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Conceptual Design Document (CDD)

Spacial HEO Autonomous Detector & Evaluator (SHADE)

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Project Customers

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Contents

I. Project Description

A. Purpose

As of April 1, 2020, 2,666 satellites orbit the Earth[2], with the global satellite industry generating almost $280B in revenue. The European Space Agency predicts the "space highways" above the Earth will become more congested than ever, threatening orbital collisions. To prevent these types of errors, Space Situational Awareness (SSA) systems collect optical and radar data to track and characterize the orbital environments. To reduce orbital congestion,many satellites are placed in Highly Elliptical Orbits (HEOs), rather than Geostationary Earth Orbits (GEOs).

A HEO is an orbit with its Perigee in Low Earth Orbit (LEO) and Apogee above LEO. These orbits have high eccentricity, which gives them the advantage of achieving lengthy dwell times over specific points on the Earth. Additionally, many rockets and satellites are disposed in HEO to comply with de-orbit regulations. While HEOs have many advantages and applications for communication and safe disposal, their reentry orbits are difficult to predict with conventional observations or algorithms. For this reason, timely and accurate reentry predictions have implications for liability, recovery, safety, and security. As a result the Aerospace Corporation receives requests from the SSA community to predict reentries; however, current prediction methods are difficult and expensive. To mitigate this issue,the Aerospace Corporation seeks a low-cost and efficient ground-based sensor to track HEO reentry profiles.

Two previous senior design projects (WRAITH and GHOST) sought to fill this need. GHOST was designed to autonomously detect and track satellites in GEO, MEO and LEO, and make orbital predictions based on the tracking images. WRAITH sought to build upon GHOST by tracking objects in HEOs, operating autonomously for 12 hours, and making the system deployable by two people in less than 30 minutes. Because of the coronavirus pandemic, WRAITH's project ended on March 13, 2020, without completing the project. Both GHOST and WRAITH were tested at component levels, though neither demonstrated full, autonomous operation at a system level.

The Spacial HEO Autonomous Detector and Evaluator (SHADE) project will continue the design and development of the partially unfinished and untested WRAITH system. In its current state, WRAITH is large, bulky, and difficult to assemble and deploy within 30 minutes. SHADE will enable the existing orbit tracking sensor to track LEOs, MEOs, GEOs and HEOs and will improve upon its portability, durability and ease of use. SHADE's modifications will allow a single operator who is unfamiliar with the system to deploy SHADE within 30 minutes. A solar power system will enable SHADE's deployment to last more than the current 12 hours possible through WRAITH, autonomously. Finally, SHADE's modifications will be restricted to a budget of $5000; thus, providing and economical solution for the SSA community to accurately predict the reentry trajectories of HEOs.

These modifications will require significant hardware and software re-designs. SHADE's power system will be completely re-designed, allowing for the implementation of solar power. The entire system will be deployed by a single operator in less than thirty minutes, however the system in its current state weighs more than the 50 lbs limit set by OSHA for a single operator. WRAITH's existing software requires command line inputs, which can be time consuming, thus SHADE's software must also be re-designed.

B. Project Objectives

Several of the following levels of success carry over from the final report of the WRAITH project. Since WRAITH is incomplete as of the end of the project, the carry-over levels of success may be amended once the capabilities of the system are determined.

Table 1 Levels of Success

Category	Level 1	Level 2	Level 3
Scheduling	Accept list of NORAD satellite IDs and sort based on field of view (FOV), time, and visibility constraints. Capability for up to 6 objects per hour. [WRAITH]	Prioritize objects according to human input or probability of image capture. [WRAITH]	Adjust schedule to search for a missing or maneuvered object, and issue an alert when this occurs. [WRAITH]
Image Processing	Extract endpoints of streaks at photometric signal-to-noise ratio (SNR) of 30 or less. [WRAITH]	Level 1.	Determine missing space object or the camera will maneuver to find the object. [WRAITH]
Orbital Determination	Accurate orbit determination using Batch filter. [WRAITH]	Level 1.	Predicting possible orbits for missing objects. [WRAITH]
Pointing	Tracking HEO orbits near apogee (GEO). [WRAITH]	Tracking HEO orbits near perigee (LEO). [WRAITH]	Search for missing objects using predicted possible locations. [WRAITH]
Environmental Control	Retract environmental protection in accordance with onboard sensors. Safety hardware will protect against light rain, wind, and a TBD temperature range. [WRAITH]	Level 1.	Retract environmental protection in accordance with remote override from operators. Updates ground station with environmental state and safety hardware status. [WRAITH]
Modularity	One operator deploys all modules that each weigh 50 lbs or less. On-site system construction is required after transportation but before deployment.	Level 1.	One operator deploys all modules that each weigh 35 lbs or less. There is minimal required on-site assembly.
Power Efficiency	Demonstrate full, autonomous operation for two nights.	Demonstrate full, autonomous operation for three nights.	Demonstrate full, autonomous operation for five nights.

The requirements and levels of success in this table were created according to the design group's best knowledge of the existing system. Because of the current challenges, including the lack of documentation and limited abilities to access WRAITH, the team has not been able to test the system. As the design team develops more familiarity with WRAITH, the design requirements and levels of success may change. Though the team would like to set requirements to limit the scope of the project as early as possible, these modifications are not yet possible given the current nature of the project.

1. Levels of Success: Clarifications

The Level 1 levels of success for scheduling and orbit determination require SHADE to track six objects per hour and use a batch filter for object orbit determination, respectively. The system's tracking capability is a legacy requirement from the WRAITH and GHOST projects. During these past projects, the customer desired the system to track at least six objects within the hour; therefore, the minimum success level would be achieved if six objects are tracked by SHADE. Additionally, Functional Requirement (FR) 6 states that the system shall process an object's location prediction within five minutes of the end of the visibility window. This requirement implies that the system can image up to 12 objects per hour under an optimal distribution of objects within the schedule. A safety factor of two was applied to this requirement to account for various exposure and slewing times between observation attitudes for this first level of success.

In terms of orbit determination, the batch filter is a legacy software component from the WRAITH and GHOST projects. A batch filter is a least-squares regression filter with linear and non-linear capabilities. It collects multiple data points during a fixed period and processes all data together non-recursively. The filter begins using a physical model representing an object's equations of motion. This model is used to predict the object's location at a given time. The physical and predicted locations are then compared to find the co-variance object location. The object's next location is estimated from the time derivatives of the model states. GHOST and WRAITH implemented at non-linear batch filter for object determination that required six data points from an image to define an orbit. SHADE will continue to use this legacy software.

C. Concept of Operations

SHADE will begin its operations in the transport vehicle, where it will be able to withstand the vibration environment involved in off-road transport. The modular design of SHADE will allow a single operator to carry each module to the deployment site (assumed to be less than 100 feet from the vehicle). The operator will assemble the system, and power the system on. SHADE will be preloaded with a list of Two Line Elements (TLEs), and use its automated scheduling algorithm to create a prioritized list of objects to track. SHADE will use its on-board weather sensors to determine whether the conditions are safe for operation. If they are, SHADE's environmental shield will open and the system will begin its imaging sequence. If the conditions are not suitable for imaging, SHADE will remain in safe mode, and the environmental shield will remain closed.

SHADE's imaging sequence involves taking long exposure images of objects of a predicted orbit path. If SHADE determines there is an object present, it will take two more exposures of the same object, as three images are necessary for an orbit determination. If not, SHADE will begin a searching pattern to find the object. Once the orbit is determined, SHADE will store the orbit data, and repeat the process for the next object. SHADE will remain in safe mode between object passes.

After SHADE's full deployment, the operator will return to the site, disassemble the modules, and transport them back to the vehicle, again within 30 minutes.

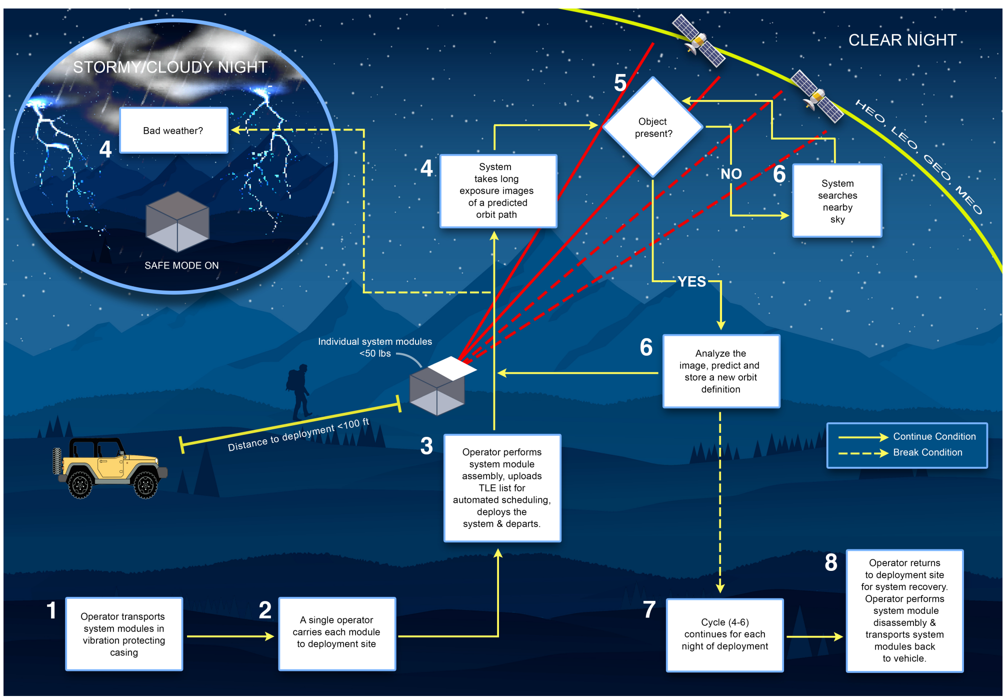

Fig. 1 SHADE Concept of Operations

D. Functional Requirements

1) The system shall schedule predicted locations and visibility windows for objects in LEO, MEO, GEO, and HEO orbits.
2) The system shall function autonomously in standard operating conditions with no human intervention for at least two nights.

3) The system shall autonomously enter and exit a safe mode to protect itself from adverse weather.
4) The system shall autonomously point to and track objects in LEO, MEO, GEO, and HEO.
5) The system shall image objects with apparent magnitude of less than 10.
6) The system shall create and save an orbit estimate for each object imaged within five minutes of the end of the associated visibility window.
7) The system shall be deployed in 30 minutes and broken down in 30 minutes by one operator.
8) The system shall be capable of making observations on multiple nights during a single deployment.

E. Functional Block Diagram

The functional block diagram shows the interactions between different systems in SHADE.

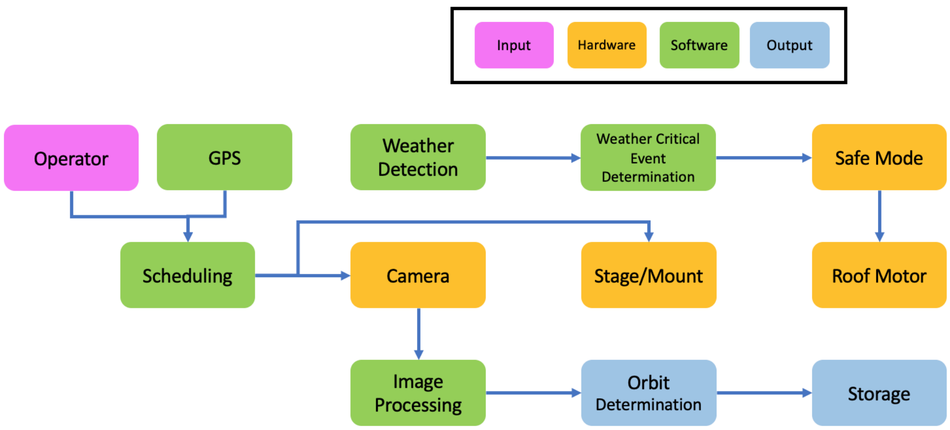

Fig. 2 SHADE Functional Block Diagram

II. Design Requirements

This section outlines each functional requirement and the corresponding design requirements that flow down from them. Each requirement has a justifying motivation and verification, detailing the objectives behind the requirement and the specific process for verification.

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

Motivation: 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.

Verification: 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]

Motivation: 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.

Verification: 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]

Motivation: 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.

Verification: 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]

Motivation: The customer wants to ensure that each input object is observed at least once.

Verification: 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]

Motivation: 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.

Verification: Test - SHADE will create an initial schedule and be forced to recalculate a new schedule with different priority values.

FR 2: The system shall function autonomously in standard operating conditions with no human intervention for at least two nights.

Motivation: 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.

Verification: 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 defined in Appendix VI.A with no impact to orbit determination capabilities.

Motivation: 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.

Verification: 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 2.2: The system shall contain a battery capable of supplying operational power levels for 12 hours without recharging. [Met by WRAITH design, integration untested]

Motivation: During the 12 hour active period per day, the system shall be capable of operating continuously which requires power draw.

Verification: 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.

FR 3: The system shall autonomously enter and exit a safe mode to protect itself from adverse weather, as defined by conditions worse than the Standard Operating Conditions defined in Appendix VI.A.

Motivation: 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.

Verification: 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]

Motivation: 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.

Verification: 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]

Motivation: 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.

Verification: Test - The operator override will be initiated while experiencing Standard Operating Conditions to verify deployment of active weather protection.

FR 4: The system shall autonomously point and track objects in LEO, MEO, GEO, and HEO. [Met by WRAITH design, unit tested]

Motivation: 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.

Verification: 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]

Motivation: 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.

Verification: 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]

Motivation: 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.

Verification: 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]

Motivation: A control algorithm is necessary to avoid overshooting or undershooting the target.

Verification: 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.

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]

Motivation: 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.

Verification: 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.

Motivation: 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.

Verification: 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]

Motivation: 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.

Verification: 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.

FR 5: The system shall image objects with apparent magnitude of less than 10. [Met by GHOST design]

Motivation: 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.

Verification: 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 ≥ 6 angular measurements in the inertial frame from a single orbit visibility window. [Met by GHOST design]

Motivation: 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.

Verification: 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]

Motivation: 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.

Verification: 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 boresight or space object inertial position. [Met by GHOST design, unit tested]

Motivation: The system needs quality images for processing and orbital determination.

Verification: 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 within captured images and reporting that information to the scheduler. [Met by WRAITH design, untested]

Motivation: As part of the customer requirements, SHADE must scan for and locate missing space objects if they are not located along their predicted orbit.

Verification: Test - SHADE will be given bad data to determine whether the system can recognize, signal an alert, and search for the missing space object.

FR 6: The system shall create and save an orbit estimate for each object imaged within five minutes of the end of the associated visibility window.

Motivation: The purpose of this system is to provide orbital estimates to the user after each deployment.

Verification: 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]

Motivation: The system must know where the azimuth and elevation measurements were taken otherwise the orbit determination will be wrong.

Verification: 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]

Motivation: 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.

Verification: 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]

Motivation: 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.

Verification: 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]

Motivation: 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.

Verification: 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]

Motivation: 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.

Verification: Test - In order to determine the camera latency, the images will be time stamped with GPS time from the on-board GPS receiver.

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]

Motivation: Reduce deployment and tear down time of the system.

Verification: 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).

Motivation: 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.

Verification: 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.

Motivation: 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 $\tilde{7}$g. [**?**]

Verification: 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.

Motivation: 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. [**?**]

Verification: Test - System can be tested both on a shaker table and during travel.

DR 7.1.3: The system shall utilize passive protection to protect sensitive components not requiring elemental exposure to function from adverse weather. [Met by WRAITH design, passive protection untested].

Motivation: The passive protection should protect the system modules not requiring active protection from adverse weather.

Verification: 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.

Motivation: To quicken the process, a document outlining the operation of SHADE in the field may be of use.

Verification: 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

Motivation: 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

Verification: 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.

Motivation: To eliminate the need for time-consuming manual calibration of the system attitude during setup, SHADE will automatically run an attitude determination routine.

Verification: Test - Have the system display the attitude to the screen , verify attitude by other means.

FR 8: The system shall be capable of making observations on multiple nights during a single deployment.

Motivation: 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.

Verification: 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 in Appendix VI.A.

Motivation: 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.

Verification: 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 °C.

Motivation: Efficiency of the solar panels varies inversely with the thermal coefficient. Keeping the panels cool during operation is key to extracting maximum efficiency.

Verification: 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].

Motivation: To avoid damaging the components while not in use, the temperature within the enclosures for each module should be maintained at a safe level.

Verification: Test - System can be placed in extreme environments to verify maintenance of proper temperatures.

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.

Motivation: 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.

Verification: 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.

> **Motivation:** 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.
>
> **Verification:** 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.

> **Motivation:** 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.
>
> **Verification:** Test - Provide the scheduler the same list of objects with different specified mission durations to compare the resulting schedules.

III. Key Design Options Considered

A. Modularity

In order to satisfy functional requirement 7, SHADE will implement a modular design to reduce the amount of weight the operator will need to carry in one trip. The following options look at how different components can be contained in various groups.

Modularity Option	Pros	Cons
Option 1: • Actuation Mount and Telephoto Lens/Camera • Processor and Weather Protection Box • Environmental Suite • Solar Panel • Battery Pack	Camera and Mount will already be connected Weather Protection Box will be light	Awkward casing for transport will be needed for the camera and mount Power system will need to be connected during setup
Option 2: • Actuation Mount and Telephoto Lens/Camera • Processor, Battery Pack, and Weather Protection Box • Environmental Suite • Solar Panel	Camera and Mount will already be connected Power system will already be in place Least amount of trips needed	Weather Protection Box will be heavy Awkward casing for transport will be needed for the camera and mount
Option 3: • Actuation Mount • Telephoto Lens/Camera • Processor, Battery Pack, and Weather Protection Box • Environmental Suite • Solar Panel	Power system will already be in place Easier to transport for actuation mount and camera	Weather Protection Box will be heavy Camera and Mount will need to be assembled
Option 4: • Actuation Mount • Telephoto Lens/Camera • Processor and Weather Protection Box • Environmental Suite • Battery Pack • Solar Panel	Weather Protection Box will be light Easier to transport for actuation mount and camera	Power system will need to be connected during setup Camera and Mount will need to be assembled More trips between site and vehicle

Fig. 3 Modularity Options Pros and Cons

The current front-running option is option 2. This is currently the best option because this offers the least amount of trips between the vehicle and the deployment site. However since the weight of the main weather box and the setup time for each component is unknown, a different option may be used once design and testing begins.

B. Materials

Using the trade study done by WRAITH, the moon roof for the weather protection box will still be used in SHADE's design. However, the current design is too heavy for one operator to carry and a trade study will to be done on current and alternate materials. In addition to scaling down the current box, the options for new materials include Type 316 Stainless Steel, Magnesium Alloy (AZ31) and Polycarbonate Plastic. Each of these materials are machinable with the proper tools.

1. 6061-T6 Aluminum

This aluminum is used in the current WRAITH design. Since there was no trade study done on other materials, this will serve as a baseline for the alternate materials. The aluminum has a density of 2.7 g/cm^3, a thermal conductivity of 167 W/mK, and a emissivity of 0.1. The cost for a 1/4" thick 12"x12" sheet is 27 dollars.

Fig. 4 WRAITH Weather Protection Box with 6061-T6 Aluminum

2. Type 316 Stainless Steel

Although the Stainless Steel is extremely heavy, the benefits for using this material is its extreme durability and great thermal protection. It has a density of 7.99 g/cm^3, a thermal conductivity of 14.6 W/mK, and a emissivity of 0.28. The cost for a 1/4" thick 12"x12" sheet is 141 dollars. Although this option does not seem to be a good choice for the weather protection box, it was considered due to the fact that the box will be scaled down in size and therefore the weight and price point may be reconsidered.

Fig. 5 Type 316 Stainless Steel Sheet

3. Magnesium Alloy (AZ31)

The magnesium alloy was considered because it is one of lightest metal alloys found in industry. The alloy has a density of 1.77 g/cm^3, a thermal conductivity of 96 W/mK, and a emissivity of 0.07. The cost for a 1/4" thick 12"x12" sheet is 207 dollars and is the most expensive option. Due to the fact that it is also easy to manufacture and still extremely light weight for a metal alloy this is a front runner among the material options.

4. Polycarbonate Plastic

Polycarbonate is the only plastic material considered in this trade study due to its high imapct strength compared to other plastics. In addition it does not degrade in sunlight which can be a factor if the SHADE system is not picked up right after its night deployment. The polycarbonate has a density of 1.15 g/cm^3, a thermal conductivity of 0.21 W/mK, and a emissivity of 0.9. The downside of using polycarbonate is that it is translucent in nature but this can be

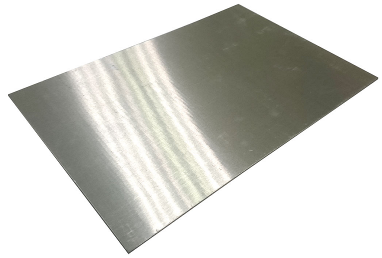

Fig. 6 Magnesium Alloy (AZ31) Sheet

changed with a layer of paint. In addition polycarbonate plastic sheets come in a minimum thickness of 1/2" which might increase the weight of the system slightly. The cost for a 1/2" thick 12"x12" sheet is 85 dollars.

Fig. 7 Polycarbonate Plastic Sheet

Figure 8 shows the Pros and Cons for each type of material for the weather protection box. These materials are also analyzed in the following section under the Materials Trade Study.

Material Option	Pros	Cons
6061-T6 Aluminum (Current)	Inexpensive Easy to Manufacture Sturdy/Durable	Heavy weight Does not offer insulation
Type 316 Stainless Steel	Easy to Manufacture Very Sturdy/Durable Well Insulated	Expensive Extremely heavy
Magnesium Alloy (AZ31)	Easy to Manufacture Sturdy/Durable Fairly light weight	Very Expensive Poor insulation
Polycarbonate Plastic	Light weight Well Insulated Can be painted to cover translucency Cheap	Not as durable as the metal alloys Harder to Manufacture Translucent

Fig. 8 Material Options Pros and Cons

C. Fasteners

In order to reattach the camera/gimbal system to the protection box on site as well as any other modules, an investigation into fasteners was required. The options considered for fasteners were screwdrivers/screws, wrenches/bolts, Dzus Clips, wing nuts, latches, and magnets.

1. Screwdrivers/screws

Screwdrivers are a common tool used to fasten screws, and serves as a baseline option. Because of how common this method is, screws can be easily acquired and are intuitive to install. The main drawback of this method would be that the time to fasten each module would increase as the number of screws increases. Thread tolerance would also be a worry, as any mistake that occurs when milling the modules to support screws would compromise the module.

Fig. 9 Screwdrivers/screws

2. Wrenches/bolts

Wrenches are another common tool used to fasten bolts. They, like screwdrivers, are intuitive to use and bolts can be easily acquired from hardware stores. This method features the same concerns with screws and screwdrivers, mainly thread tolerance and time required to wrench in many bolts. As bolts are fastened utilizing torque, there also is the concern of space needed to bolt down the modules. If there is not a lot of clearance, a smaller wrench is needed and thus more time would be needed to fully tighten the bolt.

Fig. 10 Wrenches/bolts

3. Dzus Clips

Dzus clips are a quarter-turn lock fastener that has been utilized in many different applications, such as securing skin panels on an airplane. This fastener is small, easy to use, proven and tested, and can be acquired off the shelf. Depending on further design choices, many Dzus clips may be needed in order to secure all modules, which will require some time by the operator to make sure every part within the system is aligned and secure.

4. Wing nuts

Wing nuts is another toolless fastener that was considered. Fastening would be done by the operator by turning the wingnut on a screw for a firm fit. However, while this is toolless, the time and effort required of the operator would be compared to utilizing screws and bolts. The more the wing-bolts, the more time it takes to fully fasten each module.

Fig. 11 Dzus Clips

Fig. 12 Wing Nut

5. Latches

Sliding latches was considered because of its simplicity. Latches can be installed on both the modules themselves and the base, allowing operators to just align and lock the modules. However, these latches may not fully secure the modules, and are relatively large to other toolless fasteners.

Fig. 13 Sliding Latches

6. Magnets

Cylindrical magnets is a simple and easy to use method. Pairs of magnets could be attached to the modules and the base, allowing for easy fitting. The size and magnetic force of the magnets could be determined to find an optimal design to fasten the modules. However, if the magnetic force is weak, then the modules could be dislodged easily. If the magnetic force is too strong, there are concerns of the magnets interfacing with the electrical system that could compromise system operation.

Fig. 14 Cylindrical Magnets

<u>Fasteners Trade Pros and Cons</u>

Fasteners	**Pros**	**Cons**
Screwdriver and screw	Off the shelf Intuitive	Effort and time required to screw Requires many screws
Wrench and bolt	Off the shelf Intuitive	Bulky Effort and time required to bolt Requires many bolts
Dzus Clips	Toolless Off the shelf Some Components pre-installed Easy to use Easy to align	Some effort required to secure Require some studs to secure
Wing Nuts	Toolless Off the shelf Some Components pre-installed Easy to use Easy to align	Some effort required to secure Require many nuts to secure
Latches	Toolless All Components pre-installed Easy to use Easy to align	Bulky Some configurations loose Costly
Magnets	Toolless Off the shelf Cheap All Components pre-installed Easy to use Easy to align	Interference with electronics possible Dislodgeable depending on magnetic force

Fig. 15 Fasteners Pros and Cons

D. Passive Protection

Active and passive protection both played an important role in WRAITH, and SHADE looks to expand on the existing protection methods to encompass both environmental and vibrational protection. WRAITH designed custom commercial-off-the-shelf (COTS) boxes from manufacturer Polycase to house several components, namely, the processor and power distribution board. In keeping with the modular design, each module shall be protected from both vibrations during transport and the environment during deployment and operation. In keeping with WRAITH, various COTS boxes will be examined and traded for housing each module of SHADE, while discounting other passive solutions, such as a tent or shield, based off of WRAITH's passive protection trade study. Additionally, designing and implementing modifications to each COTS box is anticipated. Modifications such as adding holes for wires, waterproofing, and any additional vibration protection will be required independently of which casing is chosen. The four COTS cases investigated are general plastic storage containers with added insulation, the Pelican Air Case with Pick N' Pluck Foam, the Polycase WH-18 Hinged NEMA Enclosure with added insulation, and the Plano Sportsman's Trunk with added insulation.

1. Polycase WH-18 Hinged NEMA Enclosure

The Polycase WH-18 Hinged NEMA Enclosure is an ABS COTS box that comes in various sizes. The primary advantage that a Polycase WH-18 provides is the flexibility and ability for customization. The box may be customized via CNC machining, cutting any required holes for cables, threads for screws or attachments, venting, or other cutouts. THe WH-18 is made of ABS plastic. With a relatively small size and a lack of built-in foam or other vibration protection, the Polycase option would not be suitable for housing the camera and GHOST hardware, but it could be used to house other electrical subsystems. Polycase also sells cable seals and glands.

Fig. 16 Polycase WH-18 Hinged NEMA Enclosure

2. Pelican Air Case with Pick N' Pluck Foam

The Pelican Air Case is a highly durable, highly protective, HPX^2 Polymer (proprietary polypropylene blend) COTS case that comes in various sizes and is used for storage and transportation of various materials. This case has an automatic purge valve that keeps water and dust out while balancing the air pressure inside and easily-modifiable polyurethane foam for insulation and vibration protection. The case is also sealed using a EPDM O-Ring, which provides substantial weather and thermal protection. Its advantages include high durability and substantial protection against vibrations, shock, and the environment without any modifications. Disadvantages of this case are that it may be difficult to add external modifications or holes for wiring and that it is expensive.

Fig. 17 Pelican Air Case

3. Sterilite Industrial Storage Bin

The Sterilite Industrial Storage Bin, which comes in various sizes, would enable a wide range of modifications to be made, which may include adding holes for wires and heat dissipation, various sizes of insulation for weather and vibration protection inside, and other weather-proofing materials. This COTS case is made of plastic, has channeled walls to provide strength and resistance to crushing from all sides, has a fully-removable lid with two latch-style handles, key holes for tie-down during transportation, a tightly-fit lid for water protection, and a deep recessed lid that enables secure stacking with other boxes for storage. Advantages of this case are that it is lightweight and strong, it can be easily modified, and it is inexpensive. Downsides of this case are that many modifications would be needed for each module to provide vibration protection and that it does not provide high level protection off the shelf against severe weather and thermal conditions.

Fig. 18 Sterilite Industrial Storage Bin

4. Plano Small Sportsman's Trunk

The Plano Small Sportsman's Trunk is a plastic COTS box that comes in various sizes. It is of a size where it could hold any individual module during transportation and deployment, including the camera and GHOST hardware. It is lockable and has extensions so the box may tied down during transportation. Notably, Plano does not list specifications on the type of plastic used or any material properties of the box. The Plano trunk would require manual modifications for cables and vibration protection as well as sealing and waterproofing.

Fig. 19 Plano Small Sportsman's Trunk

5. Passive Protection Summary

Figure 20 provides the advantages and disadvantages of each of the COTS casing options that will be used for SHADE's passive protection system. The items listed below were also considered for the Passive Protection Trade Study; thus, these pros and cons will be further analyzed in the following section.

Casing Options	Pros	Cons
Polycase WH-22 Hinged NEMA Enclosure	Guaranteed waterproof. Durable off the shelf. Clear lid enables view inside. Metal padlocking hinges. Inexpensive. Lightweight. Some thermal protection.	Does not include insulation. Requires screws and manual assembly.
Pelican Air Case with Pick N' Pluck Foam Insulation	Guaranteed waterproof. Extremely durable off the shelf. Includes foam insulation. Easily customizable foam padding. Lightweight. Provides better thermal protection	Expensive. Less feasibility to add holes for wiring.
Sterilite Industrial Storage Bin	Inexpensive. Lightweight. Easily modified for wiring and holes. Easily stackable with multiple cases.	Cannot guarantee level of weatherproof. Low strength of plastic lid latches. Does not include foam insulation. Low thermal protection. No O-Ring seal.
Plano Small Sportsman's Trunk	Inexpensive. Lightweight. Durable. Easily modified for wiring and holes.	Does not include foam insulation. Little thermal protection.

Fig. 20 Passive Protection Option Pros and Cons

E. Choice of Battery

The power supply for SHADE is an essential component of the overall system. Early on the team identified the potential to improve the power supply both in terms of weight and longevity. Four different types of batteries were considered to power SHADE. While solar panels were also initially considered, the weight and size of the necessary panel conflicted with several of SHADE's functional requirements. This results from the required battery capacity and estimated charging abilities. The most efficient solar panels today produce about 400W of power per panel and weigh over 50lbs. As they are intended for stationary use on the roofs of buildings, commercially available solar panels also measure about 3ft by 5ft. Lithium Iron batteries have the fastest charging capacity out of the batteries researched at about 10 amps. That requires continuous power of at least 120W for nearly eight hours just to recharge. This implies that the solar panel must produce power at all points of the day. For these reasons, solar panels were eliminated from the power supply options. However, SHADE will be able to implement them in the future with the chosen battery. Below is an analysis of Sealed Lead Acid, Lithium Iron Phosphate, Lithium Ion, and Lithium Polymer batteries.

1. Sealed Lead Acid (SLA)

The current power system that is implemented in SHADE consists of three Duracell DURDC12-20NB sealed lead acid batteries. Each battery is rated at 12V with a nominal capacity of 20Ah. When connected in series, the total battery capacity is 720 Wh. Each battery weighs 13.3 lbs resulting in a power system mass of nearly 40lbs. These three batteries do power SHADE for one night, but have an average cycle life of only 175. This means they will need to be replaced every 175 nights of deployment. Each battery costs approximately $90, bringing the system cost to $270.

Fig. 21 Duracell 12V SLA

2. Lithium Iron Phosphate (LiFePO4)

Lithium Iron Phosphate batteries are the most expensive power supply in the stusy at around $750. To combat this they do have the longest cycle life. They are mostly used in RV and marine applications due to their light weight, ability to quickly recharge, and long cycle life. This battery type was also the only one to receive independent certifications. One LiFePO4 battery weigh 20.5 lbs and have a nominal capacity of 75Ah at 12V or 900Wh. This battery also does not require the use of an extra voltage regulator.

Fig. 22 Power Sonic 12V LiFePO4

3. Lithium Ion (Li-ion)

Li-Ion (Lithium ion 18650 based) Cost: $675 Weight: 10lbs Voltage: 25 Capacity: 32Ah/819Wh Cycle Life: 300-500 3rd Party Certifications: N/A Lithium ion batteries typically come in either 3.6 or 3.7 volt cells. As a result, 12V battery packs don't exists. Furthermore, few commercial companies manufacture large capacity battery packs for the general consumer. As a result, many independent companies purchase the Li-ion cells and package them themselves. For this trade, the specific battery pack product uses LG LGDBHE21865 cells and the pack is not manufactured to any standards for safety or rated output that the group could find. That being said, the manufacture rates the 25V battery pack to have a cycle life between 300 and 500 cycles and a nominal capacitance of 32Ah or 819Wh. The packs estimated weight would be 10lbs.

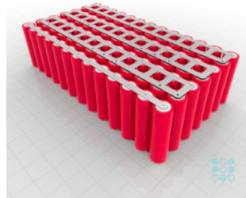

Fig. 23 Example of Li-ion Battery Pack

4. Lithium Polymer (LiPo)

Lithium Polymer batteries are a common choice for remote control enthusiasts and have some OTS solutions. Still, the group could not find a manufacture that had independent ratings for safety and output for a battery that would be required by SHADE. LiPo batteries are also prone to ignite while charging and require a special charger to maintain individual cell voltages. For the purpose of this trade the LiPo battery chosen has a nominal voltage of 48V with a rated capacity of 22Ah or 1056 Wh. The chosen pack has a weight overall of about 22lbs with an estimated cycle life of 250 to 450 cycles.

Fig. 24 Lithium King 48V LiPo

5. Battery Summary

The figure below provides a table of each power supply option along with their respective Pros and Cons. Each system will be compared later in the corresponding trade study.

Fig. 25 Battery Pro Con Table

Pro-Con Table

Power System Option	Pros	Cons
SLA Battery (Current)	Inexpensive ($270) Carry over from WRAITH "Off the shelf"	3 Batteries Heavy weight (40lbs) Low cycle life (frequent replacement) Slow charging rate
Lithium Iron Phosphate Battery	1 Battery High cycle life Lighter weight Faster charging rate "Off the shelf"	Higher cost ($750) Needs additional insulation Special charger
Lithium Ion	1 Battery Lighter weight Improved cycle life	Higher cost ($675) Hard to find "off the shelf" solution Requires extra voltage regulator
Lithium Polymer	1 Battery Lighter weight "Off the shelf" Slightly improved cycle life	High risk for fire Requires extra voltage regulator Medium cost ($400)

F. Calibration Methods

Without proper calibration, it may prove difficult for SHADE to image objects in orbit with the desired accuracy. WRAITH employed a method of manual adjustment using an onboard level, which may limit the terrain that the system could be deployed on. Thus, a trade study will be conducted on different methods of leveling and calibration.

1. Manual Mechanical Adjustment (MMA)

Using an included level for reference, the user performs the calibration on the AZ Mount Pro itself using its on-screen display (OSD). This must be performed with visible stars, limiting deployment time to after dark. Additional Cost: None Additional Mass: None User involvement: 5 minutes expected for leveling (but dependent upon terrain). User must boot the onboard computer and interact with the mount. Imaging: No image processing required, but slewing is. Disturbance Detection: None. Cannot be re-calibrated once operator has left.

2. Automated Mechanical Adjustment (AMA)

Using actuators and onboard inertial measurement units (IMU), the system would level itself after using the IMUs to define a gravity vector. This replaces manual adjustment in Method 1 with automated mechanical systems, leveling the box and using the AZ Mount Pro to determine inertial orientation. For a box with three feet, motors are required at two. Mount is told to calibrate by the computer, and an image is used to validate. This imitates Method 1, except removes operator interaction[21].

3. Camera (CAM)

The onboard system points the camera at multiple bearings, taking an image at each, and using existing star chart software to determine that direction in inertial space. This provides an inertial orientation with the same level of accuracy as the camera used in orbit determination, without using the AZ Mount Pro calibration.

4. Camera and Additional Sensors (SENS + CAM)

The AZ Mount Pro is told to calibrate by the computer, and an image is used to validate. An IMU can then be used to detect any large disturbances by measuring any change in the gravity vector before imaging, thus minimizing the possibility of miscalibration going undetected until an imaging sequence fails. This imitates the AMA method, but compensates for non-level surfaces instead of correcting it.

5. Calibration Summary

The figure below shows a table of each calibration option with the pros and cons of each design. These options will be compared later in the trade study.

Fig. 26 Calibration Pro Con Table

Pro-Con Table

Calibration Method	Pros	Cons
Manual mechanical adjustment (MMA)	No additional software required. Hardware limited to unpowered level and adjustable feet. Ensures the entire system is level, optimizing FOV.	Requires significant time from the operator, which is fundamentally opposed to FR7. Settling after setup cannot be corrected, potentially ruining any further observations.
Automated mechanical adjustment + additional sensors (AMA)	No user input required. Ensures the entire system is level, optimizing FOV.	Requires additional sensors, as well as heavy hardware such as motors or servos, and associated software. Power draw increased. Mechanical movement of the system without an operator present is risky. Physically displacing the entire system will consume power.
Camera only (CAM)	No user input required. No additional cost or mass.	Validating calibration requires valuable imaging time. With no inertial orientation data, multiple images required.
Sensors + Camera (SENS+CAM)	No user input required. Large disturbances can be detected at any time. Minimal additional mass. Accuracy identical to normal imaging.	Greatest amount of additional software required. Initial correction can only be refined under normal imaging conditions.

G. Solar Based Power Regeneration

Three solar panels currently exist in the consumer market: monocrystalline, polycrystalline and thin-film panels.

1. Polycrystalline Panel

Polycrystalline solar cells are made by melting fragments of silicon together to form wafers on the panels. The polycrystalline cells could be implemented with SHADE by designing a panel with a metal backing for thermal dissipation, and covered in glass. The solar panels would be folded to increase portability. The panels would be connected to a battery charger to recharge the SHADE batteries during the day.

2. Monocrystalline Panel

Monocrystalline panels are also made of silicon. Silicon bars are cut into wafers and formed into cells. This construction generally yields higher efficiencies than polycrystalline panels, though monocrystalline panels tend to be more expensive. The implementation would be similar to that of polycrystalline panels.

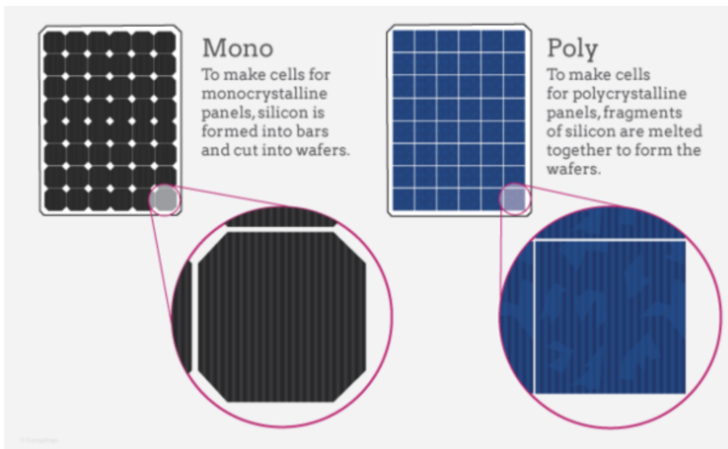

Fig. 27 Monocrystalline cells vs polycrystalline (via energysage.com)

3. Thin Film Panel

Thin film panels are usually made from Cadmium Telluride, though Gallium Arsenide panels are becoming more widely available. Though thin-film panels are more portable, and cheaper than the silicon based panels that are available, they are far lower in efficiency. These could be implemented by unrolling the thin-film panel, and connecting it to the battery charger. However, the thin-film panels are difficult to construct, and most commercial, off-the-shelf panels do not meet the requirements of the battery charger.

Fig. 28 Thin Film Solar Panel Available Commercially

4. Solar Power Summary

Solar Power Pro-Con Table

Panel Type	Pros	Cons
Monocrystalline	High efficiency Easily Scalable Sturdy Aesthetics Longer lifespan	Low thermal resistance High cost
Polycrystalline	Lower Cost Moderate efficiency	Low thermal resistance More soldering connections
Thin Film	Very portable Lowest cost Light & Flexible	Lowest efficiency Reduced scalability Shorter lifespan

IV. Trade Study Process and Results

A. Trade Study 1: Materials

Under the current design, WRAITH requires 2 persons to deploy and set-up the system. SHADE looks to modularize components during transportation and setup in order for a one person deployment team. Under OSHA guidelines, each individual component must not weigh over 50lbs. Given that there are trade studies to use a more optimal power system to reduce weight and passive protection cases used for transportation, the main focus is to reduce the weight of the weather protection box. In addition to reducing the size of the box, SHADE also looks to use a different material to reduce the weight. The trade study will consist of finding a lighter and more insulated material while retaining the structural rigidity that was offered previously.

Metric	**Weight**	**Driving Requirement**	**Rationale**
Weight	0.50	FR 7 DR 7.1	To meet OSHA safety recommendations, the weight of the weather protection box must be factored into the selection process. This weight limit is fundamental to SHADE and is prioritized appropriately.
Cost	0.10	Budget	Balancing a budget is important but material use is more so. Even though some materials are more expensive, the total cost of materials will still be relatively cheap
Thermal Conductivity	0.15	FR 3 DR 3.1 FR 8 DR 8.1	SHADE will need to be able to survive adverse weather conditions during deployment. This metric will determine the material's conductivity
Emissivity	0.05	FR 3 DR 3.1 FR 8 DR 8.1	This metric will also help determine SHADE's ability to survive in adverse weather conditions. In addition to conductivity, the material's black body radiation will also be measured using emissivity.
Reliability	0.20	FR 3 DR 3.1 FR 7 DR 7.1.1	SHADE will need to be durable enough for frequent offroad transport and will need to withstand the elements of multiple deployments. It is important to select a material to use for the weather protection box that will be able to survive and protect the sensitive systems inside over multiple deployments

Fig. 29 Material Metric Rationale and Descriptions

Materials Metric Values

Metric	1	2	3	4	5
Density (g/cm^3)	>= 3	2.4 - 2.99	1.8 - 2.39	1.2 - 1.79	< 1.2
Thermal Conductivity (W/m-K)	> 100	75 - 100	50 - 74.9	25 - 49.9	< 25
Emissivity	0.8 - 1	0.6 - 0.79	0.4 - 0.59	0.2 - 0.39	0 - 0.19
Cost 0.125”(t)/sqft ($)	> 90	90 - 70	70 - 50	30 - 50	< 30
Reliability	Immediate likelihood of failure	High likelihood of failure	Moderate likelihood of failure	Minimal chance of failure	Failure is improbable

Fig. 30 Materials Metric Values

Materials Trade Study Results

Metric	Weight	6061-T6 Aluminum	Type 316 Stainless Steel	Magnesium Alloy (AZ31)	Polycarbonate Plastic
Density	0.4	2	1	4	5
Thermal Conductivity	0.15	1	5	2	5
Emissivity	0.05	5	4	5	1
Cost	0.1	5	1	1	4
Reliability	0.2	5	5	5	4
	1.0	2.9	2.55	3.65	4.5

Fig. 31 Materials Trade Study Results

B. Trade Study 2: Passive Protection

A trade study on the passive protection COTS box options was performed using the metrics below. The metrics in this case are cost, durability, ease of modification, weight, environmental protection, and vibrational protection. The weights and rationales of each metric are given in Figure 32.

Metric	Weight	Driving Requirement	Rationale
Cost	0.1	Budget	The passive protection COTS casing must adhere to the constraints of the budget; however, this metric obtains the lowest weight because the other constraints immediately impact the system's operation.
Durability	0.2	FR 7, DR 7.1.1	The passive protection COTS casing must withstand an indefinite number of off-road transports, deployments, and operations with low risk and maintenance.
Ease of Modification	0.3	FR 7, DR 7.1.3	The passive protection COTS casing will need to be modified to meet protection requirements for waterproofing and vibration protection, as well as the requirement for toolless assembly. This is an essential factor to ensure that the environmental and vibration hazards are met.
Weight	0.1	FR 7, DR 7.1	Several modules will utilize passive protection for both environmental and vibration protection during deployment, so the weight of the casing should be factored into the weight of the module.
Environmental Protection	0.2	FR 7, DR 7.1.3	The passive protection must be able to protect the module components against unforeseen circumstances such as water, hail, temperature fluctuations, or other adverse weather effects.
Vibration Protection	0.1	FR 7, DR 7.1.2	The passive protection must be able to withstand vibrations and impulses as a result of travelling. Some modules, namely the GHOST hardware, are likely to be especially sensitive, but the other modules are less likely to sustain damage during transport.

Fig. 32 Passive Protection Metric Rationale and Descriptions

This trade study considers four COTS box options for SHADE's passive protection system: the Sterilite Industrial Storage Bin, the Pelican Air Case with Pick N' Pluck Foam, the Polycase WH-22 Hinged NEMA Enclosure, and the Plano Sportsman's Trunk. The table of metric values (Figure 32) was used to assign a scoring value to each option with 1 being the worst case and 5 as the most ideal. Using the values and weights assigned for each metric, the highest scoring case will be the chosen option for SHADE. The following sections outline the scores and rationales for each case considered. The final results of the study are presented in Figure 33.

Passive Protection Metric Values

Metric	1	2	3	4	5
Cost (per unit)	>$50	$40-$50	$30-$40	$20-$30	<$20
Durability	Not durable		Moderately durable		Extremely durable
Ease of Modification	Impossible	Difficult	Moderate	Simple	Trivial
Weight	>12 lbs	10-12 lbs	7-10 lbs	5-7 lbs	<5 lbs
Environmental Protection	Not water resistant, no thermal protection	Water resistant, little to no thermal protection	Water resistant, minimal thermal protection	Water resistant, moderate thermal protection	Waterproof, greatest thermal protection
Vibration Protection	None		Moderate		Extreme

Fig. 33 Passive Protection Metric Values

Passive Protection Trade Study Results

Metric	Weight	Polycase	Pelican	Sterilite	Plano
Cost	0.1	1	1	5	5
Durability	0.2	5	5	3	4
Ease of Modification	0.3	4	2	5	3
Weight	0.1	5	3	5	4
Environmental Protection	0.2	4	5	2	2
Vibration Protection	0.1	2	5	1	1
	1.0	3.8	3.5	3.6	3.1

Fig. 34 Passive Protection Case Study

1. *Polycase WH-22 Hinged NEMA Enclosure*
   - Cost - 1: The WH-22 has a base price of $60.55 per unit for the outdoor model. This would be further increased if customizations were added.
   - Durability - 5: The WH-22 is made out of polycarbonate with well-documented material properties including tensile and flexural stress and strain as well as Izod impact tests.
   - Ease of Modification - 4: Polycase offers the ability to order the boxes pre-machined, cutting down on work for the user but introducing a higher price.
   - Weight - 5: The WH-22 weighs 3.61 lbs, although this may increase if vibration protection is added.

- Environmental Protection - 4: The WH-22 is designed to NEMA 1, 2, 4, and 4X, providing protection against ingress of dust, dirt, water, and snow. However, it is not guaranteed waterproof.
- Vibration Protection - 2: The polycarbonate provides some amount of protection against impulse, but it is still deficit in both the impulse and cyclical loading areas

2. *Pelican Air Case with Pick N' Pluck Foam*
   - Cost - 1: The case has a cost of $236.95.
   - Durability - 5: The Pelican case is made of a proprietary polypropylene blend. Its high strength and durability have been proven through extensive load and shock testing.
   - Ease of Modification - 5: This case has been engineered to be waterproof up to 20 meters, resistant to substantial loading, and is made of a material with unknown properties. Modifications to this case will greatly reduce its other protective abilities.
   - Weight - 5: The case weighs 8.78 lbs.
   - Environmental Protection - 5: This case is waterproof up to 20 meters underwater, has an automatic pressure equalizer and provides protection in extreme hot and cold temperatures.
   - Vibration Protection - 5: This case is extremely protective against impulses and comes with foam insulation for optimal protection.

3. *Sterilite Industrial Storage Bin*
   - Cost - 5: The bin has a cost of $9.89.
   - Durability - 3: No information is provided for the case's type of plastic; however, customer reviews of this product express that it has some durability under loading and in rain.
   - Ease of Modification - 5: This case has few parts involved and is made from plastic. Modifications to add holes, insulation, internal padding, and added weather protection will be feasible.
   - Weight - 5: The case weighs 4.83 lbs.
   - Environmental Protection - 2: This case offers some protection against rain but no protection against extreme temperatures or weather conditions.
   - Vibration Protection - 1: The trunk offers little to no vibration protection and would require modification.

4. *Plano Small Sportsman's Trunk*
   - Cost - 5: The trunk has a cost of $19.99.
   - Durability - 4: There is no information available about the material properties of the trunk nor what type of material it is, but Plano is a leader in the industry and is well known for the quality of their product.
   - Ease of Modification - 3: Due to a lack of information, this is a conservative guess based on the reputation of Plano boxes.
   - Weight: - 4: No information was available on the weight of the trunk, so a reasonable estimate was chosen.
   - Environmental Protection - 2: The trunk offers little in way of environmental protection and would require extensive modification.
   - Vibration Protection - 1: The trunk offers little to no vibration protection and would require modification.

C. Trade Study 3: Power Supply

Fig. 35 Power Supply Metrics and Rationale

Metric	Weight	Driving Requirement	Rational
Weight	0.30	FR 7 DR 7.1	To meet OSHA safety recommendations, the weight of the battery(s) must be factored into the selection process. This weight limit is fundamental to SHADE and is prioritized appropriately.
Cost	0.10	Budget	Balancing a budget is important but the battery(s) implementation is more so. As a result it receives minimal weight by comparison.
Cycle Life	0.10	FR 2 DR 2.2.1	It is expected that SHADE will endure multiple deployments over its lifetime. As a result, the team must consider the frequency of battery replacement and deployment duration.
Cost/Cycle Life	0.25	Budget	This metric is important when considering SHADE's final use. It is expected that SHADE will endure multiple deployments potentially spanning several days. A single night deployment equates to one cycle. For long term use, the operator will have to continuously replace batteries with a low cycle life. As a result, this section has taken a priority in weighting.
Reliability	0.25	FR 2 DR 2.1 DR 2.2	SHADE is expected to survive in a variety of weather conditions. Entering in and out of safe mode requires electrical power and the power solution must be able to, at a minimum enter SHADE into safe mode. The power system must also be safe for the operator when charging and in transit.

<u>Power Supply Metric Values</u>

Metric	1	2	3	4	5
Weight [lbs]	> 35	30-35	25-30	20-25	< 20
Cost [$USD]	> 1000	700-1000	500-700	300-500	< 300
Cycle Life [#]	< 200	200-500	500-1000	1000-1500	> 2000
Cost/Cycle Life [$/#]	< 2	1.5-2	1-1.5	0.5-1	< 0.5
Reliability*	Immediate likelihood of failure	High likelihood of failure	Moderate likelihood of failure	Minimal chance of failure	Failure is improbable

*Reliability is quantified by independent verification and certifications of the selected batteries. These include but are not limited to UL, ISO, and similar standardizing bodies. Also included is whether or not an off the shelf solution exists for the product. In some cases, these might be small volume independent manufacturers as opposed to commercial companies.

Power Supply Trade Study Results

Metric	Weight	SLA	LiFePO4	Li-ion	Li-Po
Total Weight [lbs]	0.30	1	4	5	4
Cost [$USD]	0.10	5	2	3	4
Cycle Life [#]	0.10	1	5	4	2
Cost/Cycle Life [$/#]	0.25	2	5	2	3
Reliability*	0.25	5	4	2	2
Total	1.0	2.65	4.15	3.20	3.05

1. *Sealed Lead Acid (SLA)*
    - Weight - 1: The SLA system is comprised of 3 batteries of 13.3 lbs each. This generates a total power supply mass of approximately 40lbs. This is system with the heaviest weight.
    - Cost - 5: Each battery costs approximately $90 USD. The system as a whole would therefore cost $270. This is the least expensive battery option.
    - Cycle Life - 1: These SLA batteries have a cycle life of 150-200. For this trade study the average was taken (175 cycles). This means the SLA batteries would need to be replaced every 175 deployments on average.
    - Cost/Cycle Life - 2: Dividing the total cost by the average cycle life the batteries would cost $1.54 dollars per cycle.
    - Reliability - 5: SLA batteries are very common and are known for their low fire risk. They are also easy to find off the shelf so supply would not be an issue. For these reasons SLA batteries receive the highest reliability rating.

2. *Lithium Iron Phosphate (LiFePO4)*
    - Weight - 4: A single LiFePO4 battery would be sufficient to power the SHADE system. This one battery weighs 20.5lbs, generating an almost 20lb reduction in overall mass.
    - Cost - 2: This battery retails for approximately $750 making it the most costly battery in this study. However it would still only account for 15% of the project budget.
    - Cycle Life - 5: LiFePO4 batteries have an excellent cycle life of 2000. This is the highest in the trade study and would improve the longevity of the power supply.
    - Cost/Cycle Life - 5: Dividing cost by cycle life each deployment would cost $0.375 USD. This proves that even though the initial cost of the battery is high, the longevity it provides actually makes it more affordable long term.
    - Reliability - 4: LiFePO4 batteries come with UL, IEC, UN, and ISO certifications. This documents them as reliable fast charging batteries with a low chance of failure.

3. *Lithium Ion (Li-Ion)*
    - Weight - 5: SHADE would be able to operate on a 10lb Li-Ion battery, making it the lightest of all power supply options considered.
    - Cost - 3: Li-Ion batteries are somewhat expensive due to their energy density. The required battery would cost $675 USD, just below its LiFePO4 counterpart.
    - Cycle Life - 4: With a cycle life of 300-400, Li-ion batteries would almost double the cycle life of the current system.
    - Cost/Cycle Life - 2: Due to the large increased in initial price, the cost per cycle life is estimated at $1.92 per cycle.
    - Reliability - 2: Li-ion batteries do have an increased fire risk. While the modularity of SHADE would shelter other components from fire damage, the reliability of the system itself is lower.

4. Lithium Polymer (Li-Po)

- Weight - 4: The required Li-Po battery would weigh 22lbs when implemented. This would lower system mass and be beneficial to SHADE's functional requirements.
- Cost - 4: With a price of $400, a single Li-Po based system would not increase buy in costs significantly, with the current system at $270.
- Cycle Life - 2: With an average cycle life of 350, there is not a significant increase over the current system.
- Cost/Cycle Life - 3: With a higher cost and a small increase in cycle life, Li-Po battery based power would represent only a slight savings at $1.14 per cycle.
- Reliability - 2: Li-Po batteries suffer some of the same fire risks that Li-Ion batteries do. This coupled with fewer 3rd party certifications means the probability of failure is higher than that of other power supplies.

D. Trade Study 4: Solar Cell Technology

1. Solar Cell Options

Metric	Weight	Driving Requirement	Rational
Power Efficiency	0.40	***	The size of the solar array directly correlates to the power efficiency of the collar cells. This will also affect its portability and the potential requirement of multiple solar panels. As a result, it receives the highest weight.
Thermal Resistance	0.40	***	Solar cells lose efficiency as they heat up, decreasing the system's ability to effectively recharge the battery. This will ultimately affect when and where SHADE can be deployed for multi-night observations.
Cost	0.20	Budget	Balancing a budget is important. However, when considering the time and money spent to deploy and recover SHADE on 12hr cycles, implementing solar recharging capabilities will save money over the lifecycle of SHADE.

Fig. 36 Solar Technology Metric Rationale

Solar Technology Metric Values

Metric	1	2	3	4	5
Power Efficiency [%]	<10	10-12	12-17	17-20	<20
Thermal Coefficient [% / °C]	Larger than -0.8	-0.8 to -0.5	-0.5 to -0.4	-0.4 to -0.3	-0.3 and smaller
Cost (cell dependent)	Most Expensive		Moderately Expensive		Least Expensive

Fig. 37 Solar Technology Metric Values

Solar Technology Trade Study Results

Metric	Weight	Monocrystalline	Polycrystalline	Thin Film
Power Efficiency	0.40	5	3	2
Thermal Resistance	0.40	3	3	4
Cost	0.20	2	3	4
Total	1.0	3.6	3.0	3.2

Fig. 38 Solar Technology Trade Study

2. *Monocrystalline*
    - Power Efficiency - 5: Monocrystalline solar cells are able to convert more solar energy into electrical energy than the other technologies currently available (about 20-23%). As a result, a solar array would need less individual cells to meet the power requirements of the battery charger.
    - Thermal Coefficient - 3: Heat degrades solar cell performance regardless of technology. On average monocrystalline cells lose performance at a rate of -0.5%°C. This value differ from manufacture to manufacturer.
    - Cost - 2: Monocrystalline cells are less expensive per watt since they are becoming industry standard.

3. *Polycrystalline*
    - Power Efficiency - 3: On average, polycrystalline solar cells have a power efficiency of 15-17%.
    - Thermal Coefficient - 3: Polycrystalline cells will lose power performance at an average rate of -0.5%°C.
    - Cost - 3: Because polycrystalline solar cells are an older technology, they are generally less expensive than other solar cells.

4. *Thin Film*
    - Power Efficiency - 2: Thin film solar technologies only average around 11% efficiency.
    - Thermal Coefficient - 4: At -.35%°C, thin film solar is the most effected by temperature changes.
    - Cost - 4: Most applications for thin film solar are highly specialized. As a result, they are often more expensive than other commercial applications.

E. Trade Study 5: Fasteners

A trade study on fasteners for module attachment was performed with the metrics seen in figure 40.

Fig. 39 Toolless Fasteners Metric Rationale

Fasteners Metrics Rationale

Metric	Weight	Driving Requirement	Rationale
Cost	0.2	Budget	With the limited budget this metric is important especially if a large number of fasteners are required
Ease of use	0.35	FR 7 DR 7.2	In order to succeed in deploying within 30 minutes, this metric factors the time and effort required of the operator to secure the modules. This includes if items are preinstalled and how many items would need to be used to attach modules
Manufacturing Tolerance	0.05	Manufacturability	If the base system must feature thread tolerance, then
Mass/Bulk	0.1	FR 7 DR 7.1	How large the items are will be important on small modules and the space they will take in the system. This metric factors in relative size of the items
Security	0.25	FR 8	All modules must be aligned correctly and securely. This metric factors these as well as factor in any vibration and impulses that may be present during transport.

Fasteners Metric Values

Metric	1	2	3	4	5
Cost	>$10 Per item	$5-$10 Per item	$2-$5 Per item	$1-$2 Per item	<$1 Per Item
Ease of use	Inefficient effort and time by the operator	Extensive effort required by the operator	Some effort and time required by the operator	Little effort and time by the operator	Minimal effort and time by operator
Manufacturing Tolerance	Requires precise thread manufacturing tolerance		Requires thread manufacturing tolerance		Require minimal manufacturing tolerance
Mass/Bulk	Cannot feasibly fit within system (0 Items,>2kg)	Can fit few items within system (1-5 Items, 1kg-2kg)	Can fit some items within system (5-10 Items, 500g-1kg)	Can fit many items within system (10-20 Items, 250g-500g)	Can fit large amount of items within system (20+ Items, <250g)
Security	Loosely attaches modules	Attaches Modules	Losely secures modules	Secures modules	Secures and aligns modules properly

Fig. 40 Toolless Fasteners Metric Values

<u>Fasteners Trade Study Results</u>

Metric	Weight	Screwdriver/ Screw	Wrench/ bolt	Dzus Clips	Wing Nuts	Latches	Magnets
Cost	0.2	**4**	**4**	**4**	**4**	**2**	**5**
Ease of use	0.35	**3**	**3**	**4**	**4**	**5**	**5**
Manufacturing Tolerance	0.05	**3**	**3**	**5**	**3**	**5**	**5**
Mass/Bulk	0.1	**4**	**2**	**5**	**5**	**2**	**5**
Security	0.25	**4**	**4**	**5**	**4**	**3**	**2**
Total	1.0	**3.4**	**3.2**	**4.2**	**3.85**	**3.35**	**4**

Fig. 41 Toolless Fasteners Trade Study

F. Trade Study 6: Calibration Method

The method used to calibrate the motion of the camera stage will determine sensor and actuation hardware, as well as necessary software. Therefore, the following trade study was conducted.

1. Manual Mechanical Adjustment (MMA)

Manual mechanical adjustment of feet of box, using an included level for reference. User performs the calibration on the AZ Mount Pro itself using it's on-screen display (OSD). This must be performed with visible stars, limiting deployment time to after dark.

- Additional Cost: None
- Additional Mass: None
- User involvement: 5 minutes expected for leveling (but dependent upon terrain). User must boot the onboard computer and interact with the mount.
- Imaging: No image processing required, but slewing is.
- Disturbance Detection: None. Cannot be recalibrated once operator has left.

2. Automated Mechanical Adjustment (AMA)

Automated mechanical leveling with actuators and onboard IMU. This replaces manual adjustment in Method 1 with automated mechanical systems, leveling the box and using the AZ Mount Pro to determine inertial orientation. For a box with three feet, motors are required at two. Mount is told to calibrate by the computer, and an image is used to validate. This imitates Method 1, except removes operator interaction.

- Additional Cost: Two linear actuators (exact models TBD if selected): \$260 [21] ADXLx03 two-axis accelerometer + breakout board \$40
- Additional Mass: Two linear actuators (exact models TBD if selected): 1kg + mounting hardware ADXLx03 two-axis accelerometer <1g, +breakout board and wiring) < 10g [20]
- User involvement: < 1 minute (User must ensure that terrain is suitable for any mechanical motion of enclosure, such as removing loose material, ensuring distance from obstacles, etc.)
- Imaging: Single image required to validate calibration
- Disturbance Detection: Any time using onboard IMU.

3. Camera Only (CAM)

Onboard system points the camera at multiple bearings, taking an image at each, and using existing star chart software to determine that direction in inertial space. This provides an inertial orientation with the same level of accuracy as the camera used in orbit determination, without using the AZ Mount Pro calibration.

- Additional Cost: None
- Additional Mass: None
- User involvement: None
- Imaging: Multiple images required, as well as slew time between.
- Disturbance Detection: Imaging required to detect disturbances, may not be detected until failed imaging sequence

4. Camera with Sensors (CAM+SENS)

AZ Mount Pro is told to calibrate by the computer, and an image is used to validate. IMU (two-axis accelerometer) can then be used to detect any large disturbances by measuring any change in the gravity vector before imaging, thus minimizing the possibility of miscalibration going undetected until an imaging sequence fails. This imitates Method 2, but compensates for non-level surfaces instead of correcting it.

- Additional Cost: ADXLx03 two-axis accelerometer + breakout board $\tilde{\$}$40 [20]
- Additional Mass: ADXLx03 two-axis accelerometer <1g, +breakout board and wiring) < 10g [20]
- User involvement: None
- Imaging: Single image required to verify calibration
- Disturbance Detection: Any time from IMU

5. Rejected Option: IMU only

Onboard IMU used to orient the system in Earth Inertial frame with sufficient accuracy to remove camera involvement. IMU needs to achieve 4 arcsec accuracy on it's own. Magnetometers do not provide sufficient accuracy (with most options only providing 0.5-1 degree)[20] as well as being prone to magnets in motors, nearby magnetic field disturbances, or operation near the poles. Furthermore, the two-axis accelerometers found in research did not provide the necessary accuracy in gravitational measurement, usually only achieving arc-minute level resolution.

Fig. 42 Calibration Method Pro-Con Table

Calibration Method	Pros	Cons
Manual mechanical adjustment (MMA)	No additional software required. Hardware limited to unpowered level and adjustable feet. Ensures the entire system is level, optimizing FOV.	Requires significant time from the operator, which is fundamentally opposed to FR7. Settling after setup cannot be corrected, potentially ruining any further observations.
Automated mechanical adjustment + additional sensors (AMA)	No user input required. Ensures the entire system is level, optimizing FOV.	Requires additional sensors, as well as heavy hardware such as motors or servos, and associated software. Power draw increased. Mechanical movement of the system without an operator present is risky. Physically displacing the entire system will consume power.
Camera only (CAM)	No user input required. No additional cost or mass.	Validating calibration requires valuable imaging time. With no inertial orientation data, multiple images required.
Sensors + Camera (SENS+CAM)	No user input required. Large disturbances can be detected at any time. Minimal additional mass. Accuracy identical to normal imaging.	Greatest amount of additional software required. Initial correction can only be refined under normal imaging conditions.

Fig. 43 Calibration Method Metric Rationale

Metric	**Weight**	**Driving Requirement**	**Rationale**
User involvement	0.3	FR7 FR2	Operator must be able to prepare SHADE within set time frame. Calibration adds a significant and variable time requirement to setup process. Operator is also a significant possible source of calibration error. Operator only present at initial setup.
Imaging interruption	0.2	FR5	Using imaging resources (camera or stage) means that imaging cannot take place while calibration is generated/verified. Imaging schedule may be required if recalibration is necessary. If a single image can be used, images from typical operation can serve this purpose. If multiple images are required (i.e. stage must slew) then schedule must accommodate the calibration process.
Additional Cost	0.1	Budget	A primary objective of the SHADE system is to produce a system that can be manufactured at low cost. Additional hardware or sensors require cost saving measures elsewhere, or an increase in unit cost.
Additional Mass	0.1	FR7	Additional hardware will increase the system mass, thus requiring mass budget cuts elsewhere or further modularization.
Disturbance Detection	0.3	FR4	Calibration method should be able to detect large disturbances that invalidate the existing calibration, such as settling, shifts from wind, etc. Ideally, the calibration should be verified and modified at any time of day, regardless of system state. While any disturbance will be detected once an imaging sequence fails, early detection can result in recalibration before subsequent imaging, preventing misses imaging windows, rescheduling, etc.

Metric	1	2	3	4	5
User involvement	5+ min	1-5 min	< 1 min	< 20 seconds	None
Imaging requirement	Slewing required for disturbance detection	Slewing required for calibration	Image processing required for disturbance detection	Image processing required for calibration only	Imaging unused
Additional Cost	100+ USD	50-100 USD	20-50 USD	<20 USD	No additional cost
Additional Mass	> 1 kg	< 1 kg	< 200g	< 20 g	None
Disturbance Detection	Never	> 20 seconds required , night only	Instant, night only	> 20 seconds required, any time	Instant, Any time

Fig. 44 Calibration Method Metric Values

Metric	Weight	MMA	AMA	CAM	SENS+ CAM
User involvement	0.3	1	4	5	5
Imaging interruption	0.2	4	4	1	4
Additional Cost	0.1	5	1	5	3
Additional Mass	0.1	5	1	5	4
Disturbance Detection	0.3	1	5	2	5
Total	1.0	2.4	3.7	3.3	4.5

Fig. 45 Calibration Method Trade Study

V. Selection of Baseline Design

A. Trade Study Results and Justification

1. Trade Study 1 Results: Materials

As a result of the material trade study seen in Figure 31, the polycarbonate plastic scored the highest by a considerable margin. The density of the material, which was the highest weighted metric, is extremely light which would greatly decrease the total weight of the box as a whole. In addition, its thermal conductivity and reliability scored fairly high as well which will be beneficial towards keeping a thermally insulated system as well as maintaining a strucutrally sound enclosure.

2. Trade Study 2 Results: Passive Protection

As seen in Figure 34, Polycase COTS boxes scored the highest and, thus, will be modified and used for the remainder of this project. Although they are relatively expensive, cost is not the driving factor for this design. Instead, the low weight, high durability, and ease of modification metrics compensated for it. The ability to purchase customized boxes with cable holes already cut may be desirable if multiple units of SHADE are constructed after the end of the project. Furthermore, depending on the size of modules, smaller COTS boxes may be used, thus reducing cost further. Polycase boxes, however, are lacking in vibration protection; therefore, they will need to be corrected for modules sensitive to vibration with further design. Finally, it is worth noting that all options scored within the range of 3 to 4, indicating that any option would be fitting for this design.

3. Trade Study 3 Results: Power Supply

As seen in the corresponding trade study above, a single LiFePO4 battery is shown to be the best power supply option for SHADE. While there is a significant initial cost associated with them, LiFePO4 batteries have the lowest cost per cycle life. Reducing the current three battery system down to one would save 20lbs of system mass initially. In addition the modular structure SHADE is implementing would allow a reduction in the the size main housing case. This is because there is no longer a need for the power supply to fit in the same case with the processor and camera system. While solar panels were considered for longer deployment span, their size and weight were determined to be in conflict with key functional requirements and therefore out of the project scope.

4. Trade Study 4 Results: Solar Cell Technology

The need for solar regeneration was driven primarily by battery limitations for extended deployments. Once an adequate battery was selected based off of values from WRAITH for power consumption, a charger was selected that minimized the time required to return the battery to a full charge. From the battery capacity and Victron Energy MPPT 75/15 solar charge controller specifications, the team was able to estimate the power required and voltage levels of an associated solar panel. With the final power required number from a solar array, they group traded different solar technologies to implement. Monocrystalline solar cells became a clear winner and will be implemented in a briefcase style folding solar panel designed to meet SHADE's requirements for weight and portability.

5. Trade Study 5 Results: Fasteners

The trade study conducted in figure 41 shows that the Dzus clips are the best fastener option for SHADE. Dzus clips are inexpensive and can be bought off the shelf, which means acquiring and replacing clips will be simple. With the fastening technique being a quarter turn, fastening modules to the base system will be dependent on the number of studs required to fasten all the modules. Proven as fasteners for skin panels on airplanes, the modules would be secure, and not taking as much bulk or weight on SHADE. Studs can be easily brought on board a toolbox by an operator. While Dzus clips scored the highest of all the other options, the other options scored from 3-4, the other options could be viable depending on cost and size.

6. Trade Study 6 Results: Calibration Method

The results in figure 45 show that of the considered options, it is best to use the AZ Mount Pro's built-in calibration, (with an image to verify it's accuracy) while monitoring system stability with an onboard IMU. The inclusion of an IMU (in the form of a two-axis accelerometer) allows the SHADE computer to determine if a large shift has occurred since the last calibration. This means that recalibration can be done before the next imaging sequence, instead of waiting for imaging failures which might significantly reduce system performance. Furthermore, the lack of operator involvement both reduces setup time and allows SHADE to recalibrate itself in the middle of deployment. This will mean the addition of a two-axis accelerometer and its control software, though cost and especially mass are small relative to the entire system.

7. System Design Summary

The results of the trade studies create a basis for SHADE's design and organization. During transport to the mission location, all components will be grouped and stored in passive protection and vibration protection cases. The camera, lens, and iOptron AZ mount will be the first group, the active weather protection box and computer will be the second group, the environmental suite will be the third group, and the power system, which includes the solar panel, charger, battery, and power conditioner, will be the final group. These groups will be protected through the passive protection design choice. When SHADE arrives at the mission location, the user will organize the various groups into three modules for deployment. The first module will be the active weather protection polycarbonate plastic casing, which will contain the camera, lens, iOptron AZ mount, and computer. The second module will be the environmental suite, which will be cased in a Polycase COTS box. The third module will be the power system, and all parts except the solar panel will be contained in Polycase COTS boxes.

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VI. Appendices

A. Standard Operating Conditions

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NOTE: The values stipulated by the SOC are currently carried over from WRAITH and are subject to change as better understanding of individual component sensitivity is attained, primarily relating to solar heating now that the mission profile includes daytime residence in-situ.

The operating conditions for the SHADE system are focused on defining suitable environmental and topographical conditions for deployment. The *Deployment* characteristics focus on the conditions present at the observation site prior to deployment while the *In-situ* characteristics focus on the dynamic atmospheric conditions during the observation period.

Deployment

1) The temperature range shall be between 0°C and 40°C.
2) The average relative humidity shall be below 50%.
3) The maximum ground grade shall not exceed 10°.
4) The minimum Sky Quality Meter (SQM) shall exceed 20 $\frac{mag}{arcsec^2}$

In-situ

1) The temperature range shall be between 0°C and 40°C.
2) The wind speed shall be less than 8 $\frac{m}{s}$.
3) Lightning shall be further than 15km from SHADE.
4) The relative humidity shall be below 80%.