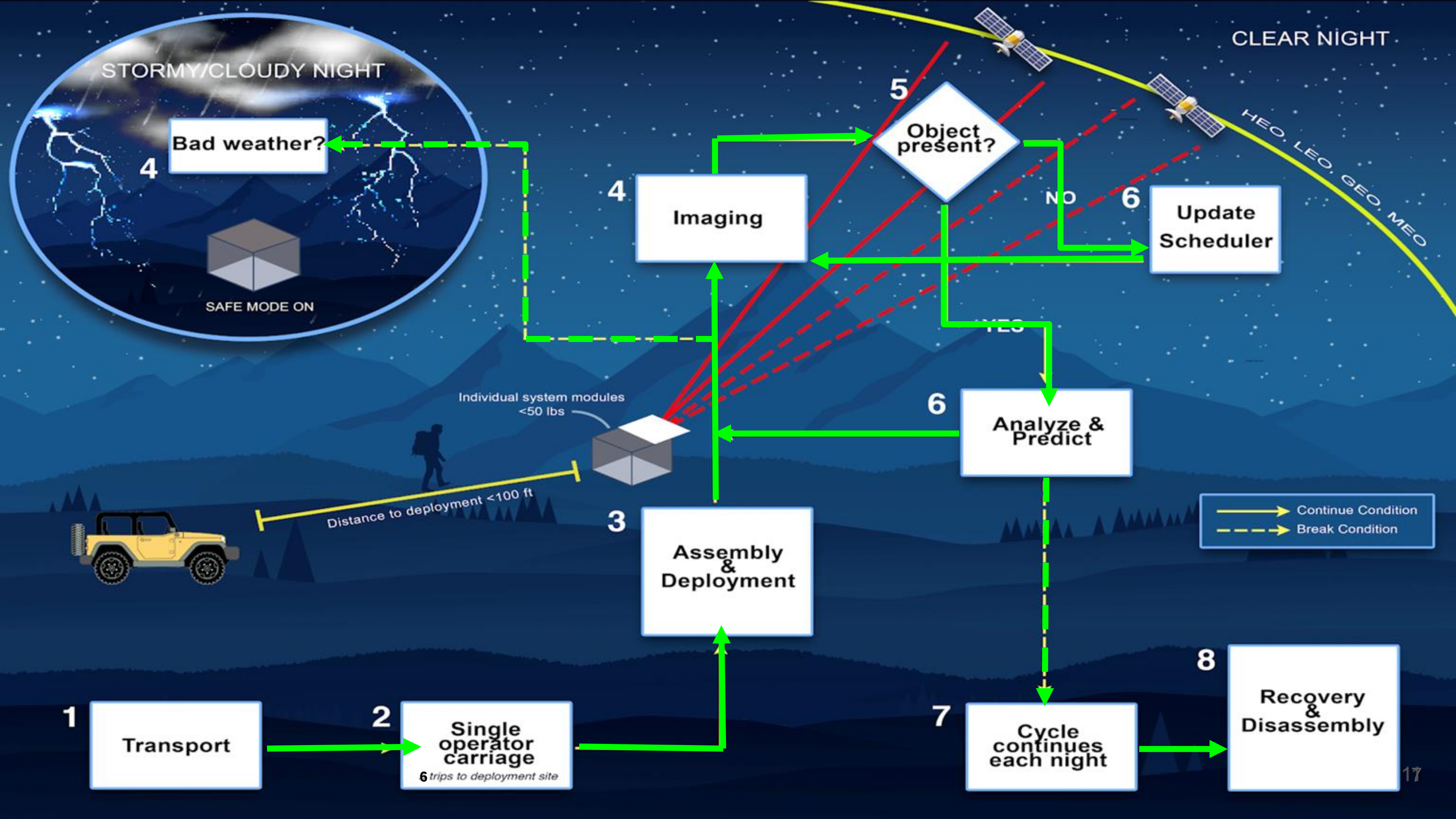
Systems operate autonomously for 12 hours

Project cut short in March 2020 due to COVID-19 pandemic

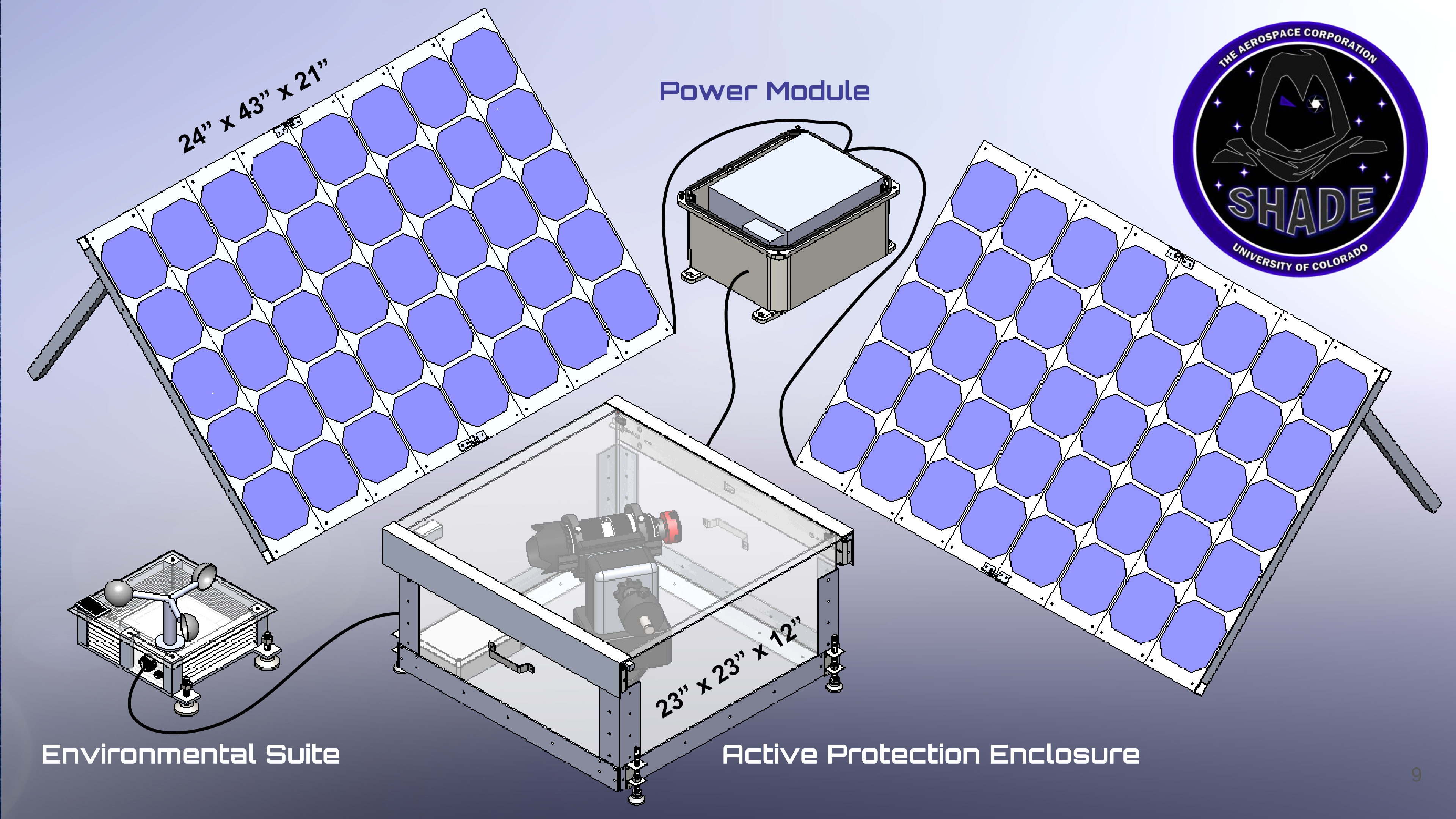
Success for SHADE

System	Goal
Power (Level 3/3)	• Five nights of continuous operation in SOC • Enters safe mode if power is lost
Modularity (Level 3/3)	• Each module weighs less than 35 lbs , (AP < 50lbs) • Minimal on-site system assembly
Environmental Protection (Level 3/3)	• Active protection triggered by sensors/remote override • Protects hardware from light rain/snow/wind • Updates system status to ground station
Scheduling (Level 2/3)	• Generates schedule based on imaging time, visibility, and FOV • Adapt schedule for missed observations or human override • Schedule up to 6 observations per hour
Tracking (Level 2/3)	• Track HEOs near apogee (GEO), and perigee (LEO)
Image Processing (Level 2/3)	• Accurately extract endpoints of varying streaks • Identifies when an object is missed and notifies scheduler
Orbital Determination (Level 3/3)	• Complete accurate orbit determination using Batch filter • Predict possible orbits for missing objects

CONOPS


STORMY/CLOUDY NIGHT
4
Bad weather?
SAFE MODE ON
CLEAR NIGHT
HEO, LEO, GEO, MEO
5
Object present?
NO
YES
4
Imaging
6
Update Scheduler
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
6 trips to deployment site
7
Cycle continues each night
8
Recovery & Disassembly

Design Solution



Power Module
24” x 43” x 21”
23” x 23” x 12”
Environmental Suite
Active Protection Enclosure
THE AEROSPACE CORPORATION
SHADE
UNIVERSITY OF COLORADO

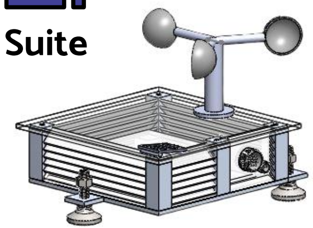
Transport Modules

Trip #1:

Active Protection Enclosure:
Weight: 50 lb

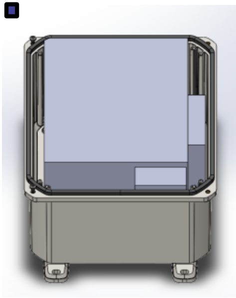
Trip #2:

Environmental Suite
Weight: 9 lb



Trip #3:

Power Module:
Weight: 29 lb

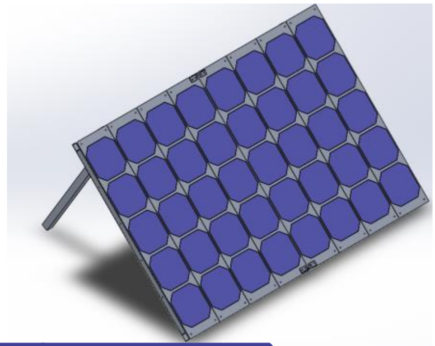


Trip #4:

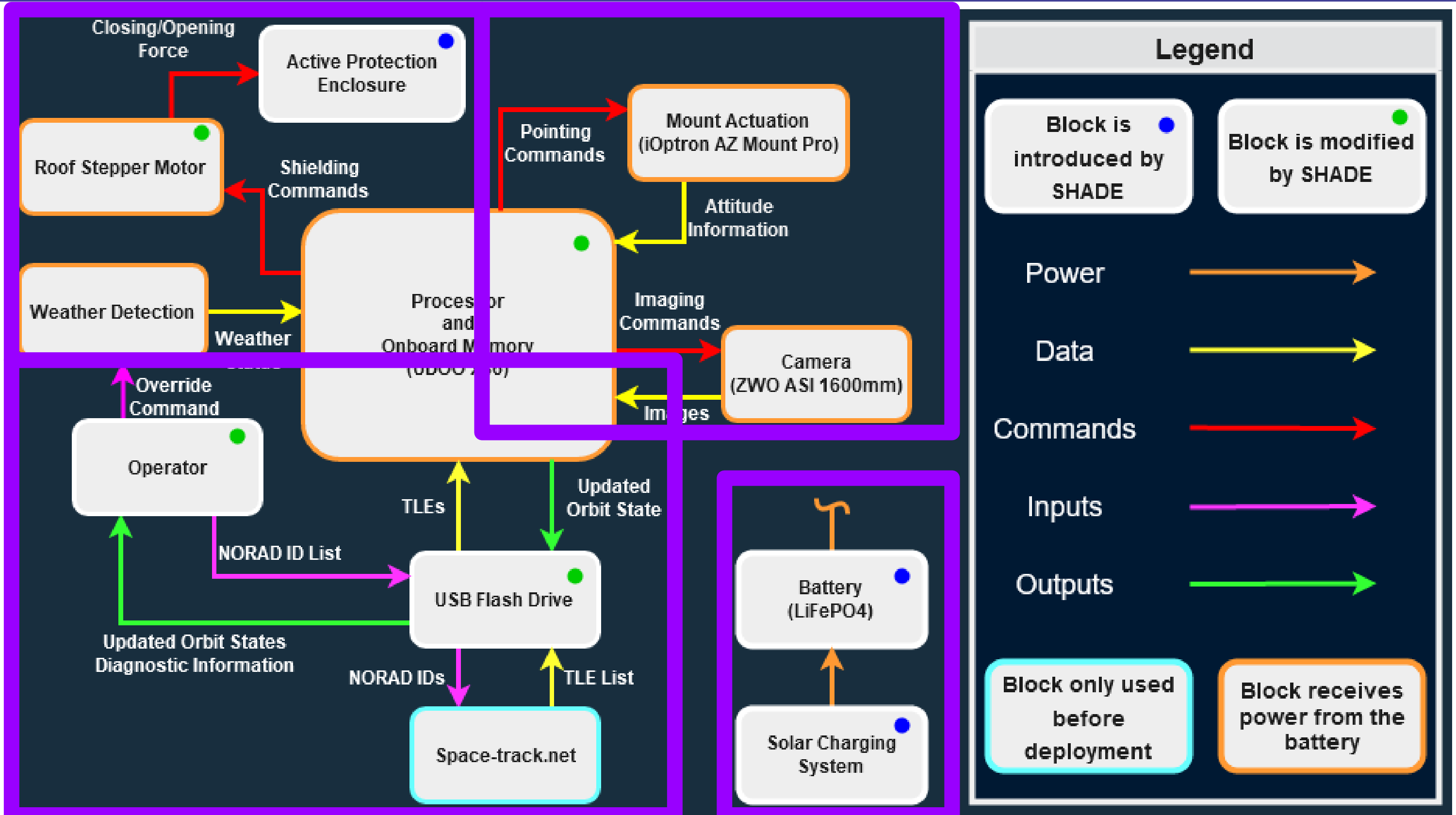
Actuation Mount & Camera:
Weight: 19 lb

Trips #5/6:

2 Solar Panels:
Weight: 26 lb (each)



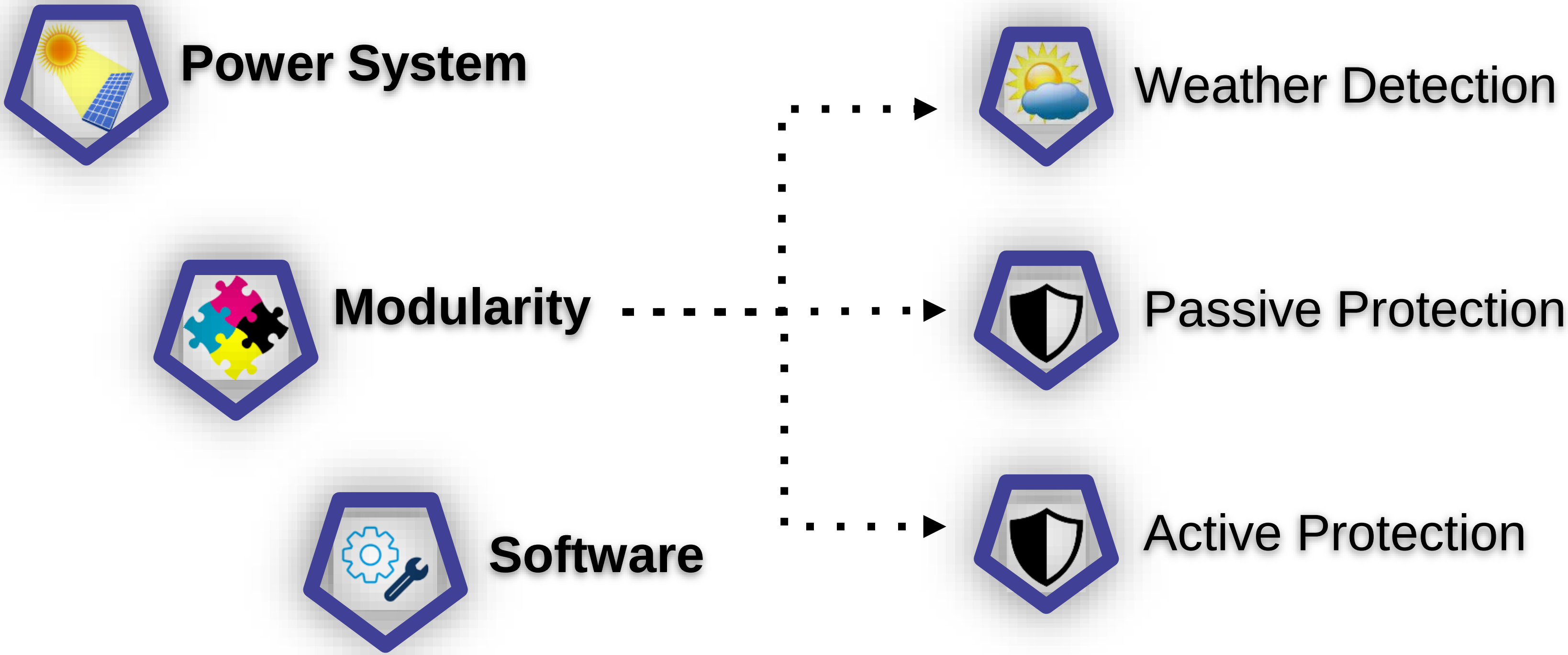
Functional Block Diagram



Design Changes Since TRR

- Vertical AP Handle Orientation - Easier to carry
- Foam inserts for processor - further mitigate risk of processor damage during transport
- New mounting rings for camera - shortens assembly time
- Added feet to solar panels - no resting on heat sinks in storage
- Power Box Modifications (level shifters, floating ground) - serial communication/processor safety

Critical Project Elements Review



Test Overview

Planned Verification & Functional Tests

Full System Tests
- 30-Minute Transport & Assembly Test
- Single Night Deployment Test
- Multi-Night Deployment Test

Power Tests
- Battery Duration Test
- Solar Charging Test
- Thermal Solar Cell Test

Active Protection Tests
- Thermal Test
- Structural Test
- Lid Actuation Test

Weather Detection Tests
- Sensor Safe Mode Shutdown
- Low-Power Shutdown Test

Software Tests
- Orbit Propagation and Scheduling Test
- Week-Long Dynamic Scheduling Test
- Image Processing Test
- Timed Software Setup Test

Completed

Partially Completed

Uncompleted

	Requirement	Relevant Tests
Functional Requirement 1	**FR 1:** *SHADE shall schedule predicted locations and visibility windows for objects in LEO, MEO, GEO,and HEO orbits.*	• Orbit Propagation • Week-Long Scheduling • Single Night Deployment • Multi-Night Deployment
Functional Requirement 2	**FR 2:** *SHADE shall function autonomously in standard operating conditions with no human intervention for at least two nights.*	• Week-Long Dynamic Scheduling • Multi-Night Deployment
Functional Requirement 3	**FR 3:** *SHADE shall autonomously enter and exit a safe mode to protect itself from adverse weather.*	• Lid Actuation • Weather Detection Tests • Single Night Deployment • Multi-Night Deployment
Functional Requirement 4	**FR 4:** *SHADE shall autonomously point to and track objects in LEO, MEO, GEO, and HEO.*	• Orbit Propagation • Week-Long Dynamic Scheduling • Image Processing • Single Night Deployment • Multi-Night Deployment

	Requirement	Relevant Tests
Functional Requirement 5	**FR 5:** *SHADE shall image objects with apparent magnitude of less than 10.*	• Image Processing
Functional Requirement 6	**FR 6:** *SHADE shall create and save an orbit estimate for each object imaged within five minutes of the end of the associated visibility window.*	• Single Night Deployment • Image Processing • Multi-Night Deployment
Functional Requirement 7	**FR 7:** *SHADE shall be deployed and recovered in 30 minutes by one operator.*	• 30-Minute Transport & Assembly
Functional Requirement 8	**FR 8:** *SHADE shall be capable of making observations on multiple nights during a single deployment.*	• Multi-Night Deployment

Test Results

Power Tests

Solar Charging and Power System

26.3lbs (each)

Solar charge controller

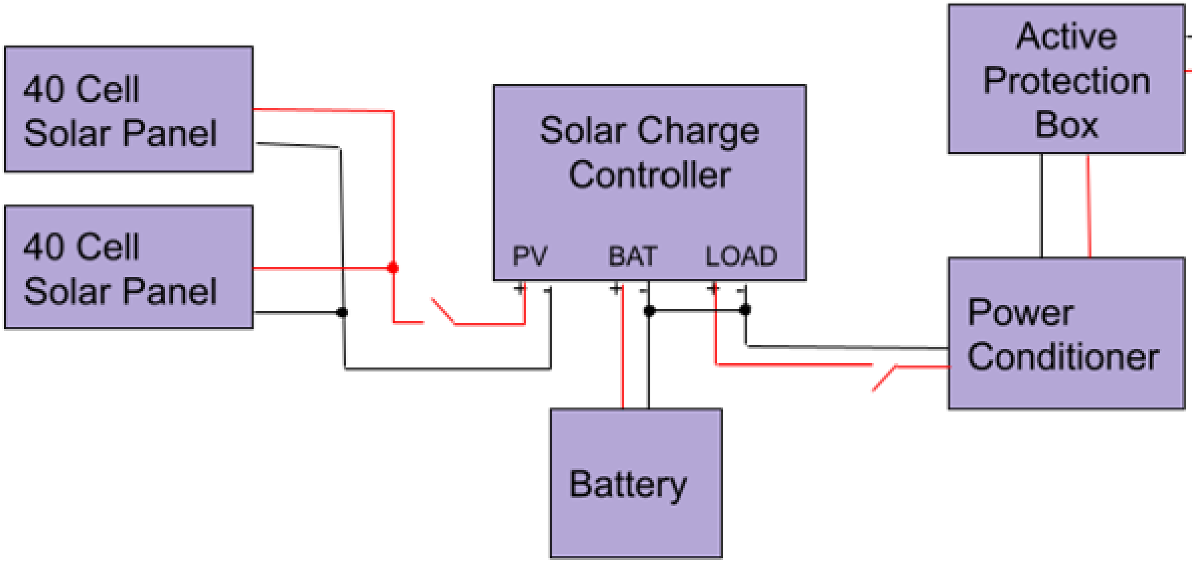
LiFePO4 Battery

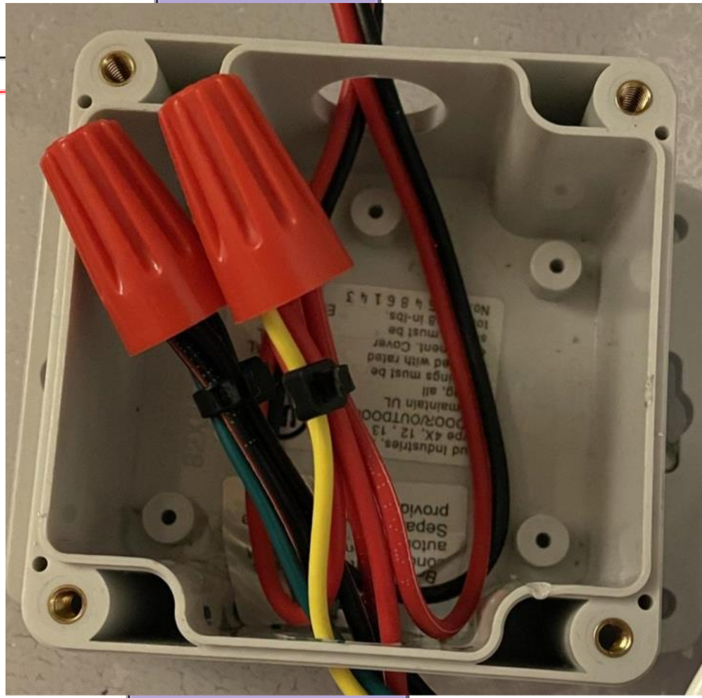
Power conditioner

29.2lbs

Solar panel array → Solar charge controller → LiFePO4 Battery / Power conditioner → Active Protection

Power Subsystem Schematic





Testing the Charging System

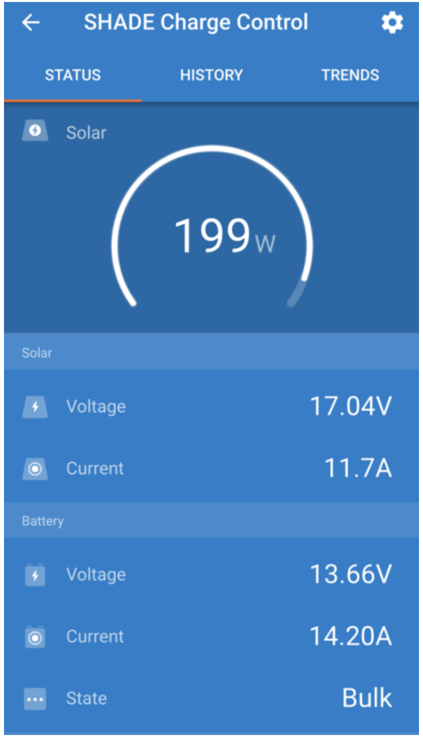
Test Day Conditions

Time - 12:32pm

Solar Irradiance - 974 W/m^2

Ambient Temperature - 20.8° C

PV Cell Temperature (est) - 52.8° F



Solar Charging Test #1

Predicted Results:
Ideal power @ 974 W/m^2 - **281W**
Power losses - **10.1%**
Estimated power - **252 W**

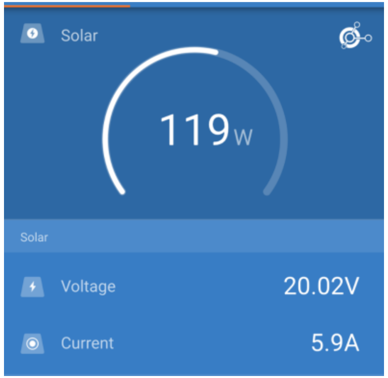
Test Results:
Max Solar Power - **199 W (~78.9% of est)**
Max Charge Current - **14.2 A (~94.7% of max)**

Solar Charging Test #2

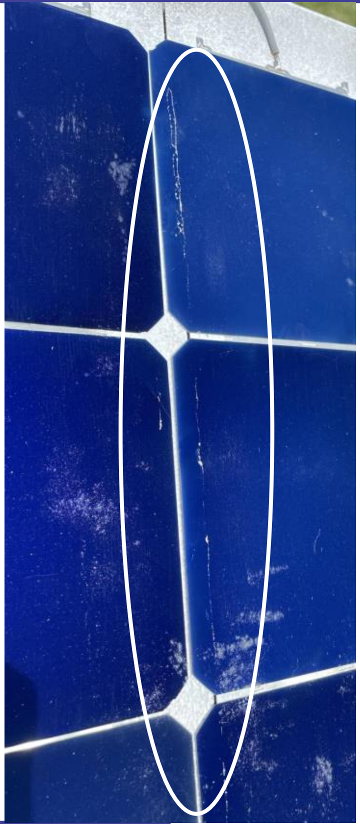
Predicted Results:
Ideal power @ 986 W/m² - **284 W**
Power losses - **6.15%**
Estimated power - **267 W** → 133 W/panel

Test Results:

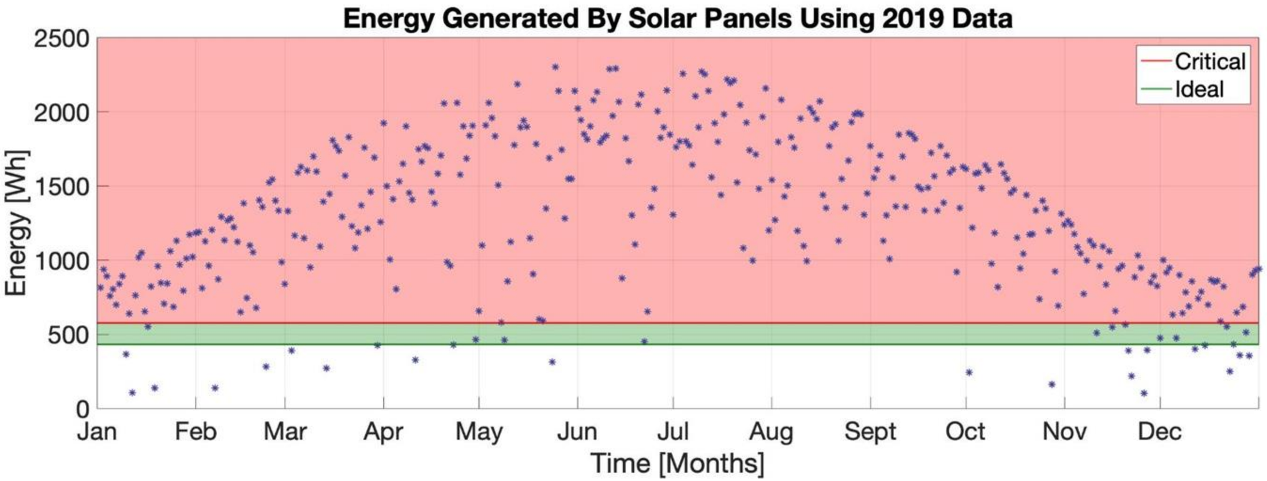
~89.4% of est



~68.4% of est



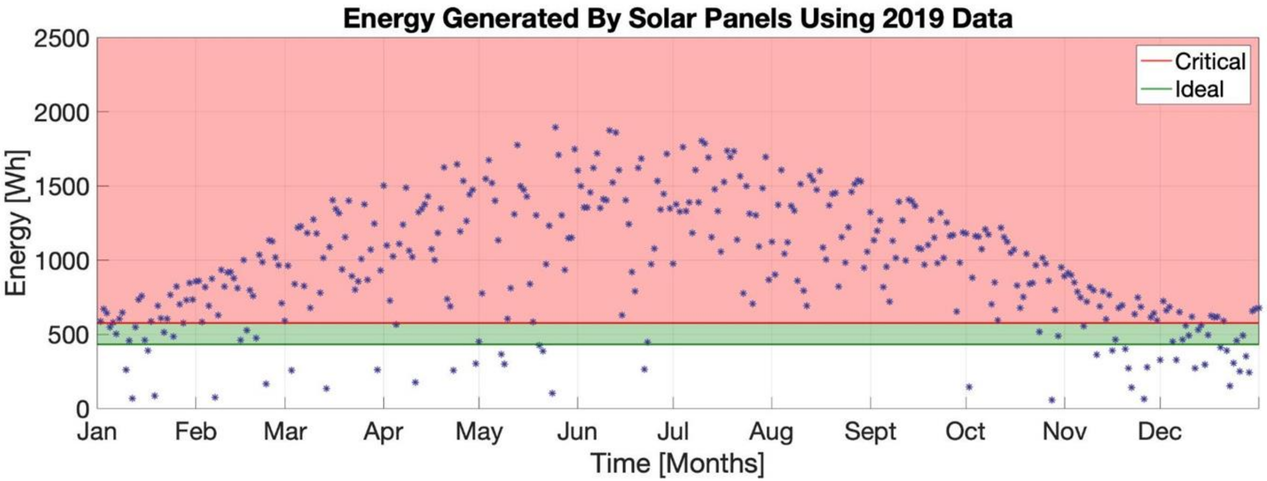
Solar Charging - Model



Results:

- 89.86% of days can charge in Critical Situations
- 92.88% of days can charge in Ideal Situations

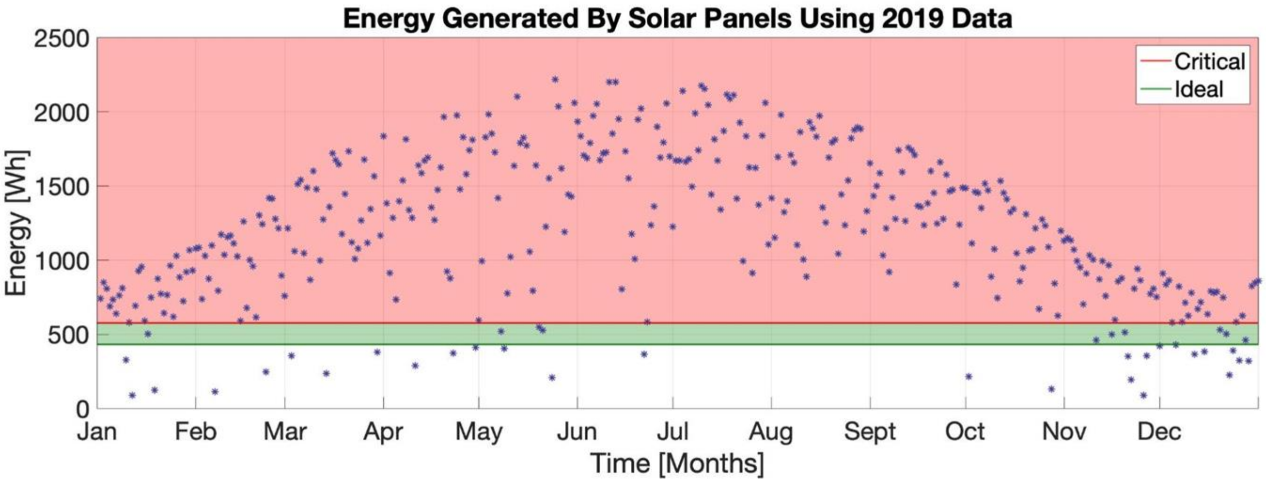
Solar Charging - Test #1



Results:

- 80.96% of days can charge in Critical Situations
- 88.36% of days can charge in Ideal Situations
- Percent Error: -27%

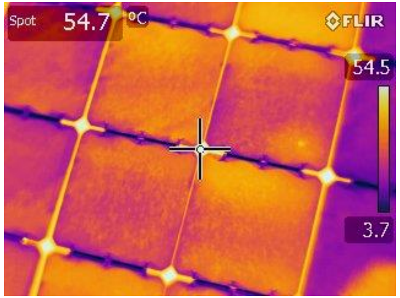
Solar Charging - Test #2

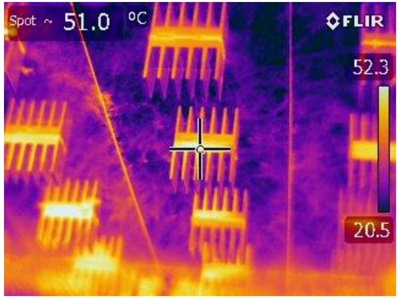


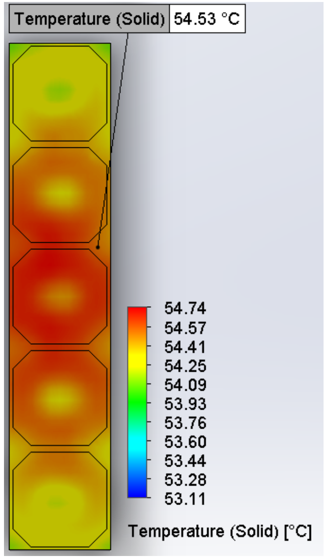
Results:

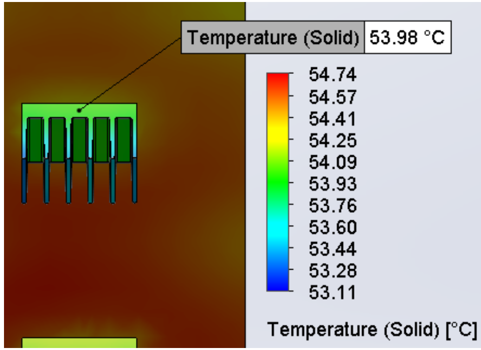
- 87.95% of days can charge in Critical Situations
- 91.37% of days can charge in Ideal Situations
- Percent Error: -8.68%

Thermal Regulation Test









- Validation of model with experimental data supports simulation of worst-case scenarios of solar panels
  - Includes summer deployment
- Outdoor test conducted from **12:30pm -3:00pm on April 2, 2021**
  - Images captured with FLIR Camera
- SOLIDWORKS Flow Simulation Model uses conditions on that day for simulation
- Notably, backplate temperature is similar between experiment and simulation
- Heat sink temperature differs by approximately **2° C**
  - Idealized simulation: Forced convection from gusts not modeled

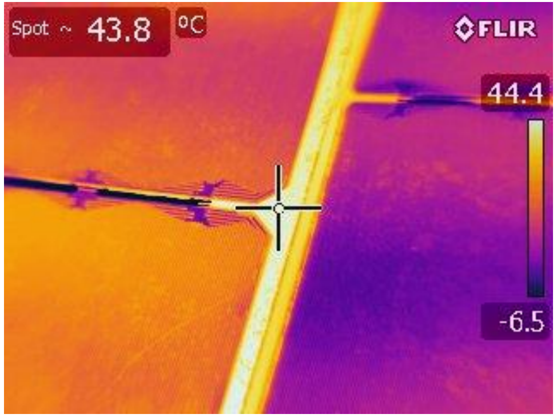
Comparison to No Heatsinks

Visible reduction in surface temperatures

Validates design choice

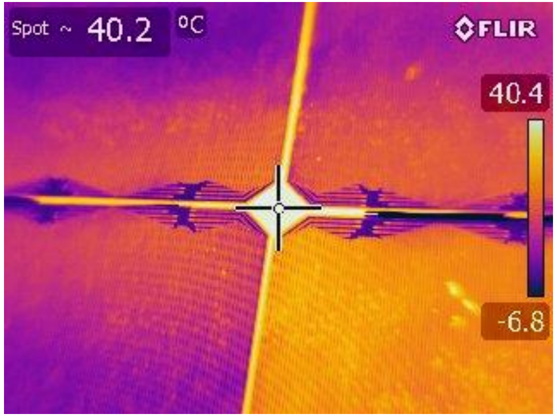
- Lower cell temperature
- Less power loss

No Heatsinks



Cell Temperature - ~44°C
Power Loss - 5.59%

With Heatsinks



Cell Temperature - ~38°C
Power Loss - 3.77%

Unforeseen Complications

Potential Overheating of Power Module

Fix: Insert vent over charge controller, use remaining Cool Coat™ thermal paint (in process)

Floating ground potential

Fix: jump input and output ground of the power conditioner to create common ground with battery

Varying serial communication voltages

Fix: Logic level converters using common ground

Active Protection Tests

Thermal Test - Overview

Purpose:

- To validate the accuracy of the thermal model and its predictions for worst case hot conditions.
- To ensure that the active protection system and internal components remain within temperature limits.

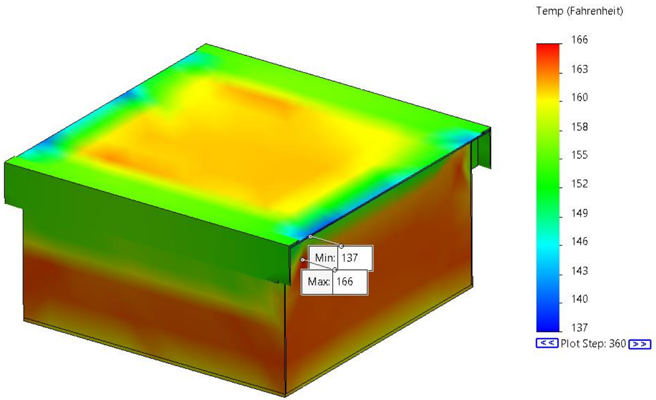
Requirements Satisfied: FR 2

Risk Mitigation: Extreme temperatures prohibiting component functionality. [DIH]

Models Validated: Solidworks active protection enclosure thermal model.

Expected Results:

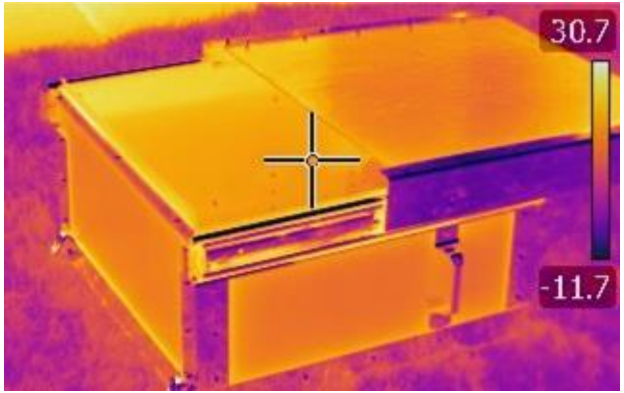
- The thermal model will provide similar wall and internal temperature results to the experimental thermal test after 3 hours.
- The thermal model will be validated and may be used to predict other environments.

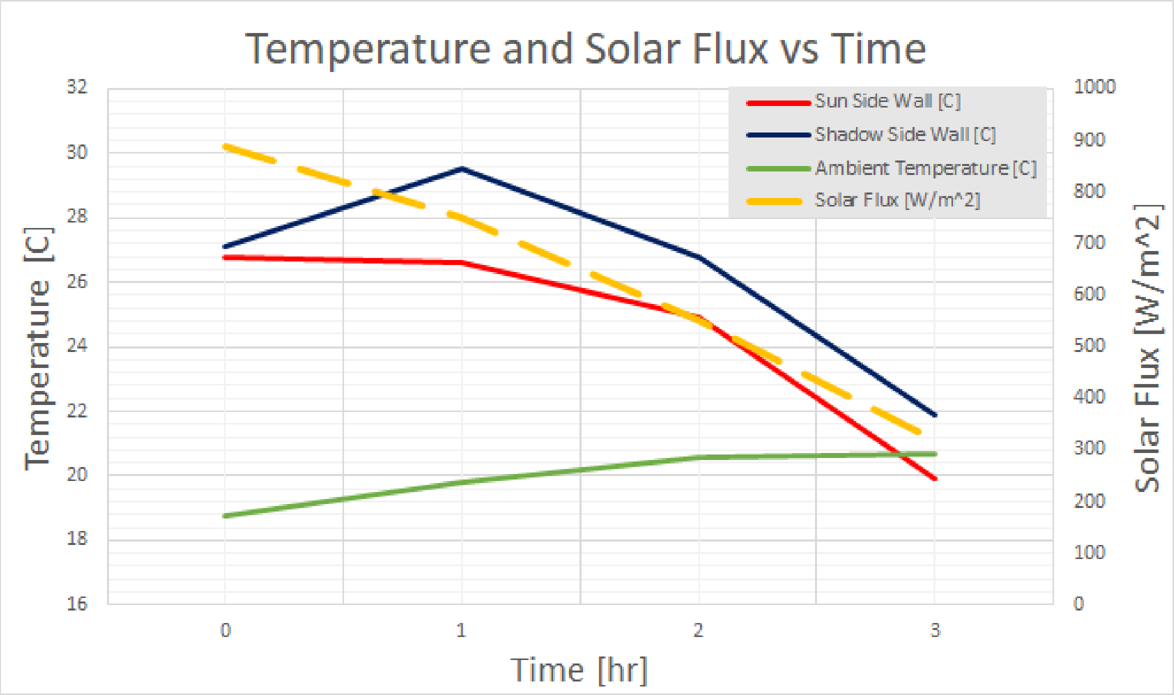


Thermal Test - Results

Wall temperatures are driven by the solar flux into the system.

Results from test were input to thermal model for comparison.

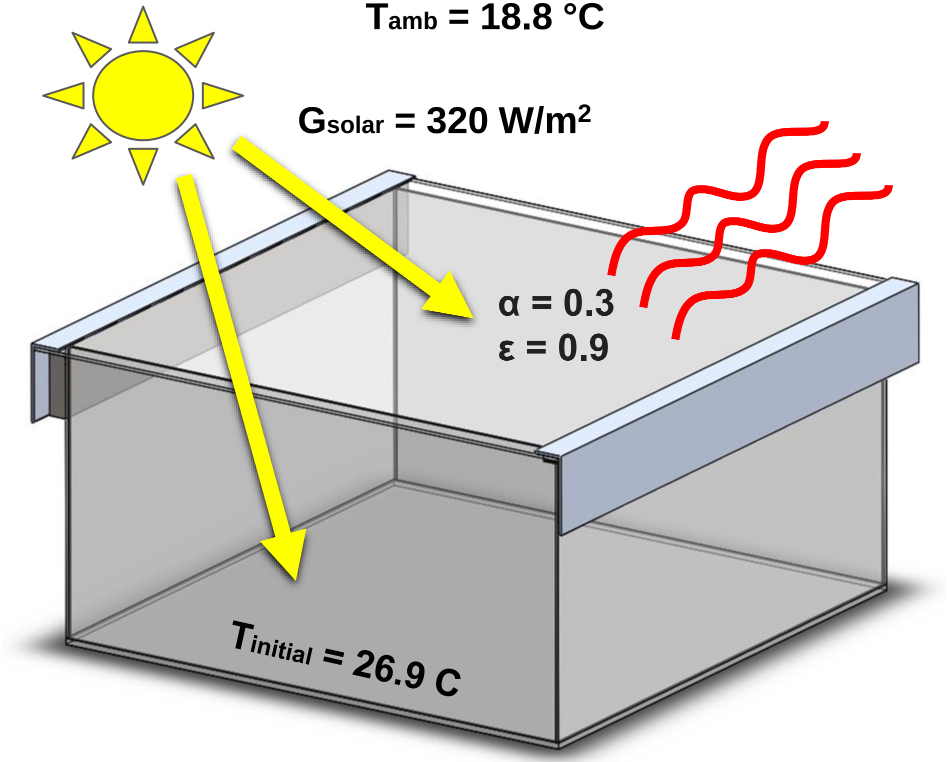




Thermal Test - Model

Setup:

- Solar flux on roof and wall:
  $G_{absorb} = G_{solar} * \alpha = 96\ W/m^2$
- 18.8˚C ambient air.
- 26.9˚C initial structure temperature.
- Natural convection (BTU/hr/ft²/F):
  $h_{Horizontal} = 0.5459$
  $h_{Vertical} = 0.4403$
- Internal and external radiation.
- ΔTime = 3 hrs

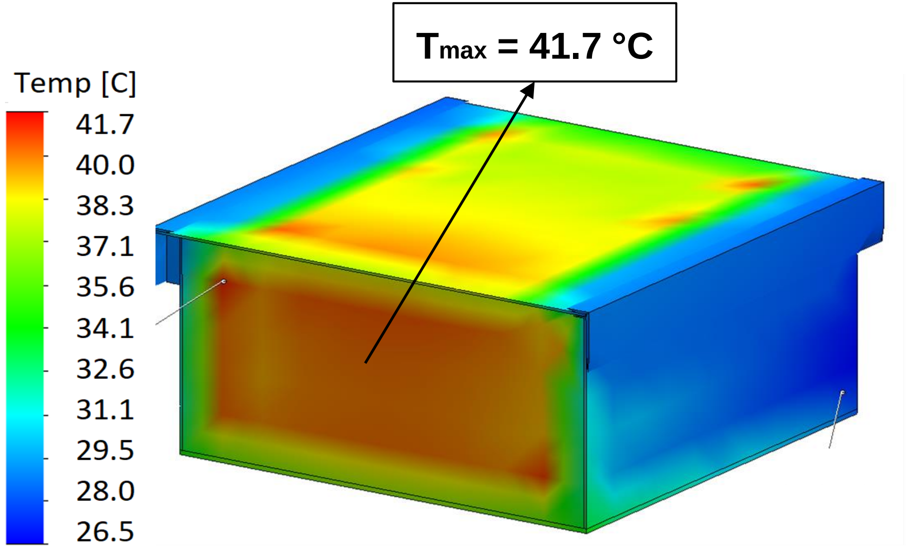


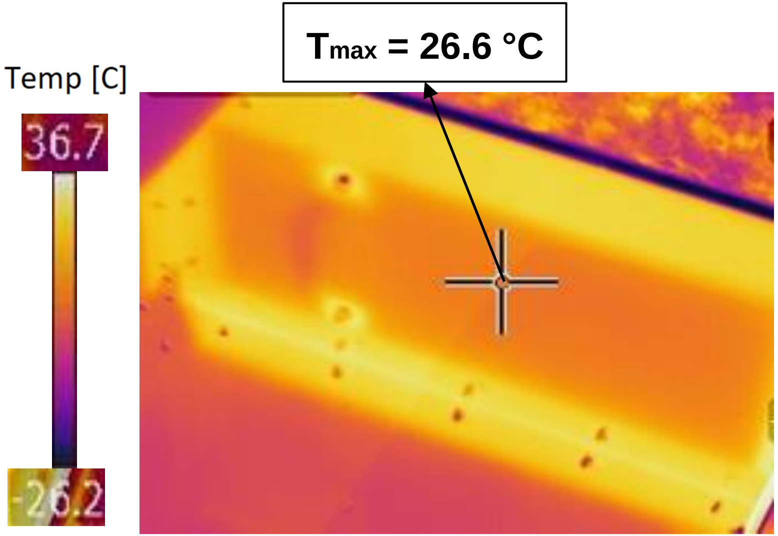
Thermal Test - Comparison

Model maximum wall temperature is 15.1˚C greater than physical result.

Test-Model comparison:

- Model overpredicts temperatures due to simplifying assumptions (no forced convection, constant solar flux).
- Comparison indicates that the model is conservative.





Thermal Test - Validation

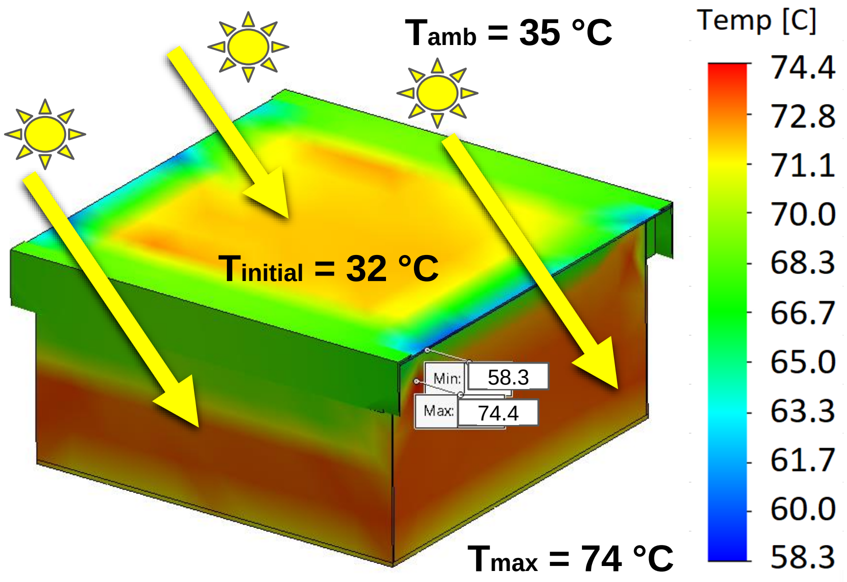
Worst case hot thermal model predictions are conservative and still do not exceed component limits.

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

Worst Case Hot

Thermal analysis setup:

- Greatest solar flux day of the year.
- Solar flux everywhere but floor: $G_{absorb} = G_{solar} * \alpha = 129.4$ W/m²
- Solar flux applied to all external surfaces except bottom.
- 35°C ambient air.
- 32°C initial structure temperature.
- Natural convection.
- Internal and external radiation.
- ΔTime = 3 hrs



Structural Test - Overview

Purpose: To ensure that the active protection system will not tip over or break under large loads on its open roof.

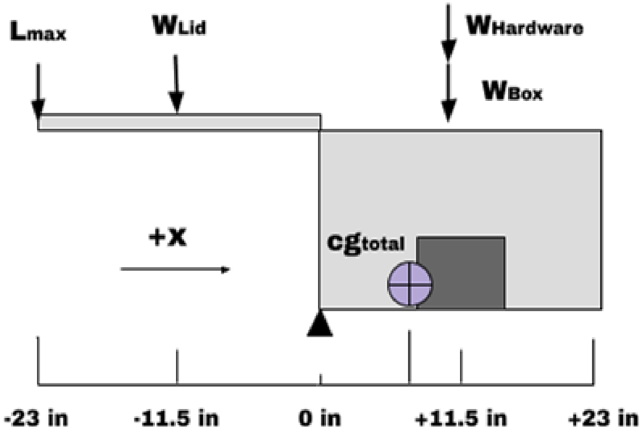
Requirements Satisfied: FR 2

Risk Mitigation: Loads on open roof tipping enclosure or breaking roof sliders, causing mission failure.

Models Validated: Hardware tipping and failure prevention models.

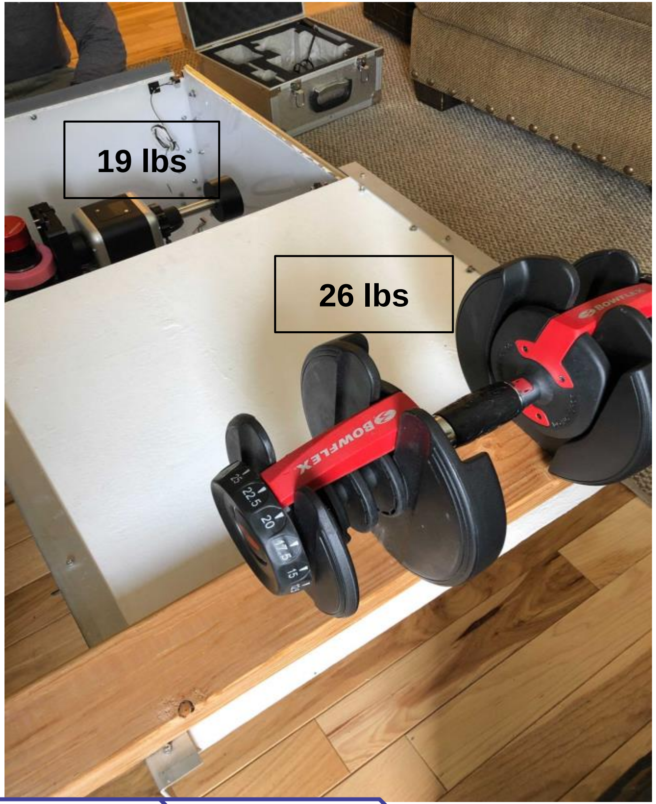
Expected Results:

- The active protection enclosure will not tip over before a maximum load of 25.7 lbs on the tip of the open roof.
- The roof sliders will not break due to this maximum tip load.
- The active protection system will tip over before the roof sliders fail.



Structural Test - Results and Validation

The fully set-up enclosure can withstand 26 lbs before tipping, and the system will tip before breaking.



Test Results:

- 2.5 lbs weights were incrementally added to end of open roof until the system began to tip over.
- The enclosure began to tip from an additional 26 lbs loaded to end of roof with all hardware inside.
- Test results were accurately predicted by model.

Lid Actuation Test - Overview

Purpose: To verify the successful operation of the roof motor and gear system.

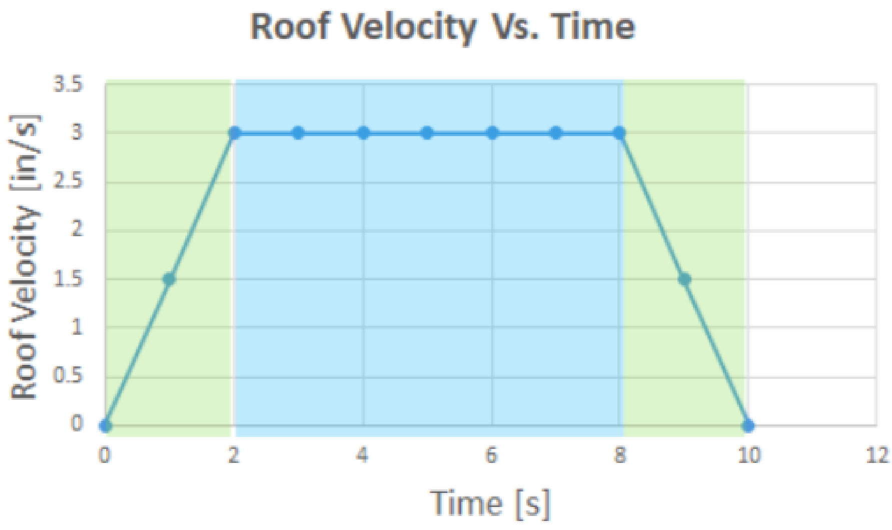
Requirements Satisfied: FR 3

Risks Mitigated: Timely roof actuation protects against quickly developing precipitation. [RCR]

Models Validated: Lid actuation velocity model.

Expected Results:

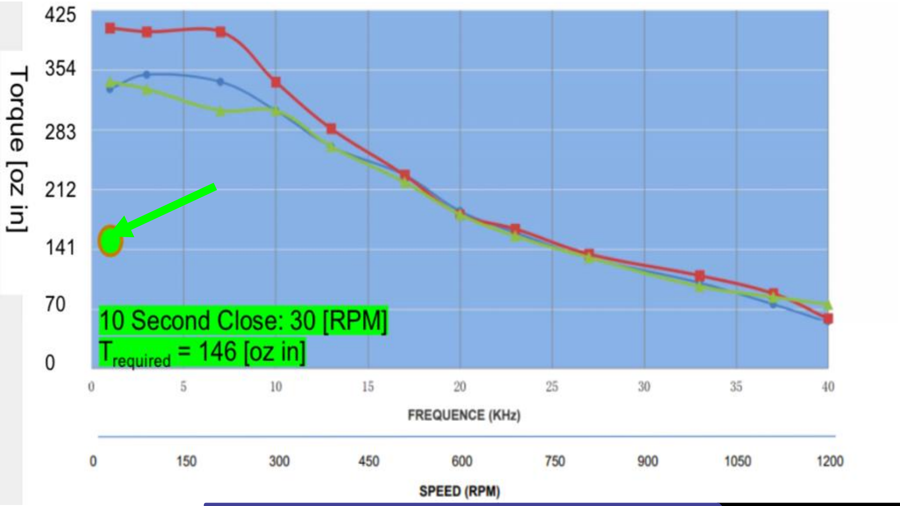
- The roof will open/close in 10 s
- The roof will open/close completely.



Lid Actuation Test - Results and

Motor successfully opened roof in 10 seconds, meeting WRAITH's initial legacy design point.

WRAITH Initial Design Point



SHADE Testing

2X Speed

Software Tests

Scheduler Test

Input Satellites:

- ISS (LEO)
- Galileo 22 (MEO)
- Meridian 8 (HEO)
- Satellite Data System F-6 (HEO)

Deprioritized satellites when they were marked as imaged.

Output Az-El and RA-Dec coordinates

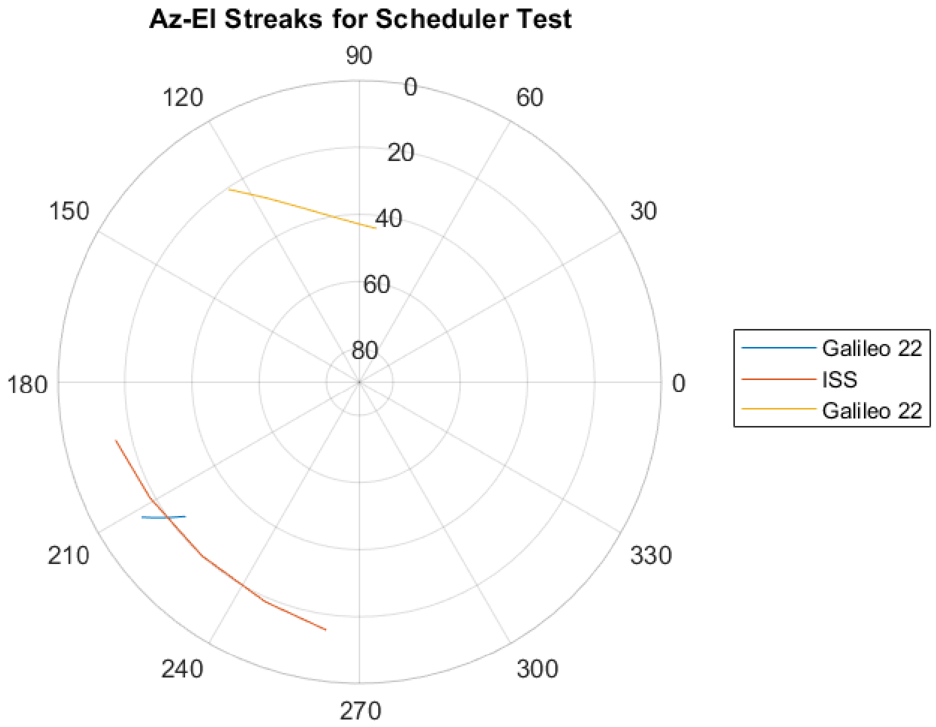
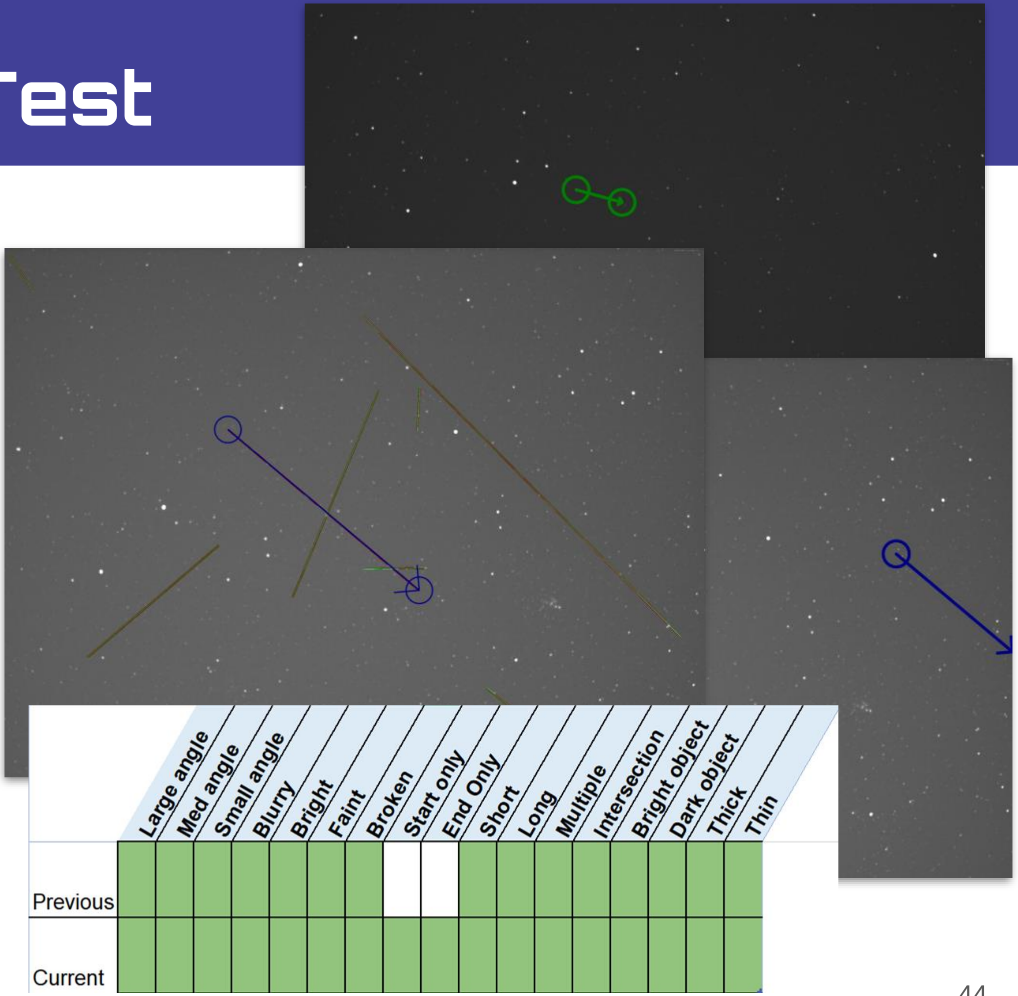


Image Processing Test

- Astrometry
  - Astrometric calibration performed with astrometry.net 3rd party software suite
  - Successful transformations (both ways) between equatorial and image coordinates
- Detected all streaks in image
  - Includes intersecting streaks
- Selected best streak based on predicted shape
  - Includes partial streaks (single endpoint)

<u>More testing using results of future full system tests required</u>



Software Setup

4-8 minutes (depending on GPS lock)

- Connect additional devices (1 min)
  - monitor to HDMI and power
  - USB flash drive
- Run startup procedure (2-6 min)
  - Wait for boot
  - Rough calibration of mount (up to 1 min)
  - Observe system running self-test
  - Includes GPS lock acquisition (up to 3 mins)
- Removing peripherals (<1 min)

```
INFO: 04/17/2021 10:00:13 PM - MainProcess - Starting Hardware
INFO: 04/17/2021 10:00:13 PM - MainProcess - Starting hardware
INFO: 04/17/2021 10:00:13 PM - MainProcess - Performing hardware startup
INFO: 04/17/2021 10:00:13 PM - MainProcess - Found one camera: ZWO ASI1600MM
INFO: 04/17/2021 10:00:15 PM - MainProcess - Mount connected: found model 5035
INFO: 04/17/2021 10:00:15 PM - MainProcess - DummyPowerMonitor: Connected device DummyPID, sn DummySN
INFO: 04/17/2021 10:00:15 PM - MainProcess - DummyPowerMonitor initial status: V_bat=12V, I_bat=0.1A, V_
INFO: 04/17/2021 10:00:15 PM - MainProcess - Reading battery status
INFO: 04/17/2021 10:00:18 PM - MainProcess - Performing operator startup
INFO: 04/17/2021 10:00:18 PM - MainProcess - Clearing temp directory
INFO: 04/17/2021 10:00:18 PM - MainProcess -    Removing old logs...
INFO: 04/17/2021 10:00:18 PM - MainProcess -    Removing old target database...
INFO: 04/17/2021 10:00:18 PM - MainProcess -    Removing old images...
INFO: 04/17/2021 10:00:18 PM - MainProcess - Checking input data
INFO: 04/17/2021 10:00:18 PM - MainProcess - Copying input database
INFO: 04/17/2021 10:00:18 PM - MainProcess - Running Hardware Startup Procedure...
INFO: 04/17/2021 10:00:19 PM - MainProcess - DummyDoor: Opening door
INFO: 04/17/2021 10:00:29 PM - MainProcess - DummyDoor: Door open
INFO: 04/17/2021 10:00:54 PM - MainProcess - SerialStage: setting zero position
INFO: 04/17/2021 10:00:56 PM - MainProcess - SerialStage: slewing to azel (45.0, 45.0)
INFO: 04/17/2021 10:01:16 PM - MainProcess - SerialStage: slewing to azel (270.0, 45.0)
INFO: 04/17/2021 10:01:47 PM - MainProcess - SerialStage: slewing to azel (180.0, 70.0)
INFO: 04/17/2021 10:02:00 PM - MainProcess - exposing 2 s
WARNING: 04/17/2021 10:02:00 PM - MainProcess - Camera: received timestamp 21599.96898818016 s in future
DEBUG: 04/17/2021 10:02:06 PM - MainProcess - wrote /home/shadeuser/SHADE/temp/selfcheck_image.png
INFO: 04/17/2021 10:02:06 PM - MainProcess - SerialStage: slewing to safe mode
INFO: 04/17/2021 10:02:07 PM - MainProcess - SerialStage: slewing to azel (180.0, 5.0)
INFO: 04/17/2021 10:02:20 PM - MainProcess - Waiting for GPS lock...
```

Minor/Intermediate tests

Linux/Python Environment

- Automatic login and software start
  - Mounting filesystem
  - Executing python process
  - Cleanup of temporary files
- Timed sleep
  - From python to bash wrapper
  - Use of rtcwake utility
- Parallelization
  - Python limitations/GIL
  - Multiprocessing and process-safe communication

Integration

- Hardware communication
  - Serial communication
  - 3rd party APIs and proper usage
- Data handling
  - Saving/moving files
  - Persistence/serialization
- Graceful crashing/error handling
  - Ensuring hardware enters safe mode
  - Isolating/recovering from unexpected errors

System Tests

30 min Deployment Test

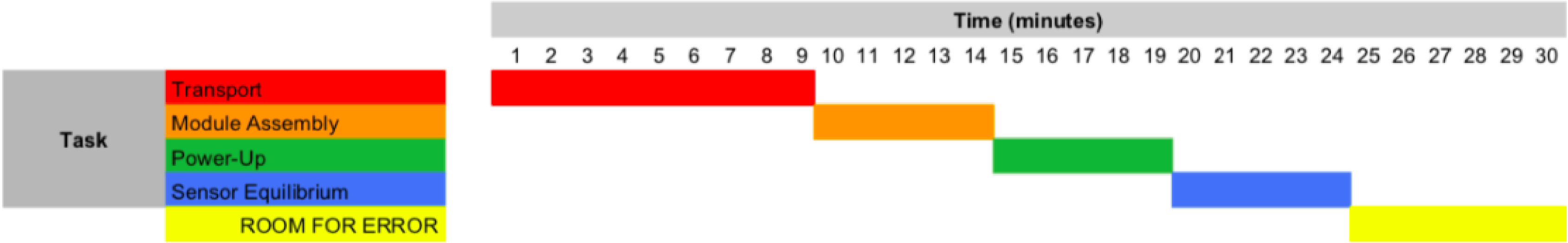
<u>Verified in April 12 Deployment Test</u>

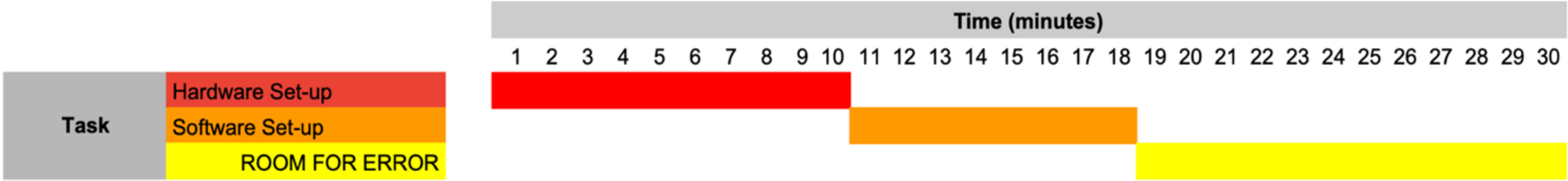
Hardware Setup Time: 10 min 17s

Software Setup Time: < 8 min

Total Deployment Time: 18min 40s

30-Minute Deployment Test (cont.)



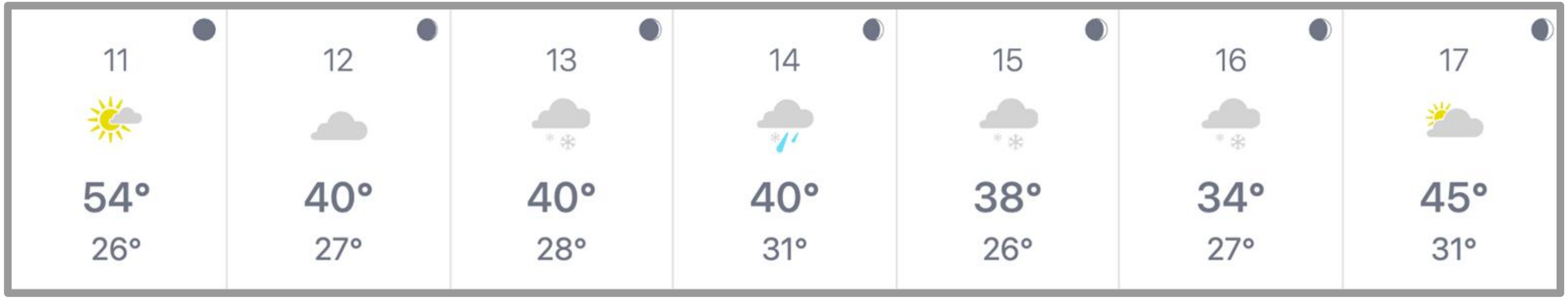


Full System Deployment Tests

Single Night Deployment - *Partially completed*
Multi Night Deployment - *Uncompleted*

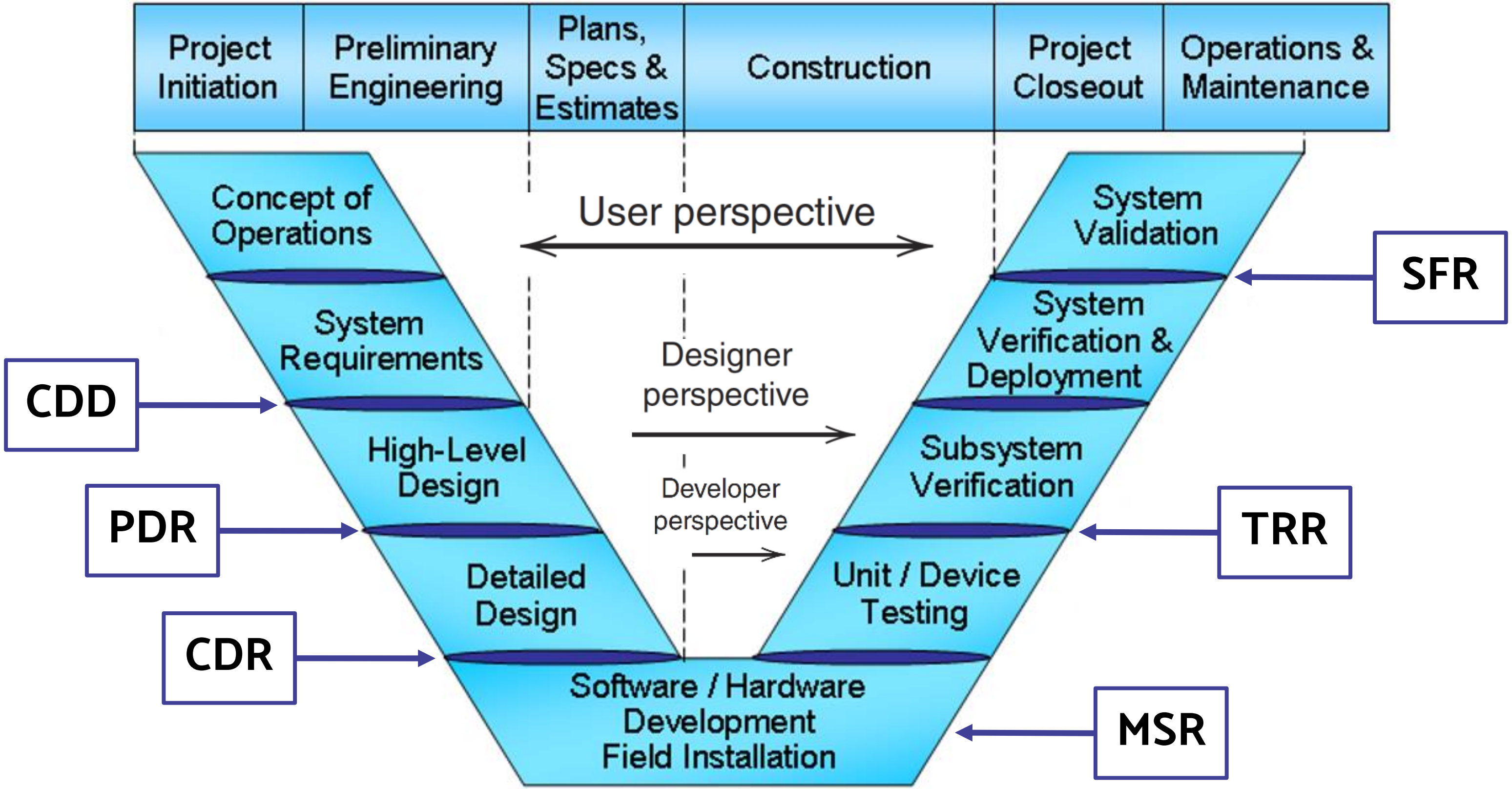
Issues Encountered:

- Weather - No imaging opportunities 4/11-4/17
- GPS Lock - Override currently being used
- Camera Focus
- Additional software debugging



Systems Engineering

The Systems Engineering V



Graphic courtesy of the FHWA Office of

Requirements Development

GHOST

Clean sheet design

Main development focuses:

- Scheduling
- Pointing
- Imaging
- Processing

WRAITH

Expansion of inherited scope

Main development focuses:

- Scheduling
- Pointing
- Processing
- Power
- Environmental Protection

SHADE

Completion of inherited work, further scope expansion

Main development focuses:

- Scheduling
- Imaging
- Processing
- Modularity
- Endurance

Key Trades

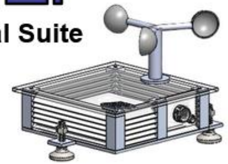
Materials Trade Study Results

Trip #1:

Active Protection Enclosure:
Weight: 50 lb

Trip #2:

Environmental Suite
Weight: 9 lb



Trip #3:

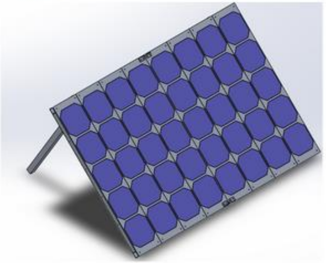
Power Module:
Weight: 29 lb

Trip #4:

Actuation Mount & Camera:
Weight: 19 lb

Trips #5/6:

2 Solar Panels:
Weight: 26 lb (each)



Sola

Metric	V
Power Efficiency	
Thermal Resistance	
Cost	
[redacted]	
Total	

TN	SUNIYAMA Polycrystalline Solar Cells
	3
	4
	3
[redacted]	
	3.4

	1.0	2.9	2.55	3.65	4.5

Risk Management - FMEA

A. Power

B. GHOST Schedu

C. WRAITH Sched

D. Imaging

E. Active Protectio

F. Weather Detecti

Likelihood of Failure	Recoverability: Trivial	Easy	Difficult	Very Difficult	Unrecoverable
Near Certainty			SOC	SLS, DIH	
Highly Likely				TOI, SPF	
Likely		LDN, ITC, RMA, PRH	PBA, SLP		
Unlikely		WFT, PRH	CMM	SDA, WDC, BOP, SDP	
Not Likely		WLD			RCR, GPS, THF, SPO, ACA

ality: e Path	Main Path	Critical Path
	C	
		E
		A B D

Key Risks & Mitigation

- Diurnal Heating [**DIH**] - 20
  - AP enclosure re-design and paint inclusion
- Starlink Streaks [**SLS**] - 20
  - Implementation of the novel image processor
- Target Orbit Instability [**TOI**] - 16
  - Scheduler redesign
- Single Point Failure [**SPF**] - 16
  - Self-diagnostics and robust operation procedures developed
- Sub-Optimal Charge [**SOC**] - 15
  - Low Power Shutdown routine and dynamic scheduling development

Legend
25
15-20
10-14
6-9
2-5
1

Key Risks & Mitigation

- Diurnal Heating [**DIH**] - 5
- Starlink Streaks [**SLS**] - 5
- Target Orbit Instability [**TOI**] - 4
- Single Point Failure [**SPF**] - 8
- Sub-Optimal Charge [**SOC**] - 5
- Schedule Slip [**SLP**] - 6

Legend
25
15-20
10-14
6-9
2-5
1

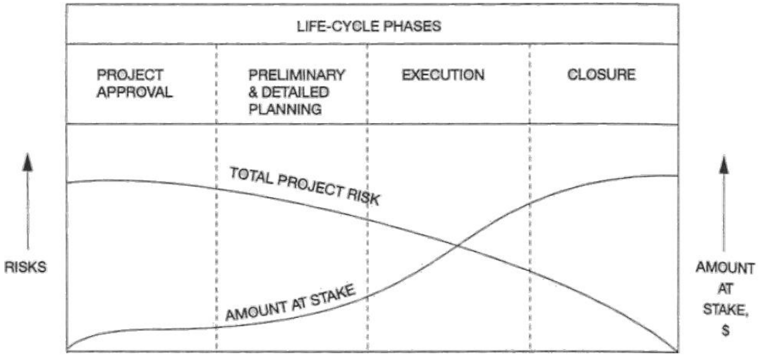
Likelihood of Failure	Recoverability: Trivial	Easy	Difficult	Very Difficult	Unrecoverable
Near Certainty	SLS, SOC, DIH				
Highly Likely	TOI				
Likely	LDN, ITC	SLP			
Unlikely		PRH, SDP, RMA		SPF	
Not Likely		WLD, SDA, ACA, WFT	PBA, CMM	WDC, BOP	RCR, GPS, THF, SPO

Lessons Learned

Proactivity

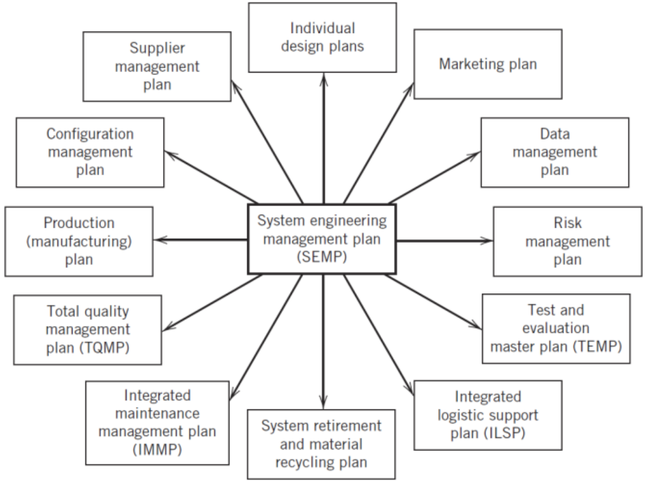
Good: Risk Management

Bad: Interface Management



Trust the process

Documentation via SEP, SEMP, SRD, WBS, SSS, FMEA, TEMP



Project Management

Management Approach/Lessons Learned

Project Management Approach: Traditional - Critical Path

- Allows team members to switch tasks based on priority
- Found to be effective for a remote projects environment

Lessons Learned	**Impact**
Two people minimum on all design elements	Minimize design oversights
Increase preliminary integration design	Solve more design issues before manufacturing
More scheduled subsystem team tag-ups	Improved task delegation & team momentum
Host formal CAD reviews/increase tolerancing	Reduces manufacturing/assembly time
Importance of appropriate scoping	Speed up legacy knowledge transfer & task delegation

Planned vs Actual Budget

CDR Budget: $3,540.00

MSR Budget: $3,750.00

Total Spent: $4,358.16

$608.16 over MSR budget, **16.2%**

Planned vs Actual Budget

Cost Overruns

UDOO Processor Replacements $583.00

Additional Thermal Epoxy $267.12

New Anemometer $62.00

Replacement part budget ($200.00)

Total Overrun $712.00

Project Effort - Industry Cost

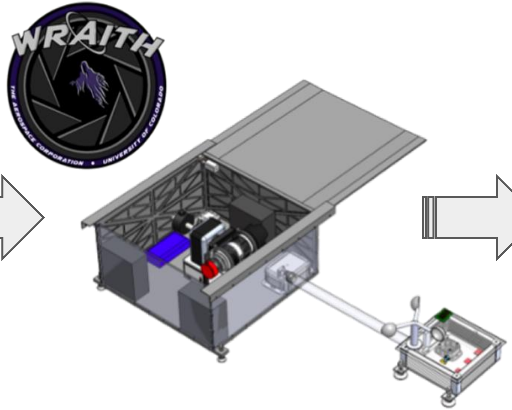
Hours averaged from SHADE timesheets

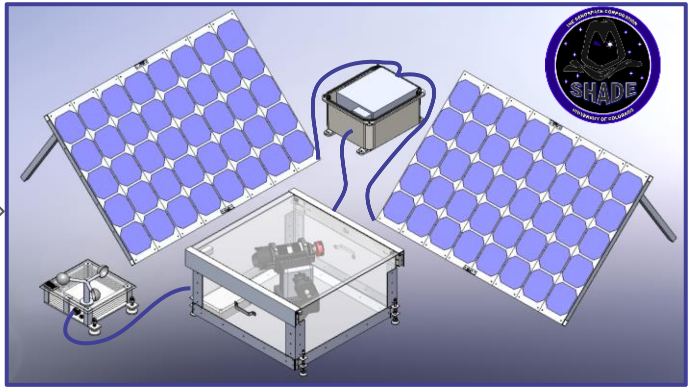
10 team members $65,000 dollars a year each -> $31.25/hr

Estimated 200% Overhead + $4400 in materials

Average Fall Hours	~118.5 hrs/week
Average Spring Hours	~120.5 hrs/week
Total Hours	3824
Industry Cost	**$361,100**

Project Effort - Industry Cost

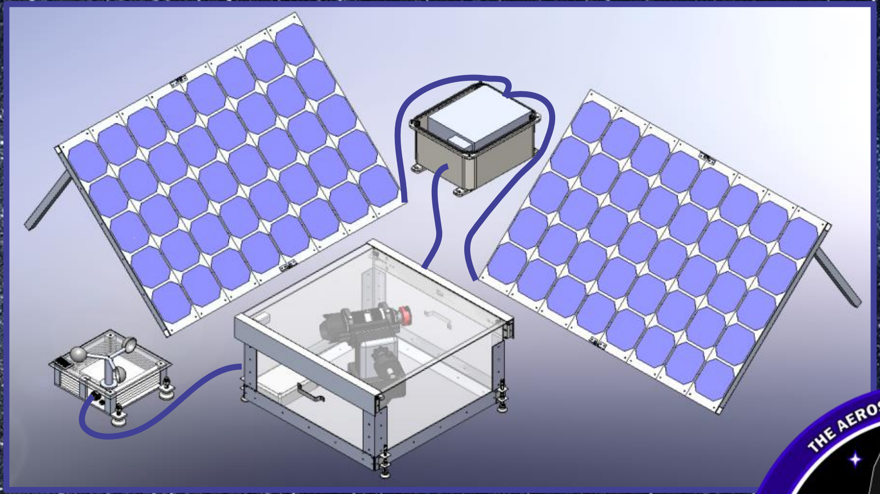




	GHOST	WRAITH	SHADE	Total
Hours Worked	~4072	~3730	~3824	~11,626
Project Cost	$5000	$3200	$4600	$12,800
Industry Cost	$381,750	$355,000	$363,100	$1,099,850

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.



THE AEROSPACE CORPORATION
SHADE
UNIVERSITY OF COLORADO

Questions?

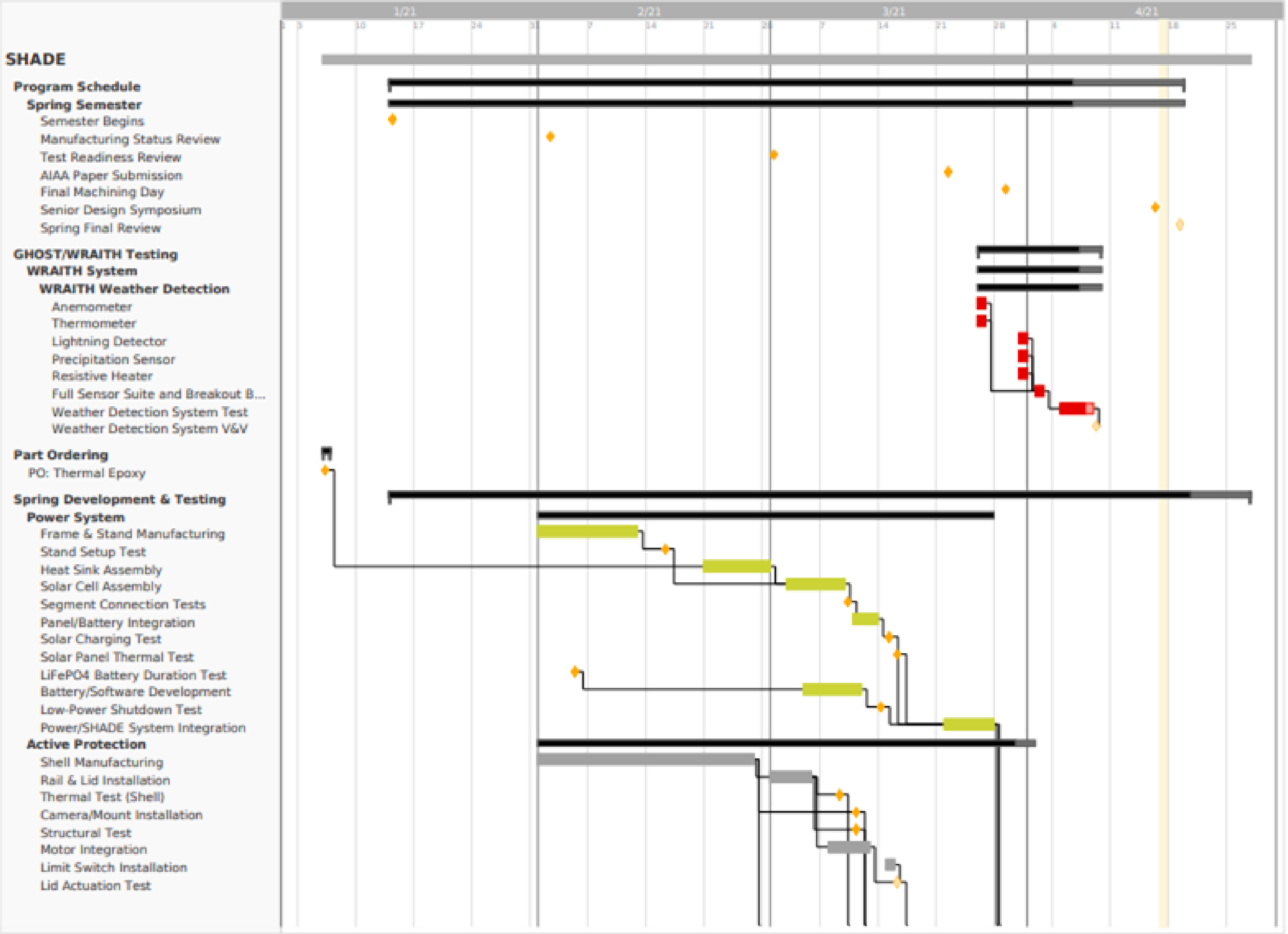
Backup Slides

SHADE Functional Requirements

1) SHADE shall predict locations and visibility windows for objects in LEO, MEO, GEO, and HEO.
2) SHADE shall function autonomously in standard operating conditions for at least two nights.
3) SHADE shall autonomously enter and exit a safe mode to protect itself from adverse weather.
4) SHADE shall autonomously track objects in LEO, MEO, GEO, and HEO.
5) SHADE shall image objects with apparent magnitude of less than 10.
6) SHADE shall create and save orbit estimates for each object within 5 mins of the end of the associated visibility window.

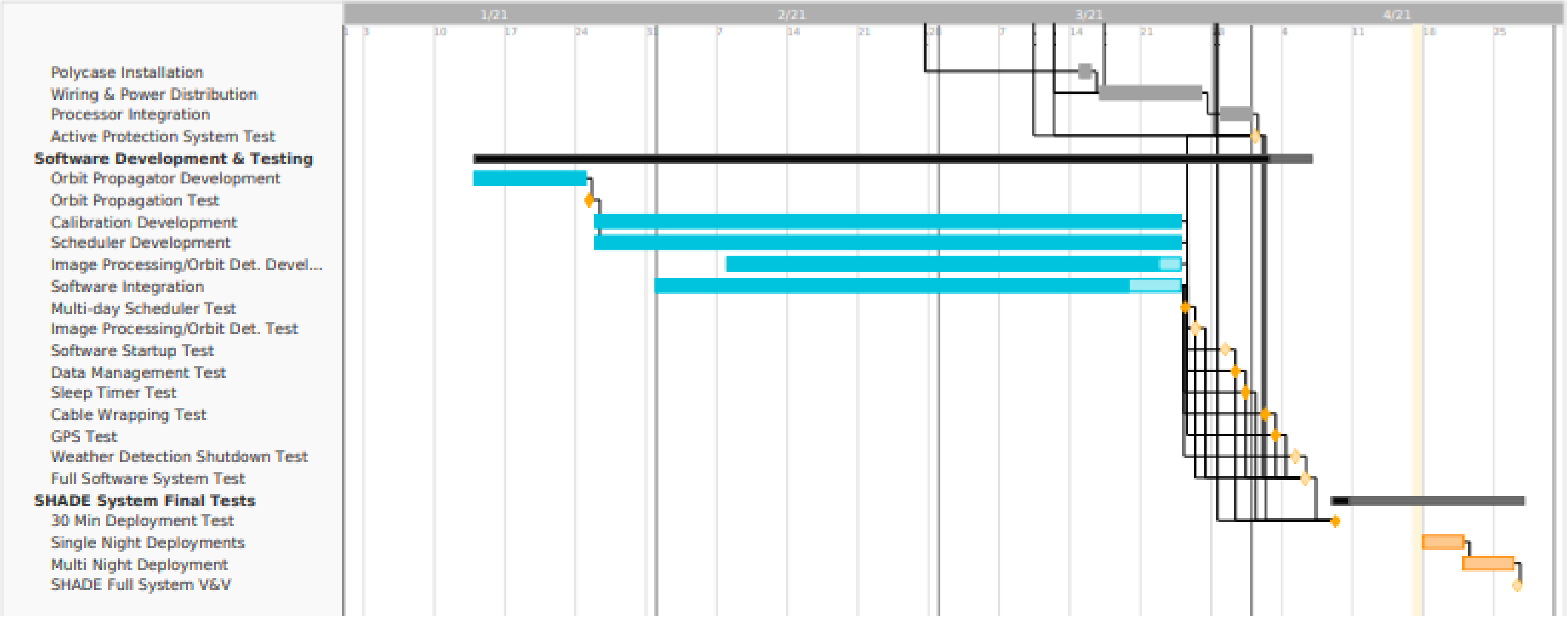
New to SHADE

7) SHADE shall be deployed & recoverable in 30 minutes by a single operator.
8) SHADE shall be capable of making observations on multiple nights during a single deployment.



1/21
2/21
3/21
4/21
SHADE
Program Schedule
Spring Semester
Semester Begins
Manufacturing Status Review
Test Readiness Review
AIAA Paper Submission
Final Machining Day
Senior Design Symposium
Spring Final Review
GHOST/WRAITH Testing
WRAITH System
WRAITH Weather Detection
Anemometer
Thermometer
Lightning Detector
Precipitation Sensor
Resistive Heater
Full Sensor Suite and Breakout B...
Weather Detection System Test
Weather Detection System V&V
Part Ordering
PO: Thermal Epoxy
Spring Development & Testing
Power System
Frame & Stand Manufacturing
Stand Setup Test
Heat Sink Assembly
Solar Cell Assembly
Segment Connection Tests
Panel/Battery Integration
Solar Charging Test
Solar Panel Thermal Test
LiFePO4 Battery Duration Test
Battery/Software Development
Low-Power Shutdown Test
Power/SHADE System Integration
Active Protection
Shell Manufacturing
Rail & Lid Installation
Thermal Test (Shell)
Camera/Mount Installation
Structural Test
Motor Integration
Limit Switch Installation
Lid Actuation Test

Printed: Apr 17, 2021



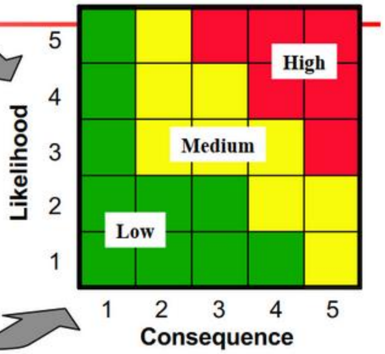
Risks - Development Info

Engineering Management Program
UNIVERSITY OF COLORADO BOULDER

Risk Matrix – "The 5-by-5"

Likelihood

What Is the Likelihood the Risk Will Happen?		
Level		Your Approach and Processes...
1	Not Likely:	...Will effectively avoid or mitigate this risk based on standard practices
2	Low Likelihood:	...Have usually mitigated this type of risk with minimal oversight in similar cases
3	Likely:	...May mitigate this risk, but workarounds will be required
4	Highly Likely:	...Cannot mitigate this risk, but a different approach might
5	Near Certainty:	...Cannot mitigate this type of risk; no known processes or workarounds are available



Consequence

Given the risk is realized, what would be the magnitude of the impact?			
Level	Technical	Schedule	Cost
1	Minimal or no impact	Minimal or no impact	Minimal or no impact
2	Minor perf shortfall, same approach retained	Additional activities required; able to meet key dates	Budget increase or unit production cost increase <1%
3	Mod perf shortfall, but workarounds available	Minor schedule slip; will miss need date	Budget increase or unit production cost increase <5%
4	Unacceptable, but workarounds available	Program critical path affected	Budget increase or unit production cost increase <10%
5	Unacceptable; no alternatives exist	Cannot achieve key program milestone	Budget increase or production cost increase >10%

High (Red): Unacceptable. Major disruption likely. Different approach required. Priority management attention required.

Moderate (Yellow): Some disruption. Different approach may be required. Additional management attention may be required.

Low (Green): Minimum impact. Minimum oversight needed to ensure risk remains low.

Risk Analysis Provides a Consistent Measurement of Program Risks

Legend
25
15-20
10-14
6-9
2-5
1

Risks - Technical

Technical Risks - Pre Mitigation				
Risk	Risk ID	Likelihood	Recoverability	Severity
Starlink Streak	SLS	5	4	20
Diurnal Heating	DIH	5	4	20
Target Orbit Instability	TOI	4	4	16
Suboptimal Charge	SOC	5	3	15
Power Budget Accuracy	PBA	3	3	9
Self-Diagnostics Accuracy	SDA	2	4	8
Weather Detection Commanding	WDC	2	4	8
COTS Moisture Management	CMM	2	4	8
Roof Closing Routine	RCR	1	5	5
GPS Signal Acquisition	GPS	1	5	5
Auto-Calibration Accuracy	ACA	1	5	5
Processor Heating	PRH	2	2	4
Weather Detection Fault Thresholds	WFT	2	2	4

Technical Risks - Post Mitigation				
Risk	Risk ID	Likelihood	Recoverability	Severity
Starlink Streak	SLS	5	1	5
Diurnal Heating	DIH	5	1	5
Target Orbit Instability	TOI	4	1	4
Suboptimal Charge	SOC	5	1	5
Power Budget Accuracy	PBA	1	3	3
Self-Diagnostics Accuracy	SDA	1	2	2
Weather Detection Commanding	WDC	1	4	4
COTS Moisture Management	CMM	1	4	4
Roof Closing Routine	RCR	1	5	5
GPS Signal Acquisition	GPS	1	5	5
Auto-Calibration Accuracy	ACA	1	2	2
Processor Heating	PRH	2	2	4
Weather Detection Fault Thresholds	WFT	1	2	2

Risks - Management

Management Risks - Pre Mitigation				
Risk	Risk ID	Likelihood	Recoverability	Severity
Single Point Failure	SPF	4	4	16
Schedule Slip	SLP	3	3	9
Schedule Driven Progress	SDP	2	4	8
Intra-Team Communication	ITC	3	2	6
Resource Management	RMA	3	2	6

Management Risks - Post Mitigation				
Risk	Risk ID	Likelihood	Recoverability	Severity
Single Point Failure	SPF	2	4	8
Schedule Slip	SLP	3	2	6
Schedule Driven Progress	SDP	2	2	4
Intra-Team Communication	ITC	3	1	3
Resource Management	RMA	2	2	4

Risks - External

External Risks - Pre Mitigation				
Risk	Risk ID	Likelihood	Recoverability	Severity
Operator Error	BOP	2	4	8
Lockdown	LDN	3	2	6
Theft	THF	1	5	5
Obscured Solar Panel	SPO	1	5	5
Wildlife Interference	WLD	1	2	2

External Risks - Post Mitigation				
Risk	Risk ID	Likelihood	Recoverability	Severity
Operator Error	BOP	1	4	4
Lockdown	LDN	3	1	3
Theft	THF	1	5	5
Obscured Solar Panel	SPO	1	5	5
Wildlife Interference	WLD	1	2	2

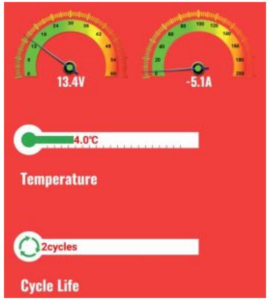
Battery Duration Test

Purpose: Testing the expected duration of the battery when subjected to full current draw

Requirements Satisfied: FR 8

Equipment: Cycle tester, VictronConnect

Facilities: Senior project space



Testing Procedure:

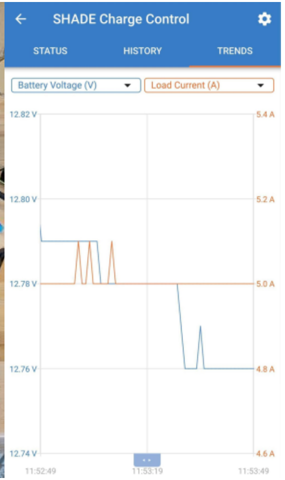
- Battery shall start with a full charge
- Cycle tester draws 5 A over an 11-hour period, ultimately drawing **55 Ah**
- Monitoring the voltage of the battery over the course of the test allows analysis of the discharge curve
- Similarly, monitoring the rate of change of the capacity will characterise the transient performance of the battery over the course of an observation window

Battery Duration Test (cont.)

Expected Results:

- ≥ 30% of the battery capacity should remain following the test

- Variation of the voltage should match the discharge curve provided



Risk Mitigation:

- Empirical knowledge of the discharge curve allows for better mission planning and scheduling

- Increased confidence that the battery will last a full 12 hour observation period (DR 2.2)

Models Validated:

- Battery discharge model

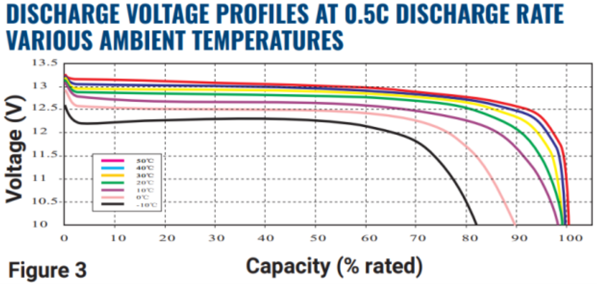
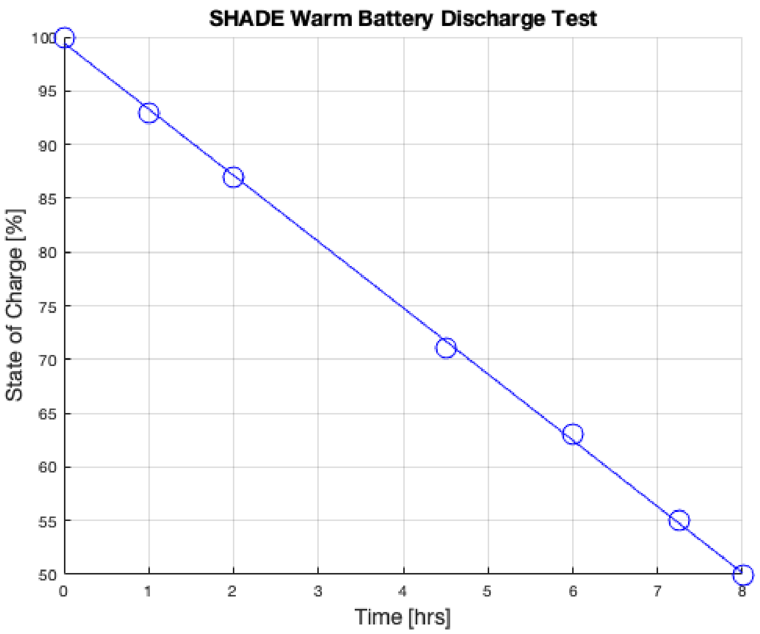
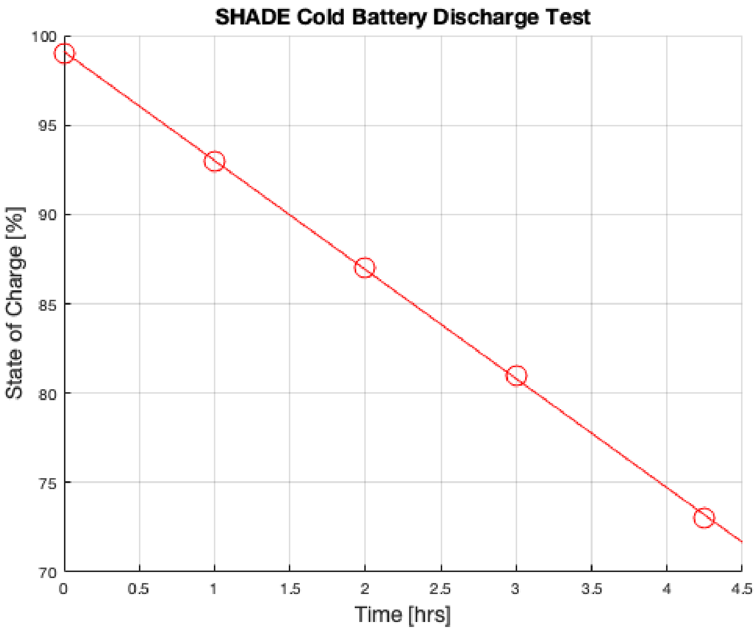


Figure 3

Preliminary Battery Discharge Rates



T = -10 C



T = 21 C

Functional Requirement	Relevant Tests	Additional Satisfaction
FR 1: SHADE shall schedule predicted locations and visibility windows for objects in LEO, MEO, GEO,and HEO orbits.	*Single Night Deployment, Multi-Night Deployment, Orbit Propagation, Week-Long Scheduling*	Accurately predicts locations and visibility windows for 90 % of the requested objects in the Single and Multi-Night Deployment assessments
FR 2: SHADE shall function autonomously in standard operating conditions with no human intervention for at least two nights.	*Multi-Night Deployment, Week-Long Dynamic Scheduling*	Completes 80 % of its requested tracking
FR 3: SHADE shall autonomously enter and exit a safe mode to protect itself from adverse weather.	*Single Night Deployment, Multi-Night Deployment, Lid Actuation, Weather Detection Tests*	-
FR 4: SHADE shall autonomously point to and track objects in LEO, MEO, GEO, and HEO	*Single Night Deployment, Multi-Night Deployment, Week-Long Dynamic Scheduling, Image Processing, Orbit Propagation*	Accurately points to and tracks 80 % of the requested objects in both the Single and Multi-Night Deployment assessments

Functional Requirement	Relevant Tests	Additional Satisfaction
FR 5: SHADE shall image objects with apparent magnitude of less than 10.	*Image Processing*	-
FR 6: SHADE shall create and save an orbit estimate for each object imaged within five minutes of the end of the associated visibility window.	*Single Night Deployment, Multi-Night Deployment, Image Processing*	Accurately creates and saves the orbit estimate for 90 % of the objects within 5 minutes of the end of the associated visibility window in the Single and Multi-Night Deployment assessments
FR 7: SHADE shall be deployed and recovered in 30 minutes by one operator.	*30-Minute Transport & Assembly*	-
FR 8: SHADE shall be capable of making observations on multiple nights during a single deployment.	*Multi-Night Deployment*	-

	Requirement	Motivation	Verification
FR 1:	The system shall schedule predicted locations and visibility windows for objects in LEO, MEO, GEO, and HEO.	SHADE shall be capable of scheduling its own visibility windows for all of the specified space objects and this requires on-board orbit propagation. Additionally, HEO is defined by the customer to be a space object with an orbit perigee below 300 km, and an apogee above 300 km but below 30,000 km.	Test - SHADE will be deployed, given input TLEs, and prompted to determine a visibility schedule. The success of the scheduling process will be measured against the operator's visual observation of satellites at the scheduled times and locations from the SHADE schedule.
DR 1.1:	The system shall accept a series of satellite catalog numbers and TLEs as inputs from the user. [Met by GHOST design]	The only knowledge the user will have is the satellite IDs of the objects of interest. Thus, SHADE shall be capable of retrieving the TLEs for these objects and using those as the only input.	Test - SHADE will be given a series of satellite IDs and nothing more. If SHADE accepts these and operates normally then the requirement is satisfied.
DR 1.2:	The system shall compute predicted observation windows for each input object based on input state information, environmental information, and system location. [Met by GHOST design]	All factors that could influence the quality of a visibility window need to be considered in the on-board scheduler otherwise SHADE may not efficiently capture all necessary observations with sufficient quality.	Test - SHADE will determine its own location and environmental data and produce an observation schedule for itself. If a human can visually find the space objects at their scheduled times and locations then the requirement is satisfied.
DR 1.3:	The system shall create an observation schedule that ensures at least one observation per deployment for each input object. [Met by WRAITH design, untested]	The customer wants to ensure that each input object is observed at least once.	Test - A series of satellite IDs will be inputted to SHADE and an operator will observe whether SHADE schedules at least one viewing window for each.
DR 1.3.1:	The system shall be capable of creating a new schedule if a visibility window is missed. [Met by WRAITH design, untested]	It is common to fail to image a satellite for a variety of reasons. If a satellite is missed, SHADE shall be able to reorder the schedule to prioritize that object later in the deployment.	Test - SHADE will create an initial schedule and be forced to recalculate a new schedule with different priority values.

	Requirement	Motivation	Verification
FR 2:	The system shall function autonomously in standard operating conditions with no human intervention for at least two nights.	The customer would like to leave the system outside over the course of multiple nights without any human interaction and be able to pick it up in the morning.	Test - SHADE will be deployed, given its inputs, and left to run for 36 hours with no human interaction. Upon pickup, orbit outputs and image archive review will determine autonomous success or failure.
DR 2.1:	The system shall operate in conditions defined by the Standard Operating Conditions with no impact to orbit determination capabilities.	Since adverse weather is an important part of this project, it is important to define the standard operating conditions in which the system should operate nominally.	Test - The system will be deployed in a variety of environmental conditions that lie within the standard operating conditions and performance will be measured.
DR 22:	The system shall contain a battery capable of supplying operational power levels for 12 hours without recharging. [Met by WRAITH design, integration untested]	During the 12 hour active period per day, the system shall be capable of operating continuously which requires power draw.	Test - The battery will be subjected to an operational loading and the time to drain the battery will be measured as well as voltage versus time.

	Requirement	Motivation	Verification
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.	One of the customer's expectations is that the system will be able to operate for extended periods of time unattended, which requires protecting the system from potential adverse weather during that time.	Test - The system will be tested under simulated weather conditions to determine whether the system can autonomously enter and exit safe mode.
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]	To protect the system from adverse weather, the system will require active weather protection to supplement the passive protection in the event of more severe conditions.	Test - The weather system will be tested under controlled conditions to assess its resistance to water and against light debris carried by wind.
DR 3.2:	The system shall accept a safety override from the operator to activate and deactivate the active weather protection. [Met by WRAITH design, untested]	While the system will be capable of autonomously activating and deactivating the weather protection, to mitigate the risks to the system, an operator will have the ability to manually put the system into a safe mode.	Test - The operator override will be initiated while experiencing Standard Operating Conditions to verify deployment of active weather protection.

	Requirement	Motivation	Verification
FR 4:	The system shall autonomously point and track objects in LEO, MEO, GEO, and HEO. [Met by WRAITH design, unit tested]	The purpose of the previous system, GHOST, was to track objects in LEO, MEO, and GEO given the rising number of satellites and space debris currently orbiting Earth. SHADE has been expanded to include HEO orbits and to operate autonomously.	Test - SHADE will be deployed in the field and directed to point towards and track objects bounded within each orbit type.
DR 4.1:	The system shall have a pointing accuracy within 4 arcseconds. [Met by GHOST design]	This system is tracking objects in space in varying orbits, as such the pointing accuracy needs to be high in order to obtain the desired data.	Test - The system will be directed to point towards a well known object in the night sky, such as the North Star, and the accuracy of the image will be determined.
DR 4.2:	The system shall slew at a rate of 2 deg/s. [Met by GHOST design]	Objects passing perigee in HEO are moving quickly. Due to this, a higher slew rate is required in order to take tracking images of these objects.	Test - In a laboratory setting, SHADE will be commanded to rotate a certain distance while recording the duration to determine the angular speed.
DR 4.2.1	The system shall contain an on-board control algorithm to actuate the camera gimbal. [Met by GHOST design]	A control algorithm is necessary to avoid overshooting or undershooting the target.	Test - The system shall be directed to point at a given target, and when the control algorithms command the actuators to successfully move the imaging system to aim at the target, the test will pass.

	Requirement	Motivation	Verification
DR 4.3:	The pointing and tracking subsystem shall interface autonomously with the scheduler to receive commands. [Met by GHOST design, longer term functionality untested]	To point at the correct target window, the actuators that control pointing will require input from the scheduler. This is also necessary when a pass is missed to re-orient the imaging system.	Test - This criteria will be satisfied when the scheduler successfully commands the actuators to point the imaging equipment at a designated target.
DR 4.4:	[Legacy Software] The computer shall interface with the camera gimbal autonomously.	Pointing the camera at a desired location is a fundamental requirement for SHADE's operation. The gimbal must be able to aim the camera at the correct point in the sky in preparation for an imaging sequence, as determined by the scheduler.	Test - A set of azimuth-elevation coordinates will be fed to the gimbal, with the resulting physical pointing direction evaluated externally. Further testing will include the camera, with pointing direction evaluated using star maps.
DR 4.5:	[Legacy Software] The main computer shall fully interface with the camera sensor autonomously, initiating image capture and receiving resulting data. [Met by GHOST design]	Images captured by the camera are critical to the orbit determination process. The camera sensor itself shall be initiated at the proper time by the on-board computer, and the results shall be freely available for processing.	A simple script will initialize the camera, expose the sensor for a predetermined amount of time, and save the resulting image in a usable format (such as .bmp, .png, etc.) within the time frame allocated by the scheduler.

	Requirement	Motivation	Verification
FR 5	The system shall image objects with apparent magnitude of less than 10. [Met by GHOST design]	SHADE will be able to image the objects in the sky once it is pointed correctly at them. These images are the basis for the image processing which then feeds towards the goal of orbit determination.	Test - SHADE will be fed correct and incorrect images to showcase abilities in measuring quality and look for missing space objects. Additionally, SHADE will be tested in the field.
DR 5.1:	The system shall provide $\geq$ 6 angular measurements in the inertial frame from a single orbit visibility window. [Met by GHOST design]	SHADE needs at least 6 angular measurements for the OD software to work correctly with no under-determined matrices. These can be gathered in pairs through three measurements that each have a start and end point to the streak line.	Test - The scheduler will be tested for a minimum of 3 unique captures for each space object pass. The image processing will be tested based on these 3 captures to ensure 6 measurements are gathered.
DR 5.2:	The system shall process captured images and screen for quality and missing space objects. [Met by GHOST design, unit tested]	Quality images that include both the start and end of a streak during a single capture are necessary for the software to identify start and end points. Furthermore, if the space object is not present, the system needs to recognize this, notify the scheduler, and take action to locate that space object.	Test - SHADE will be given quality images and bad images to determine if it can differentiate between them. Additionally, SHADE will be given images with and without space object streaks present to determine if the space object is off of its predicted course.
DR 5.2.1:	The system shall be capable of identifying and rejecting images that cannot be processed for bore- sight or space object inertial position. [Met by GHOST design, unit tested]	The system needs quality images for processing and orbital determination.	Test - SHADE will be given good and bad images to determine whether proper distinctions can be made by the system.
DR 5.2.2:	The system shall be capable of identifying missing space objects	As part of the customer requirements,	Test - SHADE will be given bad data to

	Requirement	Motivation	Verification
FR65	The system shall create and save an orbit estimate for each object imaged within five minutes of the end of the associated visibility window.	The purpose of this system is to provide orbital estimates to the user after each deployment.	Test - The orbit estimation software will be run on-board and timed in under five minutes.
DR 6.1:	The system shall have knowledge of its own location in latitude, longitude, and altitude to within 10 meters. [Met by GHOST design]	The system must know where the azimuth and elevation measurements were taken otherwise the orbit determination will be wrong.	Demonstration - The GPS unit will be turned on and it will be verified that a location is being provided.
DR 6.2:	The system shall save orbit estimates as well as comparisons to previous orbit estimates for each tracked object to the on-board memory. [Met by WRAITH design, untested]	The orbit estimates shall be saved in the on-board memory in a format that can be read by the operator once the deployment is complete.	Test - The orbit estimates will be output and read by an operator after the test deployment and compared with current orbit element data online.
DR 6.3:	The system shall be capable of converting six sets of angular measurements into an orbit estimate within 4 minutes. [Met by WRAITH design, untested]	The orbit estimates must be made no later than five minutes after the end of the pass, however with image processing taking up a small portion of time, a buffer was added in.	Test - Orbit estimates will be time-tagged and compared to the time of the end of the observation window.
DR 6.4:	The system shall process an image within 10 seconds. [Met by WRAITH design, untested]	SHADE will be able to image the objects in the sky once it is pointed correctly at them. These images are the basis for the image processing which then feeds towards the goal of orbit determination.	Test - SHADE will be fed correct and incorrect images to showcase abilities in measuring quality and look for missing space objects. Additionally, SHADE will be tested in the field.
DR 6.4.1	The system shall maintain a clock drift less than 5 milliseconds when compared with GPS time. [Met by GHOST design]	Timing is key for orbit determination. GHOST struggled to produce precise time latency results, which is necessary to increase the fidelity of an SSA tracker.	Test - In order to determine the camera latency, the images will be time stamped with GPS time from the on-board GPS receiver.

	Requirement	Motivation	Verification
FR 7	The system shall be deployed in 30 minutes and broken down in 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]	Reduce deployment and tear down time of the system.	Test/Inspection - The operator will inspect to ensure proper size and weight while also running the operation process to keep under the allotted time.
DR 7.1	The individual system modules shall weigh less than 22.68 kilograms (50 lbs).	The system is to be placed in the field by one operator who should be able to lift the system with ease.OSHA standards typically cite 50 lbs (22.68 kg) per person for lifting.	Test - The system modules will be weighed by scale.
DR 7.1.1	The system modules, when located inside their travel casing, shall withstand impulses up to 7 g in any given direction.	The deployment site may require off-road vehicular transportation, thus the expectation of a more varied vibrational profile experienced during travel. Grzesica categorises the expected off-road vibrational environment as containing infrequent impulses of up to ~7g.	Test - The system shall undergo vibration testing, up to 7 g, along all three axes.
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.	Aside from the larger spikes due to potholes or ruts, non-paved roads will tend to generate a semi-constant vibrational environment, Grzesica showed oscillations of approximately the above conditions.	Test - System can be tested both on a shaker table and during travel.

	Requirement	Motivation	Verification
FR 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].	The passive protection should protect the system modules not requiring active protection from adverse weather.	Test - The passive weather resistance will be tested under controlled conditions to assess its resistance to water and against light debris carried by wind.
DR 7.2:	SHADE shall be set up and taken down in accordance to the process document titled: SHADE System Operation Manual.	To quicken the process, a document outlining the operation of SHADE in the field may be of use.	Test - The setup and tear down process will be timed separately through their laid out process in the system operation manual.
DR 7.3:	[Legacy Software] SHADE shall be able to startup and perform all tasks with no user input beyond supplying a target list file via external USB drive	SHADE needs to be set up quickly, and preferably by a person with potentially limited knowledge of SHADE's core design. As such, the onboard operating system will startup and initiate itself as soon as it is powered on and detects the target list on an external USB drive	Test - With a monitor and keyboard attached, and necessary file on an installed USB drive, the system activity will be monitored following boot. The computer must start the OS, perform all calibrations, develop its imaging schedule, and begin executing that schedule with no user input.
DR 7.4	During setup, SHADE shall execute an automatic attitude determination routine.	To eliminate the need for time-consuming manual calibration of the system attitude during setup, SHADE will automatically run an attitude determination routine.	Test - Have the system display the attitude to the screen , verify attitude by other means.

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	Requirement	Motivation	Verification
FR 8	The system shall be capable of making observations on multiple nights during a single deployment.	Being able to deploy the SHADE system for more than one night at a time greatly increases the scheduling flexibility along with facilitating a greater number of observations per deployment without the need to retrieve the system every day.	Test - The system will be left in place over the course of multiple nights.
DR 8.1:	SHADE shall be resilient to diurnal temperature fluctuations over the range of temperatures described by the Standard Operating Conditions	The previous iterations of the system were designed on the assumption that the system would not be left in the field for more than one day-night cycle, allowing for design for resilience to cold temperature without considering solar heating during the day. Longer missions require that the effects of solar heating now be considered.	Test - Place the various weather protection enclosures in similar solar heating conditions and monitor internal temperature.
DR 8.1.1:	During charging, the magnitude of the thermal coefficient for the solar panels shall not exceed -0.5% per degree C.	Efficiency of the solar panels varies inversely with the thermal coefficient. Keeping the panels cool during operation is key to extracting maximum efficiency.	Test - The temperature of the panels can be measured in different solar heating environments.
DR 8.1.2	While not in use, the internal temperature of the *MOST SENSITIVE ENCLOSURE* shall be maintained between [TBD Range].	To avoid damaging the components while not in use, the temperature within the enclosures for each module should be maintained at a safe level.	Test - System can be placed in extreme environments to verify maintenance of proper temperatures.

	Requirement	Motivation	Verification
DR 8.2	The solar charging system shall be capable of providing a constant 12.5V input voltage to the SHADE system during adequate solar conditions.	The battery employed by the SHADE system nominally charges at 300 watts to be filled completely during the day, thus the solar system needs to be able to provide power of this nature.	Test - Simulate different solar incidences conditions and monitor panel power output.
DR 8.3:	[Legacy Software] Computer shall predict location of an object at an arbitrary time up to five nights in the future.	Because objects can only be imaged at certain times, it is necessary for the computer to be able to predict the location of an object in an LEO/MEO/HEO/GEO orbit at an arbitrary point in the future, and determine the portion of sky that must be imaged to track the object. Five nights was chosen as being the longest possible mission duration for SHADE.	Test - a series of objects (both indicative of most target bodies, as well as a selection of edge cases) will be fed to the orbit propagation software. Its position will be determined at a series of times up to five nights in the future, and the results compared to existing orbit propagation solutions.
DR 8.4:	When creating the initial schedule, the scheduler shall be able to consider the total mission duration when prioritizing observation windows.	In increasing the mission duration, SHADE will now have more opportunities to make observations of the same object, allowing more flexibility in creating the overall observation schedule.	Test - Provide the scheduler the same list of objects with different specified mission durations to compare the resulting schedules.

Battery Charging Simulations - Hot Day

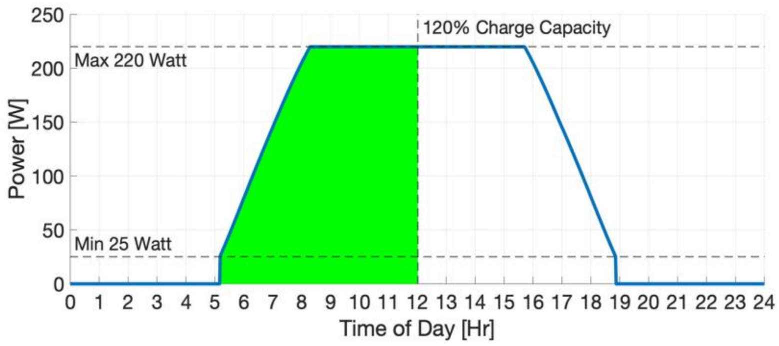
Power Generated From Solar Panel

Full Day: 2.3 kWh

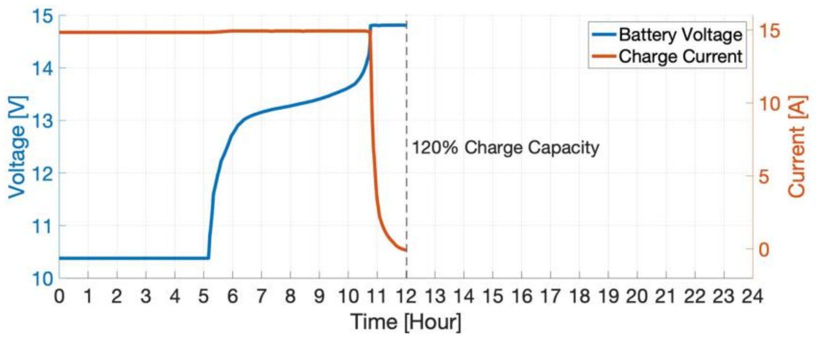
Sunrise: 5:35 AM

Sunset: 8:34 PM

120% Charge By 12 PM



Battery Charge Profile



Battery Charging Simulations - Cold Day

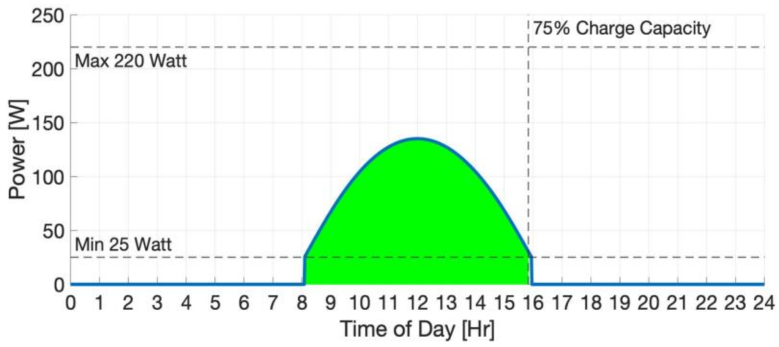
Power Generated From Solar Panel

Full Day: 723 Wh

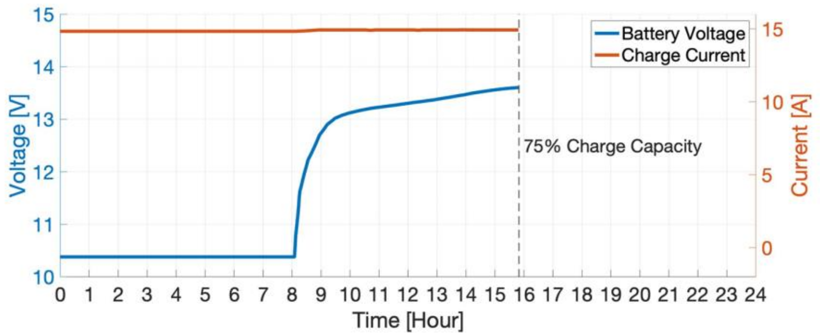
Sunrise: 7:22 AM

Sunset: 4:43 PM

75% Charge By Sunset



Battery Charge Profile



Sources of Error for Solar Model

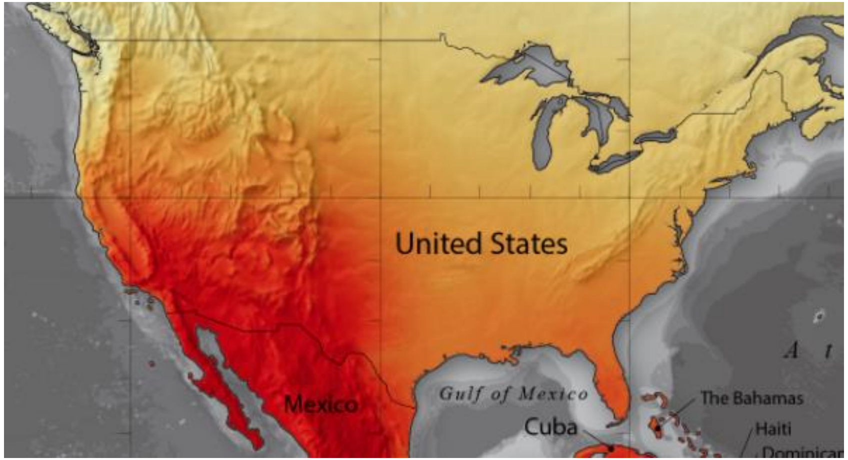
- **PV Cell Temperature**
  - Forced Convection
- **PV Derating Factor**
  - Soiling of Solar Panels
  - Wiring Losses
  - Shading
  - Aging
- **Incident Radiation**
  - Angle of Solar Panels

$$T_c = \frac{T_a + \left(T_{c,NOCT} - T_{a,NOCT}\right)\left(\frac{G_T}{G_{T,NOCT}}\right)\left[1 - \frac{\eta_{mp,STC}\left(1 - \alpha_P T_{c,STC}\right)}{\tau\alpha}\right]}{1 + \left(T_{c,NOCT} - T_{a,NOCT}\right)\left(\frac{G_T}{G_{T,NOCT}}\right)\left(\frac{\alpha_P \eta_{mp,STC}}{\tau\alpha}\right)}$$

Historical Data References

National Solar Radiation Database

- Physical Solar Model v3
  - 4 x 4 km resolution
  - 5 minute intervals
- Data points
  - Date/Time
  - GHI
  - Ambient Temperature



Itemized Budget and Money Spent

System	Item	Price Per Unit	Units	Budget	Total Price
Power	MAXEON Solar Cells	$ 2.79	100	$ 300.00	$ 260.00
Power	Thermal Adhesive	$ 400.00	1	$ 300.00	$ 570.24
Power	Alumium for framing	$ 139.27	1	$ 150.00	$ 116.56
Power	Aluminum Sheet 18x18x0.025	$ 40.12	4	$ 200.00	$ 132.25
Power	1.813" Wide Extruded Aluminum Heatsink - 1 in	$ 0.78	80	$ 90.00	$ 86.22
Power	LifePo4 Smart Lithium Battery	$ 747.95	1	$ 800.00	$ 747.95
Power	ZQ-121006 Outdoor Electrical Enclosure	$ 63.24	1	$ 80.00	$ 63.24
Power	SmartSolar MPPT 75 I 15 charge controller	$ 118.15	1	$ 120.00	$ 118.15
Power	Friction Hinge	$ 20.50	8	$ 150.00	$ 139.36
Active Protection System	Rain Guard Water Sealers SP-2001	$ 43.78	1	$ 55.00	$ 43.29
Active Protection System	Polycarbonate sheets	$ 302.02	1	$ 250.00	$ 302.02
Active Protection System	Custom Corner Guards	$ 58.76	1	$ 75.00	$ 58.76
Active Protection System	Corner Guards from Home Depot	$ 49.88	2	$ 125.00	$ 99.76
Active Protection System	Leveling Feet	$ 19.99	1	$ 20.00	$ 15.99
Active Protection System	screws and building materials			$ 80.00	$ 349.55
WRAITH Recovery	Replacement Sensors			$ 200.00	$ 62.00
WRAITH Recovery	LTE Board***	$ 5.00	1	$ 100.00	$ 97.00
Software	1 TB USB Drive	$ 19.99	1	$ 30.00	$ 19.99
Software	UDOO x86 2.0	$ 276.00	3	$ 250.00	$ 828.00
Active Protection System	Loctite Anaerobic Gasket	15.47	1	$ 20.00	$ 15.47
Active Protection System	Silicone Seal Stripping	10.99	1	$ 15.00	$ 10.99
Power	More Aluminum Tubing	$ 113.38	1	$ -	$ 113.38
Power	Battery Charger	$ 66.26	1	$ 80.00	$ 66.26
Power	Isolation Switch	$ 7.97	2	$ 50.00	$ 15.94
Active Protection System	Silicon Caulk	$ 6.78	1	$ 10.00	$ 6.78

Money Spent by Date and Vendor

Store	Date	Amount
High Tech Battery Solutions	1/8/21	$ 747.95
McMaster Carr	1/8/21	$ 139.27
UDOO	1/8/21	$ 278.00
HeatSink USA	1/11/21	$ 86.22
Midwest Steel and Aluminum	1/8/21	$ 132.25
ePlastics	1/11/21	$ 302.02
Epoxy Technology	1/28/21	$ 303.12
Direct Voltage	1/14/21	$ 279.99
McMaster Carr	1/28/21	$ 113.38
Corner Guard Store	1/25/21	$ 58.76
Amazon	1/19/21	$ 310.11
Allied Electronics	1/28/21	$ 66.25
Amazon	2/9/21	$ 88.78
Home Depot	2/16/21	$ 32.94
Home Depot	2/1/21	$ 106.33
Home Depot	2/16/21	$ (14.86)
McGuckin	2/16/21	$ 48.72
Omega	2/23/21	$ 176.08
UDOO	2/26/21	$ 278.00
DigiKey	2/23/21	$ 108.49
Amazon Return	2/25/21	$ (71.35)
Midwest Steel and Aluminum	3/9/21	$ 34.12
McGuckin	3/9/21	$ 48.37
McGuckin	11-Mar	$ 8.91
Home Depot	3/11/21	$ 72.54
McGuckin	3/16/21	$ (7.18)
McGuckin	3/16/21	$ 12.28
Omega	3/23/21	$ 91.04
UDOO	3/30/21	$ 305.00
Harbor Freight Tools	3/24/21	$ 39.99
The Home Depot	3/31/21	$ 29.76
The Home Depot	3/24/21	$ 20.89
McGuckin	4/6/21	$ 39.57
SparkFun	4/9/21	$ 31.10
DFRobot	4/9/21	$ 62.00