SHADE

Spacial HEO Autonomous Detector & Evaluator

Test Readiness Review

Team

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Sponsor

The Aerospace Corporation

Advisor

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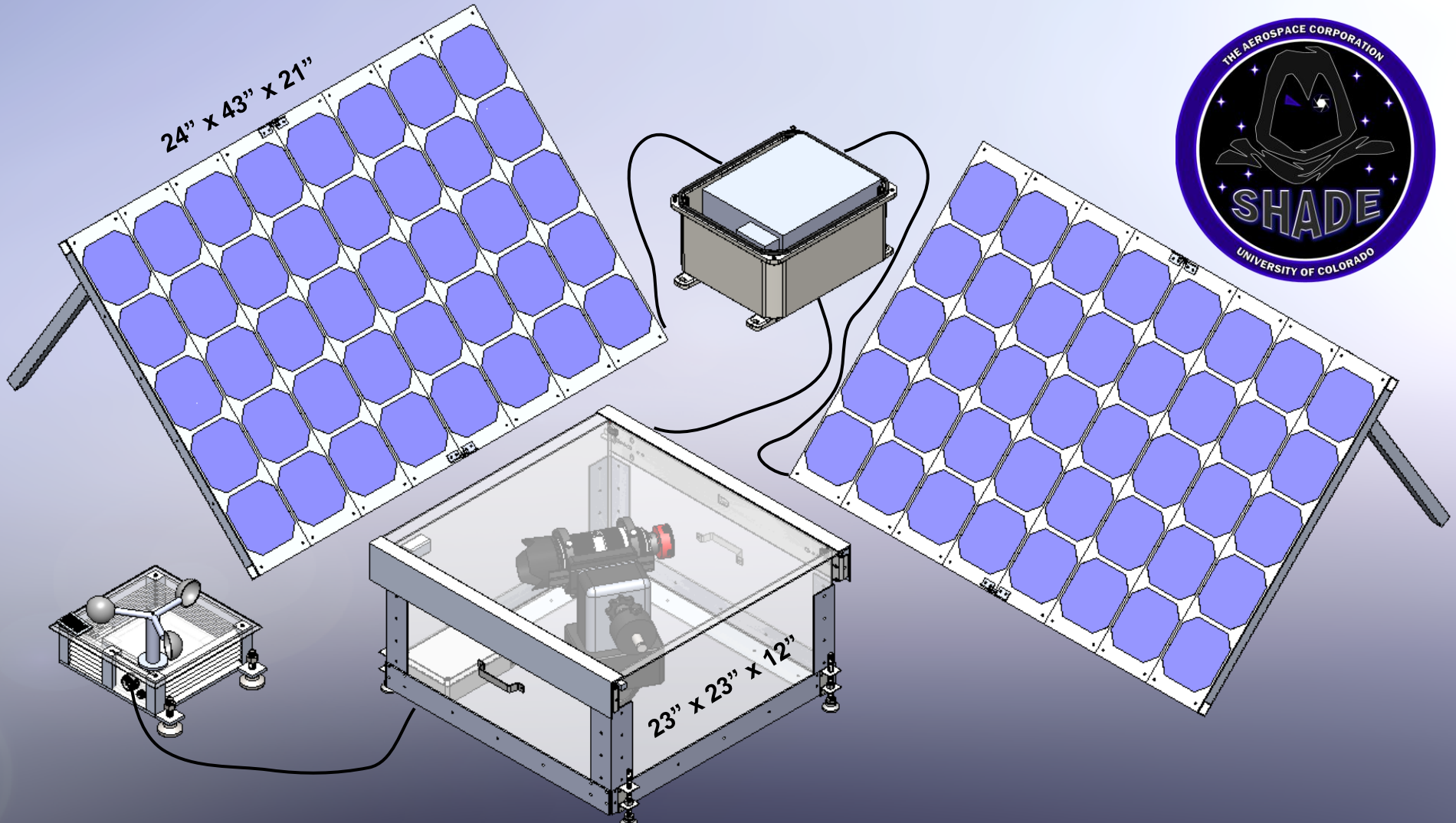
Project Overview

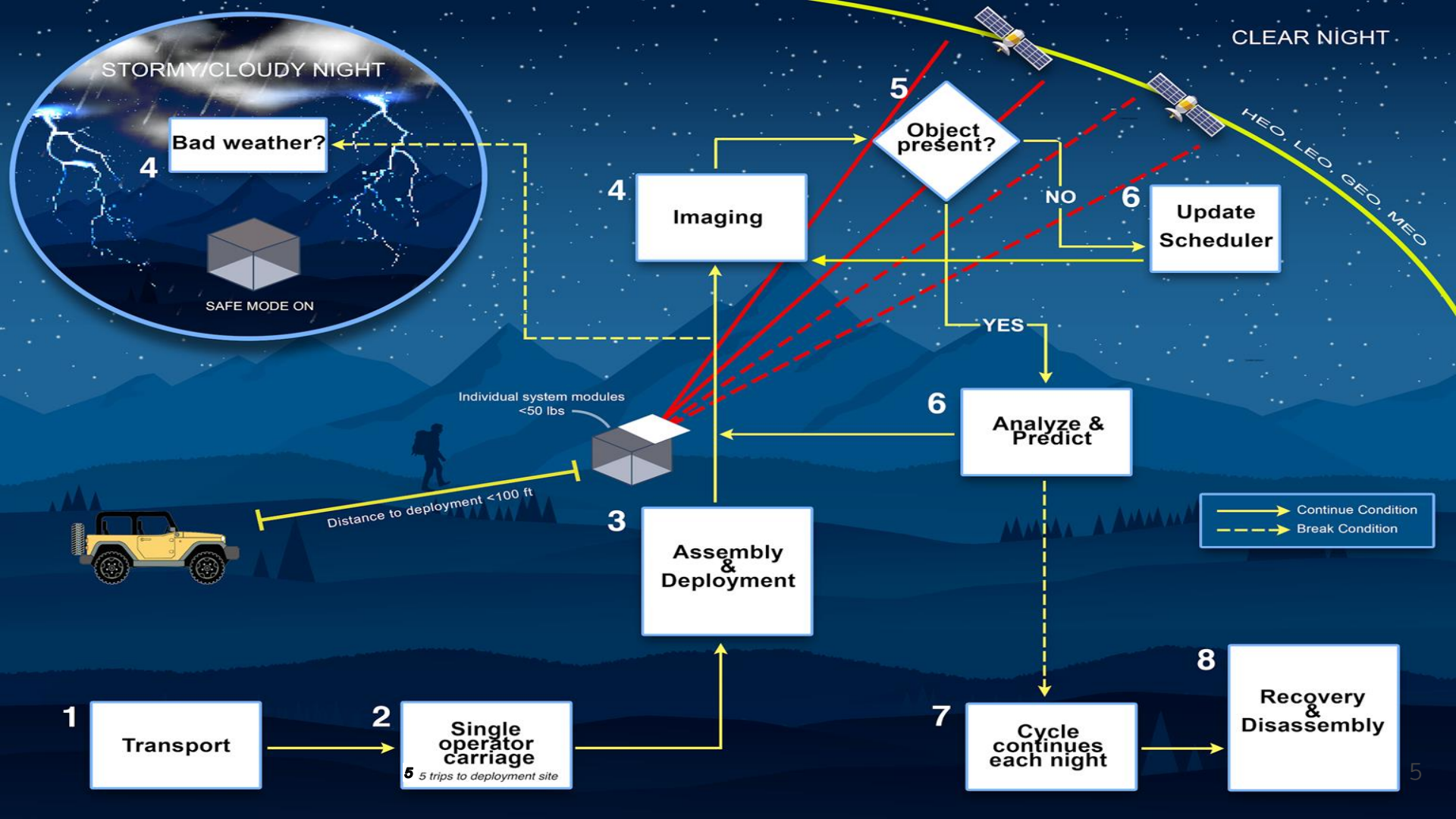
Project Goal

- ★ Increasing amount of Earth-orbiting objects
- ★ Large SSA systems now have an overwhelming number of tracks
- ★ Need inexpensive tracking solution to relieve large systems

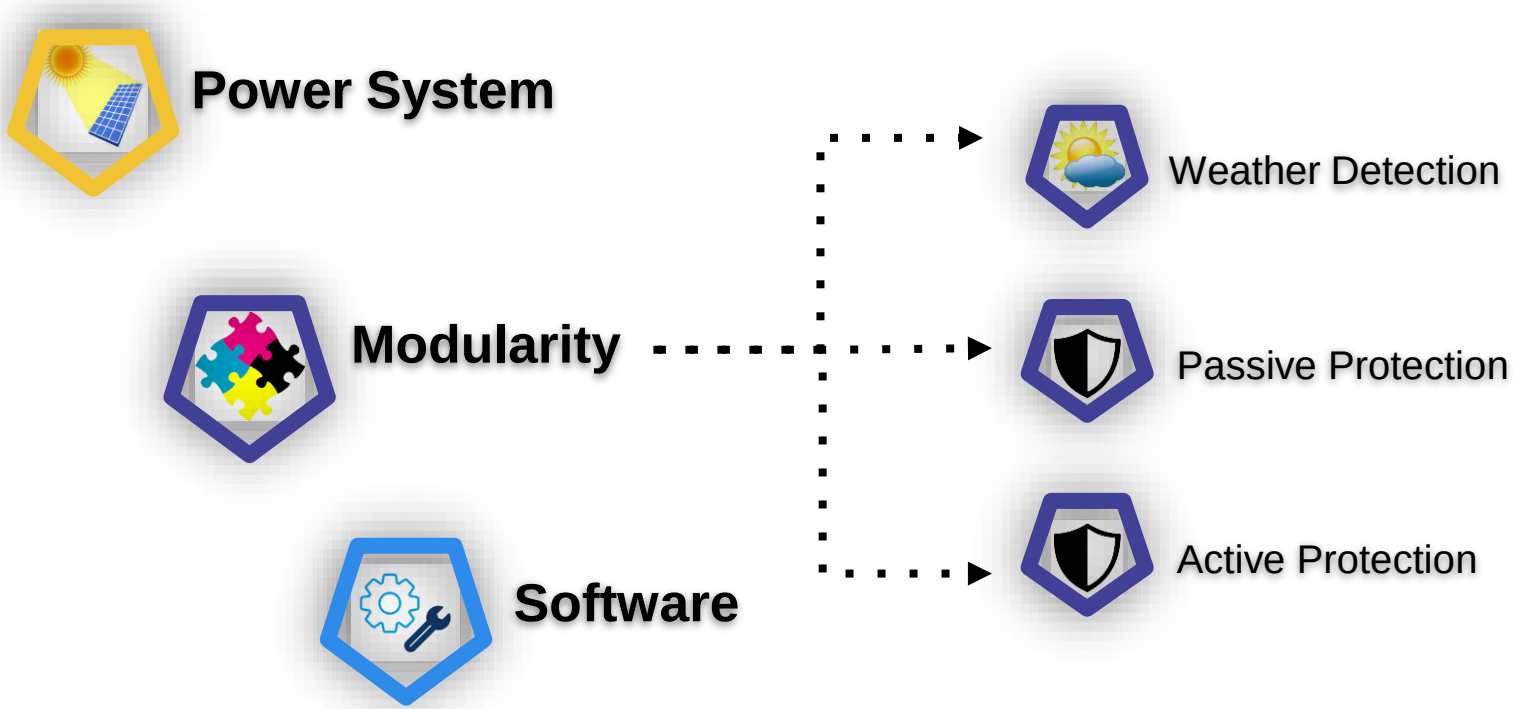
SHADE Mission Statement

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.

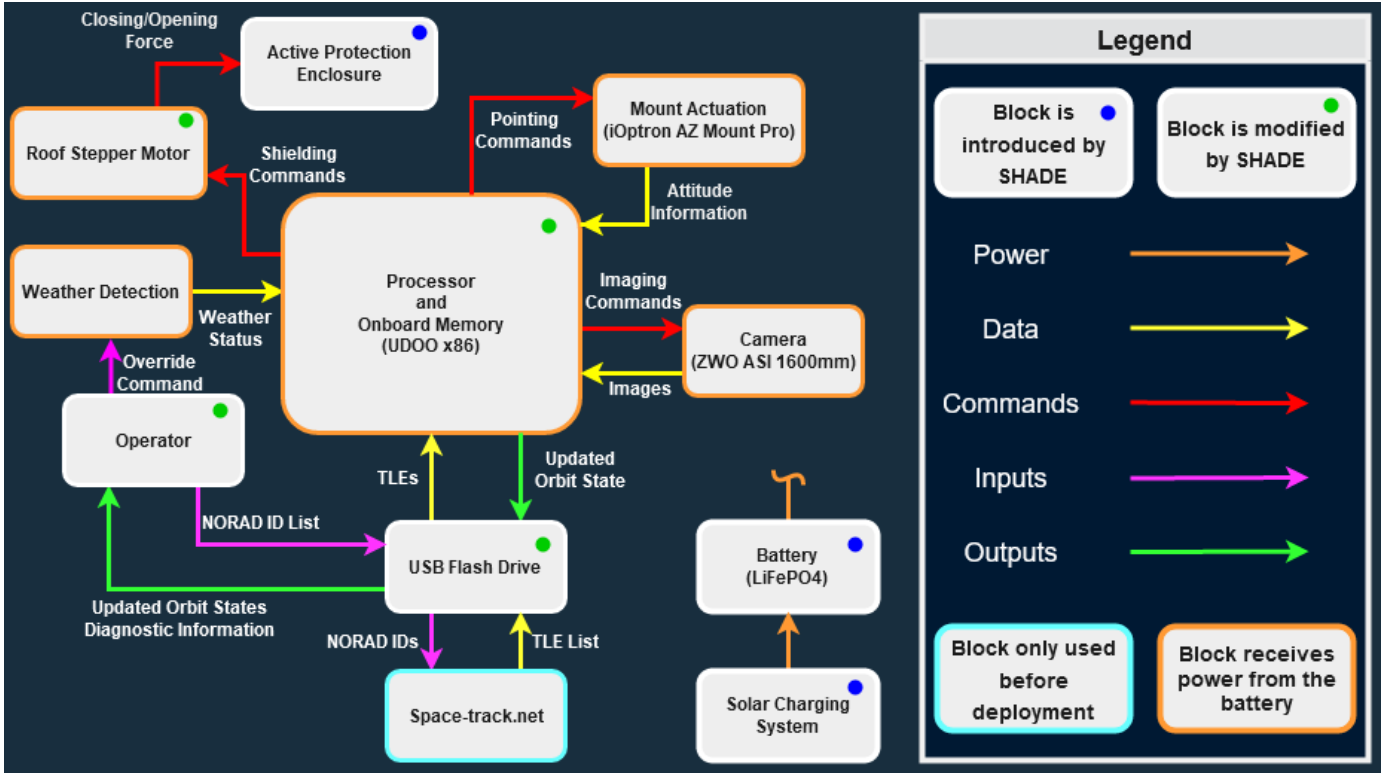

24” x 43” x 21”
23” x 23” x 12”
THE AEROSPACE CORPORATION
SHADE
UNIVERSITY OF COLORADO


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

Critical Project Elements



Physical Block Diagram

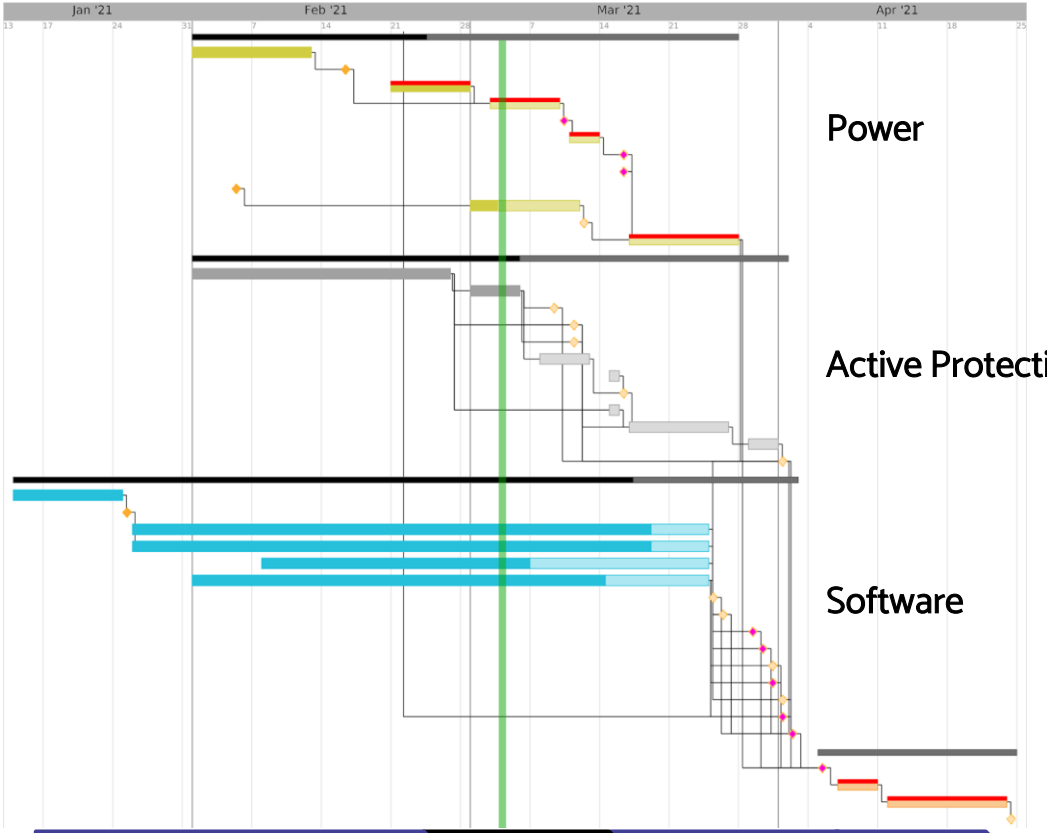


Success for SHADE

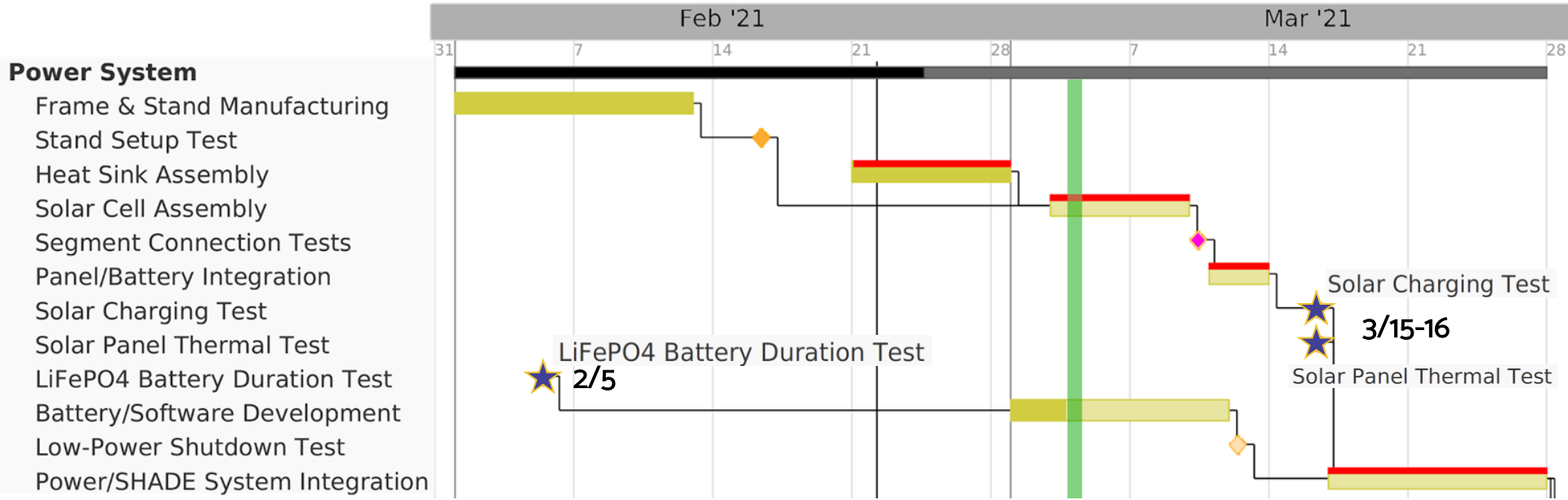
System	Goal
Power (Level 3/3)	• Five nights of continuous operation in SOC • Enters safe mode if power is lost
Modularity (Level 3/3)	• Each module weighs less than 35 lbs • Minimal on-site system assembly
Environmental Protection (Level 3/3)	• Active protection triggered by sensors/remote override • 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

Schedule

Full Spring Semester Schedule

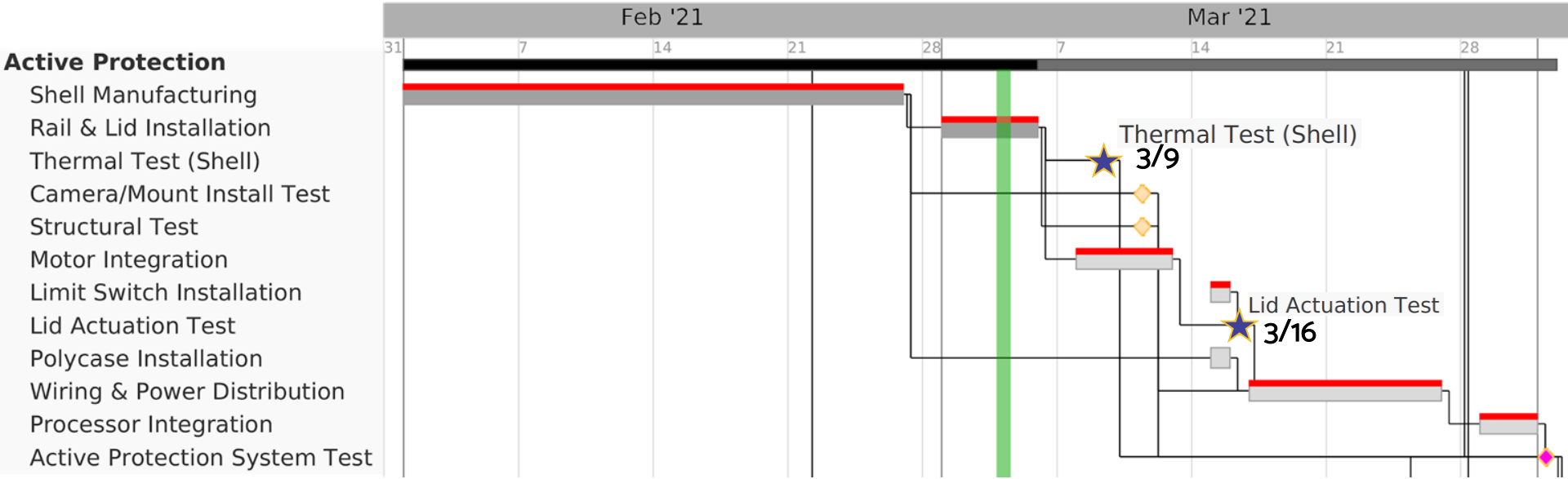


Power System



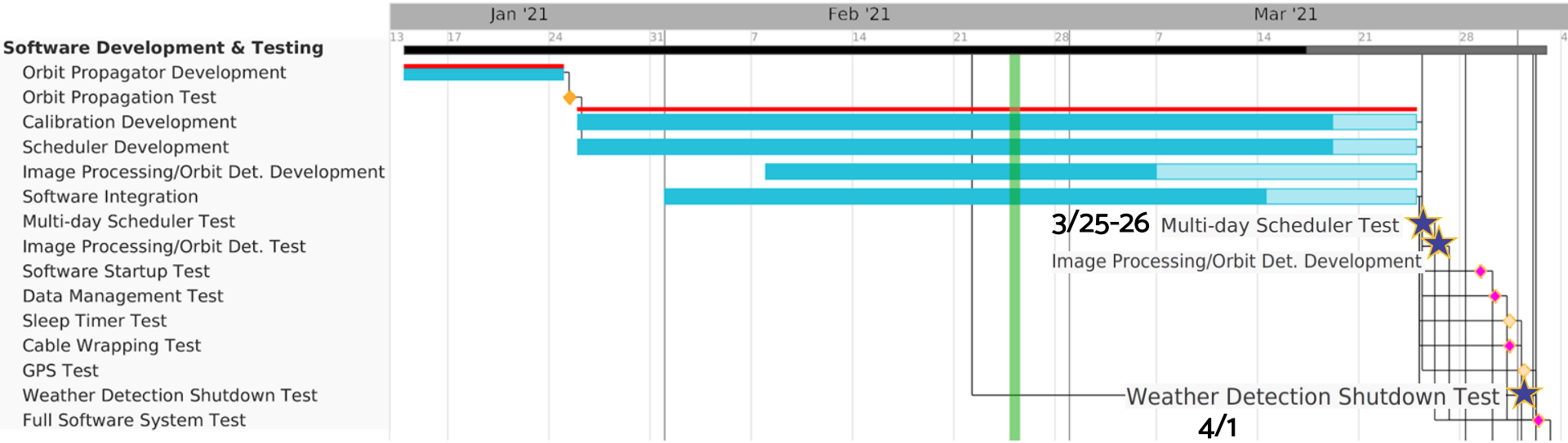
--Test described in detail

Active Protection



★ --Test described in detail

Software Systems

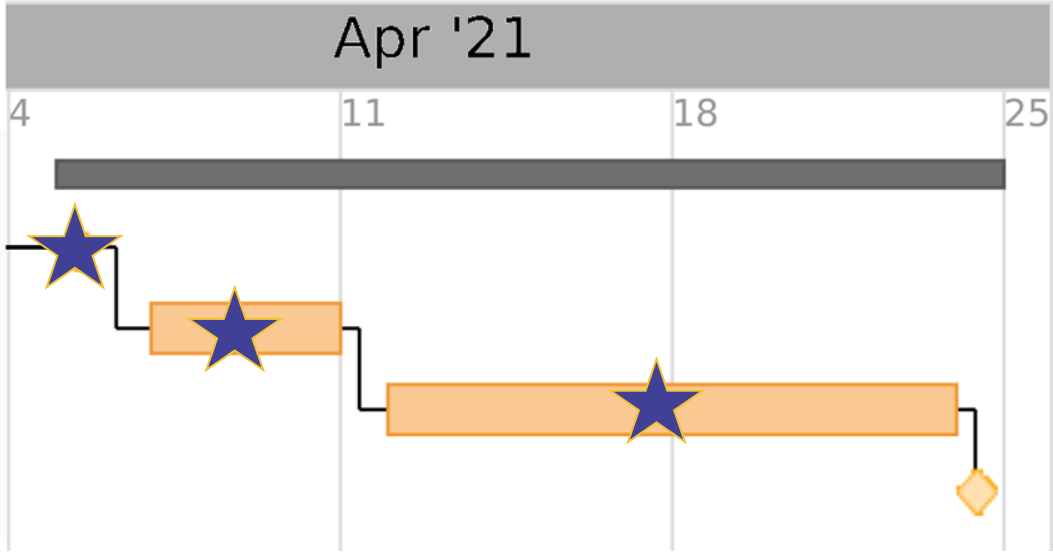


★ --Test described in detail

Full System V&V

SHADE System Final Tests

- 30 Min Deployment Test
- One Night Deployment
- Five Night Deployment
- SHADE Full System V&V



★ --Test described in detail

Test Readiness

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

Full System Tests

30-Minute Transport & Assembly Test

Purpose: Show that SHADE can be transported and deployed by a single operator in 30 minutes.

Requirement Satisfied: FR 7

Facilities: Protected outdoor space

Equipment: Full System, stopwatch, 2 team members

Testing Procedure:

1. Measure 100 ft from vehicle to field
2. Start timer and begin module transport
3. Begin module assembly
4. Conduct power-up sequence of the SHADE system
5. Equalize weather detection sensors
6. After sensor equilibrium, stop timer
7. Power-off and disassemble system modules for transport back to vehicle

FR 7: SHADE shall be deployed and recovered in 30 minutes by one operator.

30-Minute Transport & Assembly Test (cont.)

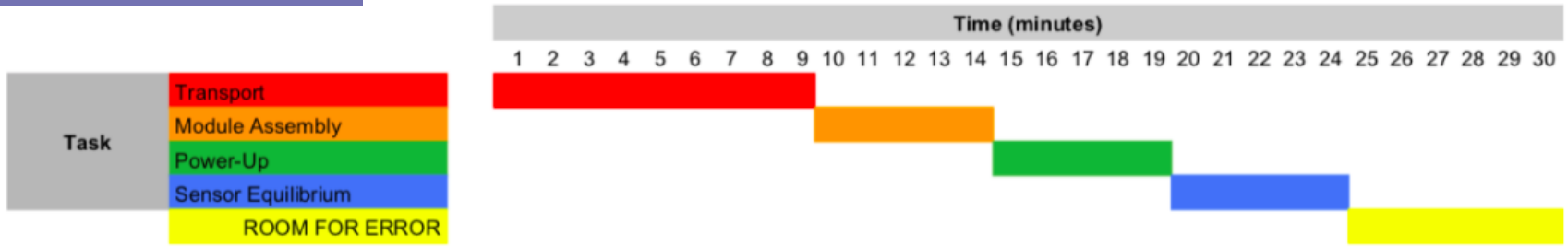
Expected Results:

- A single operator is capable of assembling and deploying SHADE in 30 minutes.
- The initial Time Budget will be altered.

Risk Mitigation:

- Failure to transport, assemble & deploy the SHADE system in 30-minutes.
- Directly related to FR 7

Model Validated:



Single Night Deployment Test

Purpose: Verify that the system is functioning properly for a single night, prior to a multi-night deployment attempt.

Requirements Satisfied: FR 1, 3, 4, 5, 6

Facilities: Protected outdoor space

Equipment: Full System

Testing Procedure:

1. At dusk, SHADE will be deployed in a location with a clear view of the sky.
2. 12 hours later, the operator will return to the deployment site and disassemble SHADE.

***Procedure follows CONOPs, except for 30-minute deployment restriction.**

Expected Results:

- Scheduler determines accurate viewing windows
- Image processing system determines accurate streak endpoints
- Accurate updated TLE list
- Weather detection adequately protects the system
- Battery can endure a full night's deployment
- Note: this assessment does not test the functionality of the solar panels.

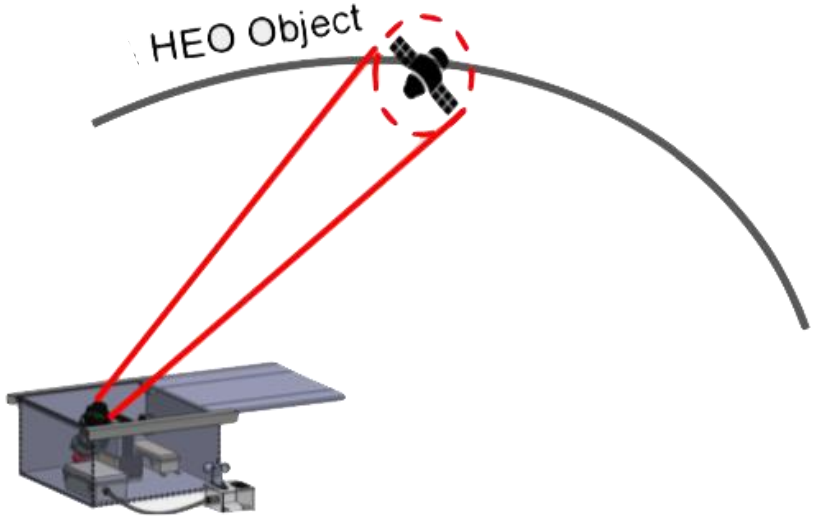
Single Night Deployment Test (cont.)

Risk Mitigation:

- Single Night Deployment failure caused by components other than the solar panels

Models Validated:

- Battery can endure a full night's deployment
- Orbit propagation and determination



Multi-Night Deployment Test

Purpose: Following a single night deployment attempt, a multi-night deployment test will verify the functionality of solar panels and ability to schedule multiple night observation windows..

Requirements Satisfied: FR 1-8

Facilities: Protected outdoor space

Equipment: Full System

Testing Procedure:

1. At dusk, SHADE will be assembled in a location with a clear view of the sky.
2. An operator will deploy the system and depart
3. 36 hours later, the operator will return to the deployment site and disassemble SHADE.

Expected Results:

- Single night deployment results achieved
- Weather detection adequately protects the system
- Solar panels are able to charge battery for the following night

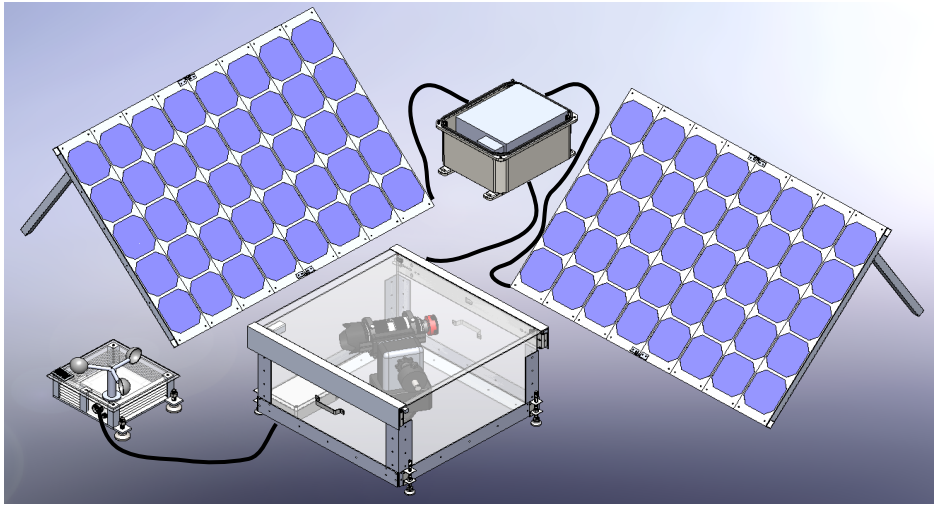
Multi-Night Deployment Test (cont.)

Risk Mitigation:

- Multi-Night Deployment failure caused by components such as the solar panels

Models Validated:

- Solar Panels can charge the battery for full night of deployment
- Weather Detection Safe Mode trigger logic



Power Tests

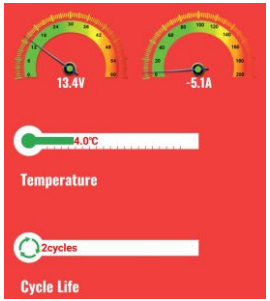
Battery Duration Test

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:

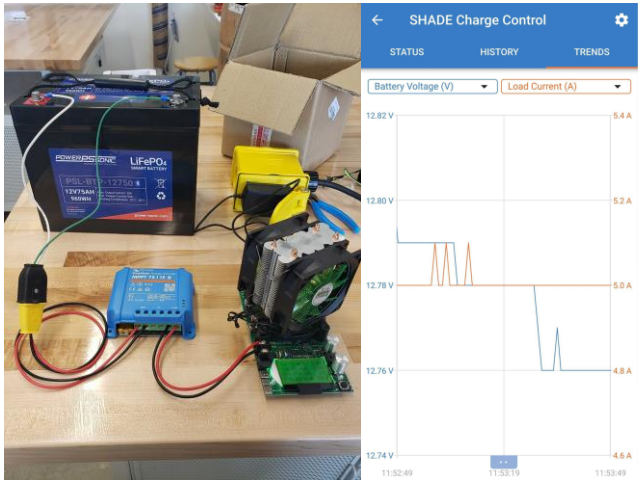
- Battery shall start with a full charge
- Cycle tester draws 5 A over an 11-hour period, ultimately drawing **55 Ah**
- Monitoring the voltage of the battery over the course of the test allows analysis of the discharge curve
- Similarly, monitoring the rate of change of the capacity will characterise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

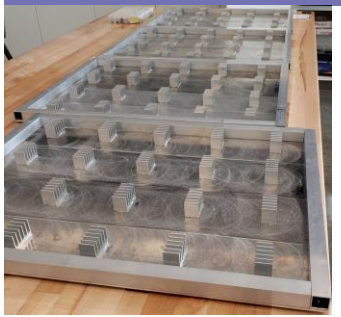
Solar Charging Test

Purpose: To assess that the solar panels have been manufactured correctly and are functioning properly.

Requirements Satisfied: FR 2, 4, 7, 8

Equipment: Multimeter, VictronConnect

Facilities: Outside



Testing Procedure:

- The battery before deployment will be at a battery capacity 80%
- The solar panels shall be deployed on a clear, sunny day between 1130 to 1530.
- Utilize Multimeter and VictronConnect to record power generation and battery voltage throughout deployment

Solar Charging Test (cont.)

Expected Results:

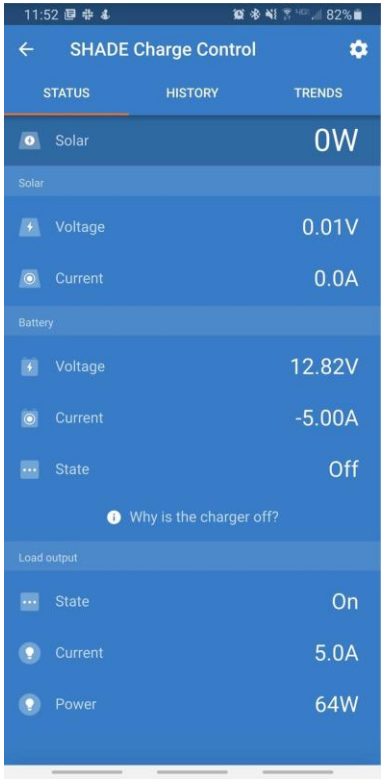
- Power generation and open-circuit voltage would closely match between the theoretical model and the test data
- Solar Cells will not short

Risk Mitigation:

- Continual power source
- Able to perform on days without clouds (Risk ID **SOC**)
- Solar cells do not contact the backplate (short out)

Models Validated:

- Solar charging model



Thermal Solar Cell Test

Purpose: To assess the effectiveness of the coupled heat sinks.

Requirements Satisfied: FR 2, 8

Equipment: IR Camera, Ambient temperature sensor

Facilities: Open outdoor area

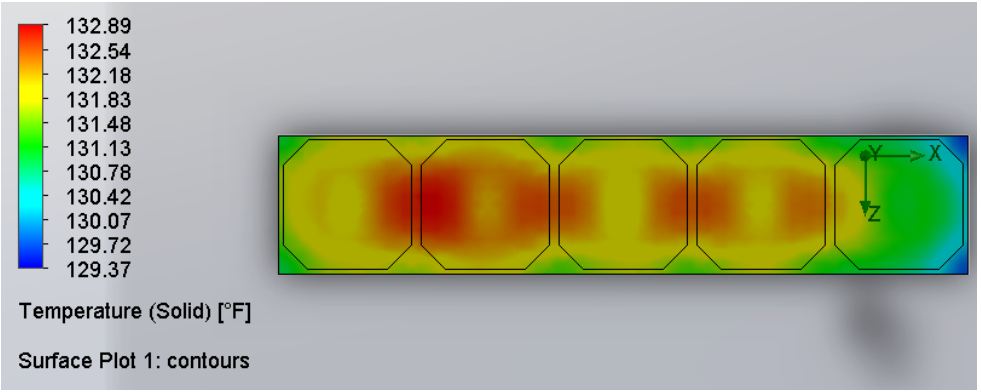
Testing Procedure:

1. Record open circuit voltage of the test pieces prior to the test
2. Record ambient temperature and solar cell temperature at 30 min intervals
    a. Use IR camera to capture heat sink temperatures, solar cell face temperatures
3. Record open circuit voltage at the end of the test
4. Build SolidWorks model using testing day's data to compare to the empirical data

Thermal Solar Cell Test (cont.)

Expected Results:

- Solar segments with Heatsinks are observed to be at a lower temperature compared to those without heat sinks
- IR camera temperature contours match similarly with SolidWorks model



Risk Mitigation:

- Failure to fully recharge battery after a full night's deployment
  - Solar charging dependent on solar cell temperature

Models Validated:

- SolidWorks Thermal Model

Active Protection Tests

Lid Actuation Test

Purpose: To verify the operation of the roof motor and gear system of the active protection box.

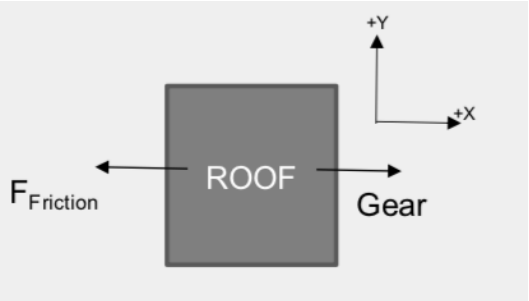
Requirements Satisfied: FR 3

Equipment: Active protection box, UDOO, Motor controller & roof motor

Risks Mitigated: Timely roof actuation protects against quickly developing precipitation (Risk ID **RCR**)

Testing Procedure:

- Observe whether or not lid glides smoothly on slides
- Observe whether or not the lid is able to open and close completely
- Verify that the lid can open/close in 10 seconds. (success criteria imposed by WRAITH)



Motor Specification Model:

$\Sigma F_x = ma_x$

$F_{Friction} = N\ \mu_{static}$

$F_{Friction} = N\ \mu$

$a = \alpha R$

$T = I\alpha$

$T_{required} = 146$ [oz in]

Gear Rate Model:

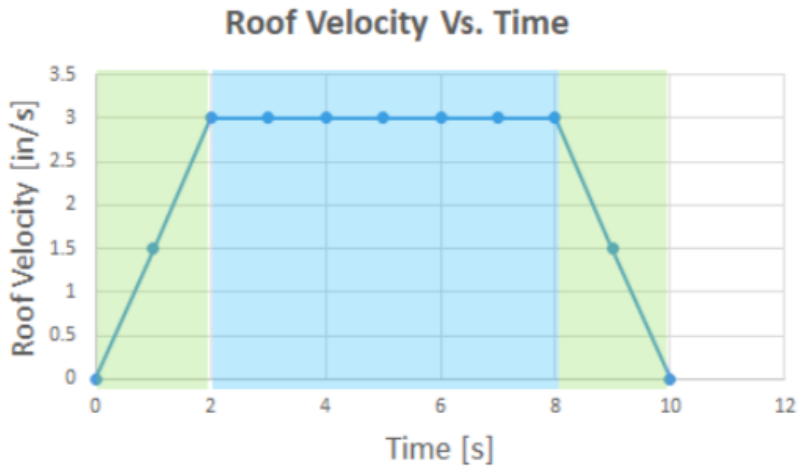
24 Teeth/Revolution

5 Teeth/Inch

24 Inches of Travel

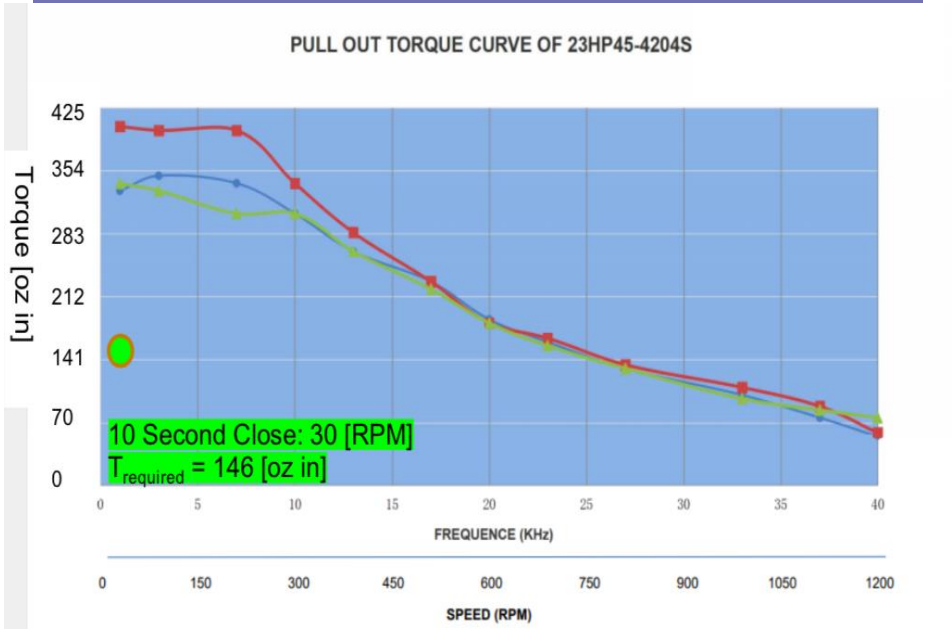
10 Second Close: 30 [RPM]

Lid Actuation Test (cont.)



Initial Testing (WRAITH)

- 125 [oz in] motor actuated roof at 1 [in/sec] reliably



Expected Results:

- The lid will open/close in 10 s
- The lid will open/close completely

Thermal Test

Purpose: To verify that the internal temperature of the active protection enclosure does not exceed or fall below the material and component temperature limits.

Requirements Satisfied: FR 3

Equipment: 2 ambient thermometers, 1 wall temperature sensor, 1 barometric sensor, 1 pyrheliometer, empty active protection enclosure.

Facilities: Sunny outdoor location.

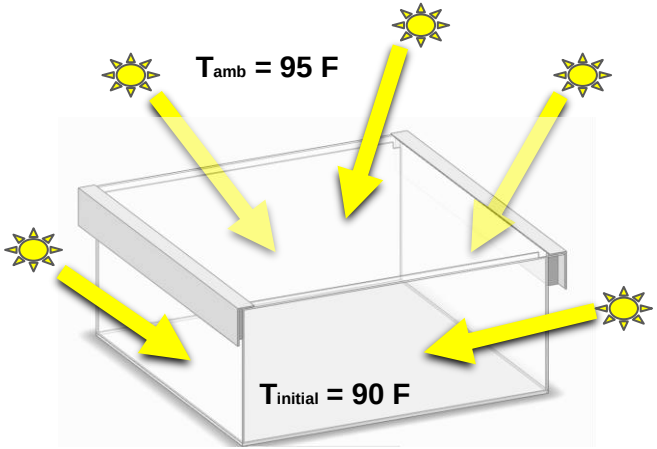
Testing Procedure:

1. Set up assembled active protection enclosure in sunny area with open roof.
2. Wait 1 hour.
3. Close the roof and record temperature, solar, and pressure parameters.
4. After 3 hours, repeat Step 3 and clean up.
5. Input initial temperature, pressure, and solar flux conditions into thermal model.
6. Rerun thermal analysis. Compare results of thermal model with experimental test.

Thermal Test (cont.)

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 then be used to predict other environments.

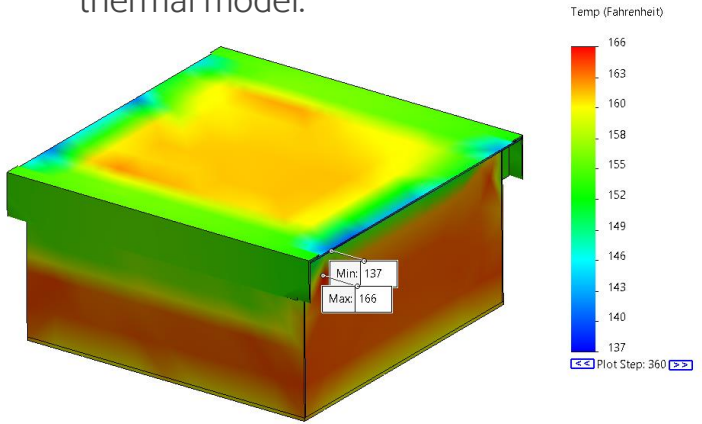


Risk Mitigation:

- Extreme (high/low) temperatures prohibiting component functionality (Risk ID **DIH**)

Models Validated:

- Solidworks active protection enclosure thermal model.



Weather Detection Test

Safe Mode Trigger Test

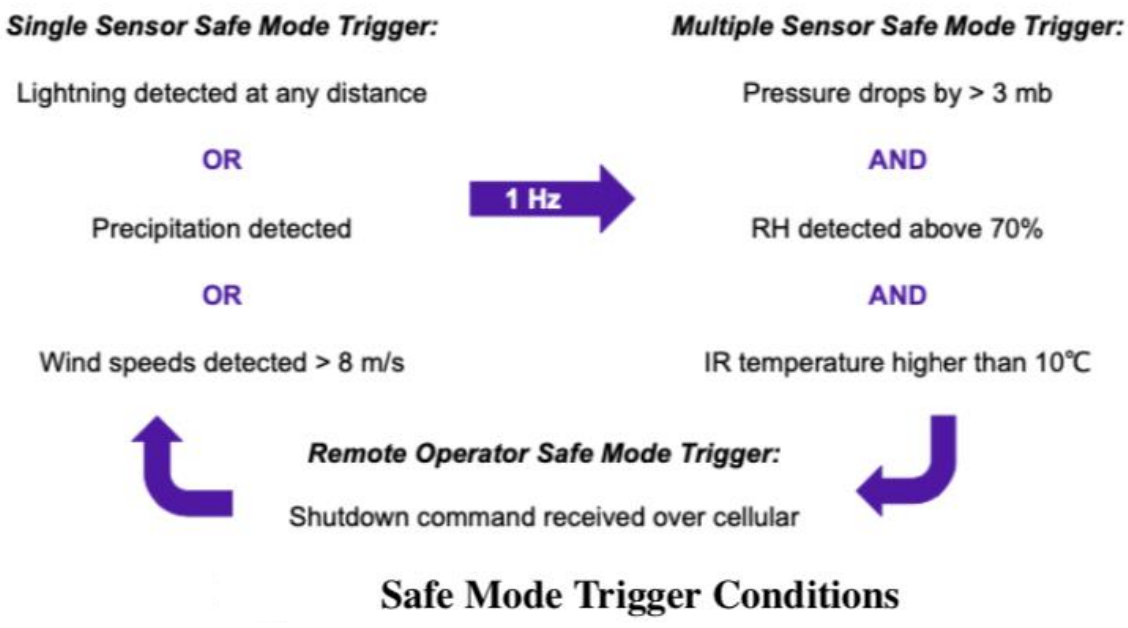
Purpose: To ensure each weather shutdown case triggers the appropriate signals, accurately telling the system to enter or exit safe mode.

Requirements Satisfied: FR 3

Equipment: Weather Detection Box, Battery, Computer

Expected Results: Sensor trigger response matches human observation

Risk Mitigation: Verifying proper trigger response
(Risk IDs **WDC** & **WFT**)



Safe Mode Trigger Conditions

Software Tests

Image Processing Test

Purpose: To assess the functionality of SHADE's streak detection algorithms.

Requirements Satisfied: FR 5

Equipment: Computer

Facilities: N/A

Testing Procedure:

1. Create images with synthetic streaks and known RA-Dec coordinates of those streaks.
2. Upload images with synthetic streaks to the computer.
3. Run the image processing function to determine RA-Dec coordinates, recording the time taken.

FR 5: SHADE shall image objects with apparent magnitude of less than 10.

Image Processing Test (cont.)

Expected Results:

- RA-Dec coordinates will coincide with known values from synthetic streaks.

Risk Mitigation:

- Image processor improperly identifying streaks
- Image processor identifying the wrong streak if there are multiple streaks. (Risk ID **SLS**)

Models Validated:

- Hough Transform for Image Processing

Scheduler Test

Purpose: To assess the functionality of SHADE's scheduler process, including orbit propagation, and target prioritization.

Requirements Satisfied: FR 1

Equipment: Computer

Facilities: N/A

Testing Procedure:

- Define multiple TLEs, a location, and a time to test.
- Call the scheduler with the defined TLEs, location, and time.
- Record passes output by the scheduler.
- Run scheduler again for multiple night deployment

FR 1: SHADE shall schedule predicted locations and locations and visibility windows for objects in LEO, MEO, GEO and HEO orbits.

Scheduler Test (cont.)

Expected Results:

- Scheduler outputs a schedule for one night.
- Viewing opportunities align with SGP4 propagation.
- If this is not the first night, scheduler de-prioritizes objects that have already been imaged.

Risk Mitigation:

- Verifying ability to prioritise objects with less stable orbits. (Risk ID **TOI**)

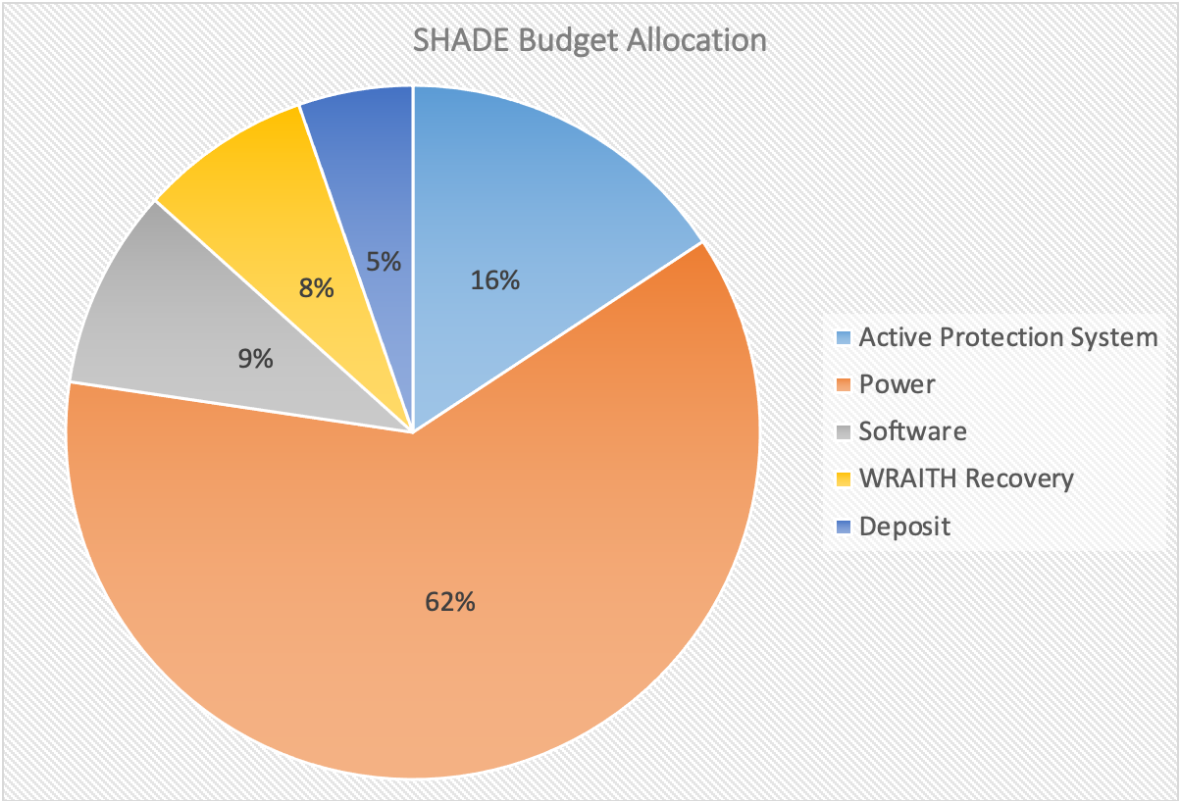
Budget

Updated Budget

Subsystem	Estimated Cost	Budget	Margin
Active Protection	$434.90	$590.00	16%
Power	$2,023.70	$2,310.00	11%
Software	$313.98	$350.00	10%
Legacy	$94.00	$300.00	75%
Deposit	$200.00	$200.00	0%
Total	$3,093.07	$3,750.00	17%

Updated Budget

Subsystem	Budget
Active Protection	$590.00
Power	$2,310.00
Software	$350.00
WRAITH Recovery	$300.00
Deposit	$200.00
Total	$3,750.00



Item	Subsystem	Status
Battery	Power	Received
Battery Charger	Power	Received
Aluminum backplate sheets	Power	Received
Aluminum tubing for frame	Power	Received
Thermal Epoxy 1	Power	Received
Thermal Epoxy 2	Power	Received
Heat Sink	Power	Received
Charge Controller	Power	Received
Friction Hinge	Power	Received
Isolation Switch	Power	Pending
Thermal Reflective Paint	Active Protection	Received
Anaerobic Gasket	Active Protection	Received
Silicon Seal Strip	Active Protection	Received
Custom Corner Guards	Active Protection	Received
Corner Guards	Active Protection	Received
Polycarbonate Sheets	Active Protection	Received
Leveling Feet	Active Protection	Received
Box Handles	Active Protection	Pending
UDOO Processor	Software	Received
Particle Weatherboard	Software	Received

Budget Comparison

Budget: $3,750.00

Total Spent: $3,255.31

Purchased **95%** of budgeted items, using **65%** of funds


Questions?

Additional Slides

Project History

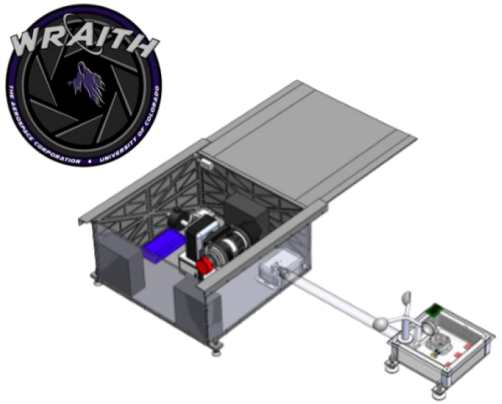
2018/19

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

Foundation systems for autonomous imaging of circular LEO and MEO objects

Validated with ISS tracking tests

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

Levels of Success

Category	Level 1	Level 2	Level 3
Scheduling [WRAITH]	• Accept NORAD Satellite IDs • Sort based on time, visibility, field of view • 6 objects per hour	• Prioritize scheduling by image capture probability or human override	• Search for missing objects and send alert
Image Processing [WRAITH]	• Extract endpoints of streaks • Signal to noise ratio of 30 or less	• Identifies when a target object is missed	• Camera maneuvers to find missing object
Orbital Determination [WRAITH]	• Accurate orbit determination using Batch filter	• Level 1	• Predict possible orbits for missing objects
Pointing [WRAITH]	• Track HEO orbits near apogee (GEO)	• Track HEO orbits near perigee (LEO)	• Search for missing objects using possible locations

Levels of Success

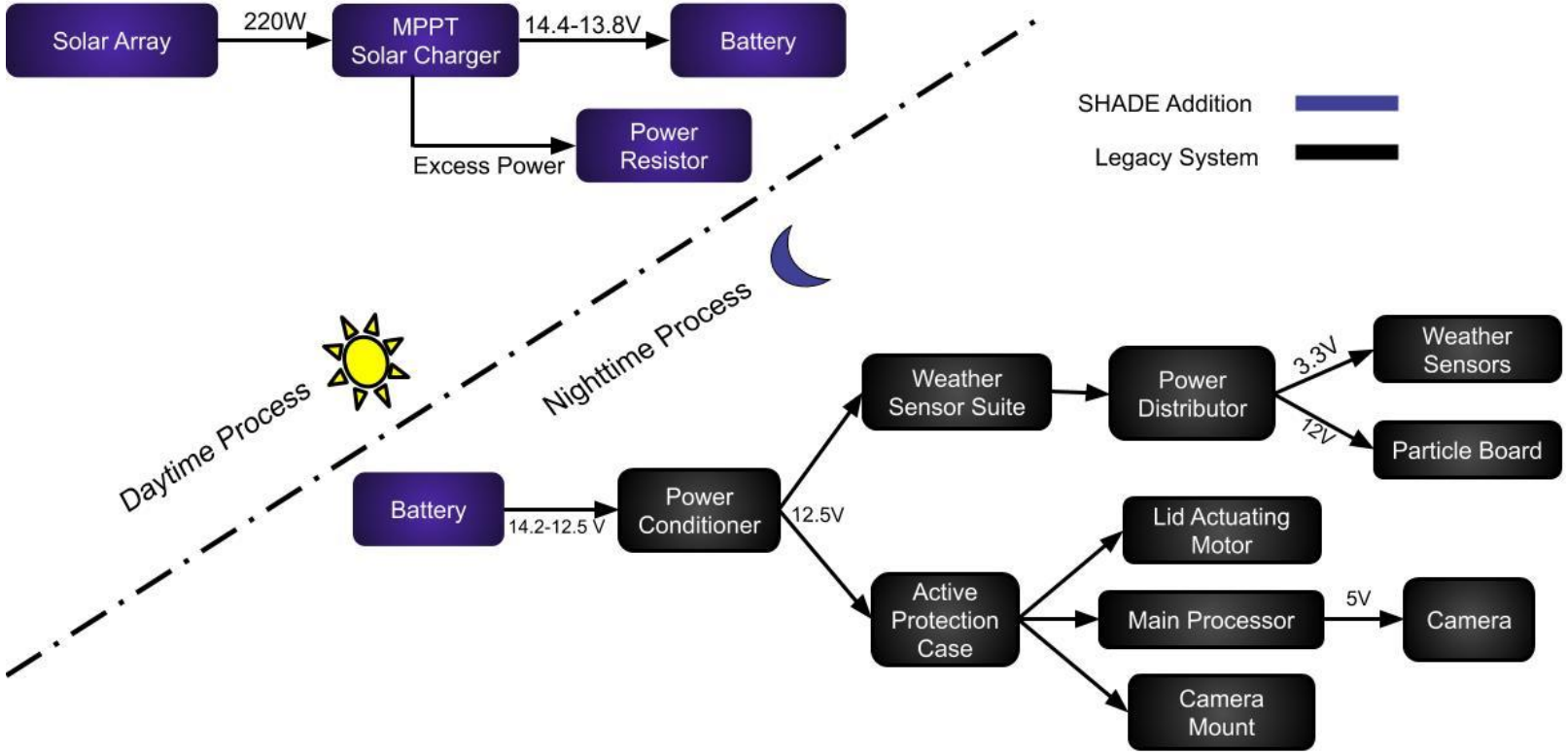
Category	Level 1	Level 2	Level 3
Environmental Control [WRAITH]	• Initiate protection from on-board sensors. • Protection from light rain/wind.	• Level 1	• Initiate protection in accordance with remote override. • Update weather & system status to ground station
Modularity	• Module weight under 50 lbs • On-site system assembly is required	• Level 1	• Module weight under 35 lbs • Minimal required on-site system assembly
Power Efficiency	• Operates autonomously for two nights	• Operates autonomously for three nights	• Operates autonomously for five nights

Satisfaction of Functional Requirements

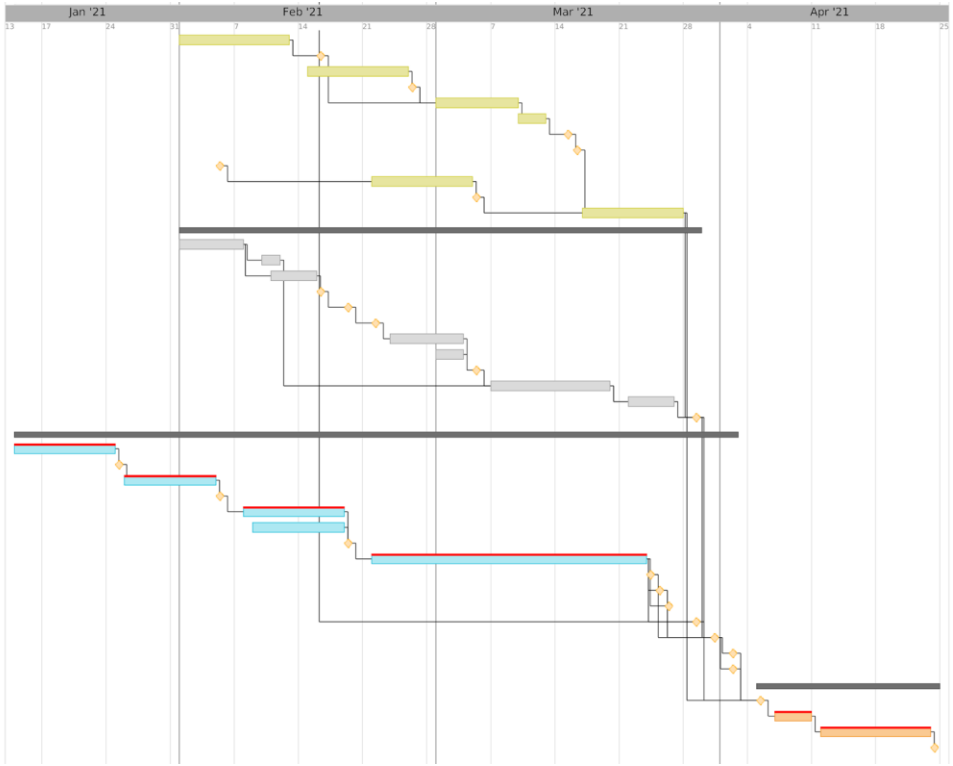
Functional Requirement	Relevant Tests	Additional Satisfaction
FR 1: SHADE shall schedule predicted locations and visibility windows for objects in LEO, MEO, GEO,and HEO orbits.	*Single Night Deployment, Multi-Night Deployment, Orbit Propagation, Week-Long Scheduling*	Accurately predicts locations and 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

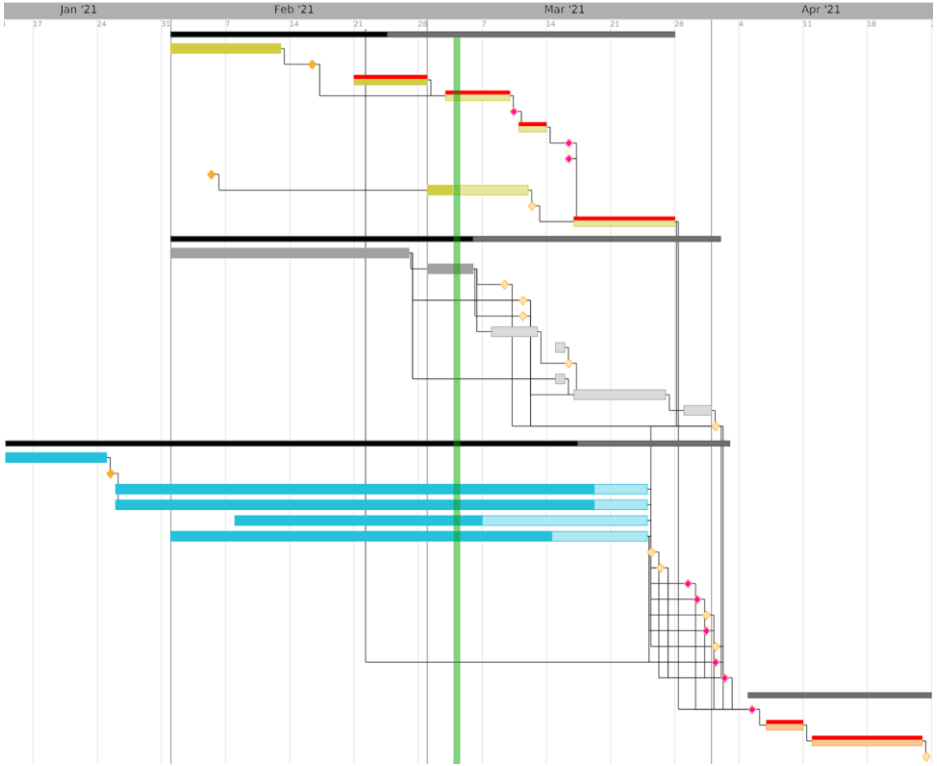
Functional Requirement	Relevant Tests	Additional Satisfaction
FR 5: SHADE shall image objects with apparent magnitude of less than 10.	*Image Processing*	-
FR 6: SHADE shall create and save an orbit estimate for each object imaged within five minutes of the end of the associated visibility window.	*Single 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*	-

Power System FBD



Spring Schedule - MSR to TRR





New Imaging System (Streak Detection)

Old System: Matched Filter

(Find where template matches image)

- Requires a “blank” image
- Can only detect single point
- Prone to false positives

New System: Hough Transform

(Detect features, i.e. lines, in image)

- Only one image required
- Can detect both endpoints
- Independent of orbit estimate

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

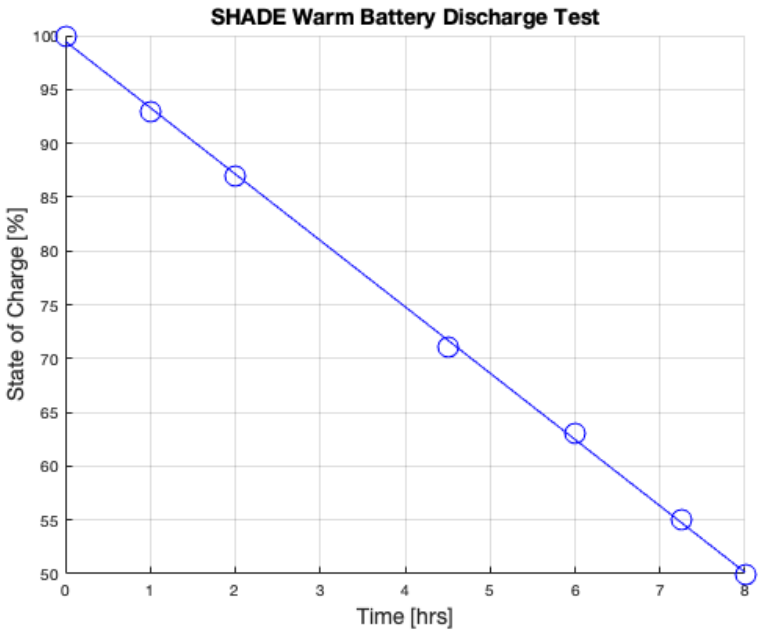
Management Risks - Post Mitigation				
Risk	Risk ID	Likelihood	Recoverability	Severity
Single Point Failure	SPF	2	4	8
Schedule Slip	SLP	3	2	6
Schedule Driven Progress	SDP	2	2	4
Intra-Team Communication	ITC	3	1	3
Resource Management	RMA	2	2	4

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

Preliminary Battery Discharge Rates



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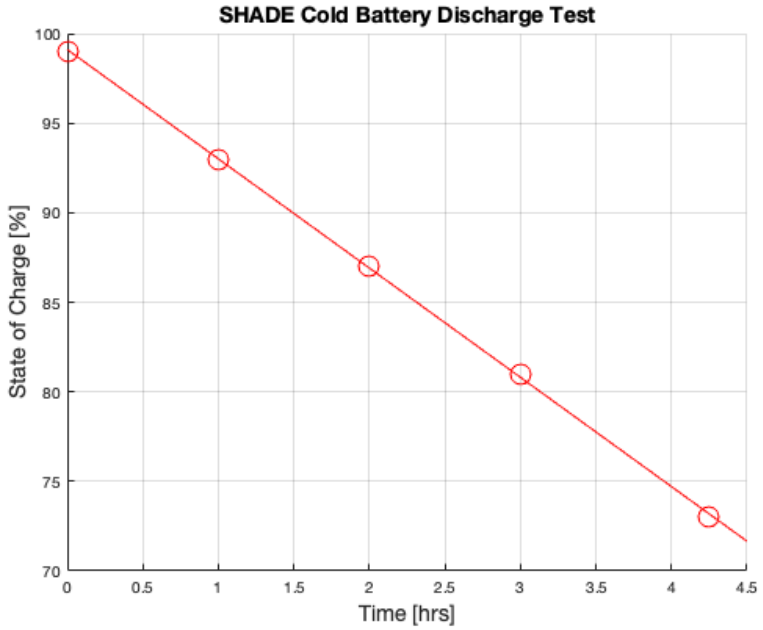

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