# University of Colorado
# Department of Aerospace Engineering Sciences
# ASEN 4018

## Project Definition Document (PDD)

**Spacial HEO Autonomous Detector & Evaluator (SHADE)**

Monday, September 14th, 2020

**Approvals**

| Roll | Name | Affiliation | Approved | Date |
|---|---|---|---|---|
| Customer | M. Stakhiv / J. Aziz | Aerospace Corporation | Mark Stakhiv<br>Jonathan Aziz | 9/14/20 |
| Course Coordinator | Jellife Jackson | CU/AES | | |

**Project Customers**



| | |
|---|---|
| Name: Mark Stakhiv<br>Email: mark.stakhiv@aero.org | Name: Jonathan Aziz<br>Email: jonathan.d.aziz@aero.org |



**Team Members**



| | |
|---|---|
| Name: Robert Redfern, Project Manager<br>Email: robert.redfern@colorado.edu<br>Phone: (720) 884-6148 | Name: Quinton Dombrowski<br>Email: quinton.dombrowski@colorado.edu<br>Phone: (720) 545-6007 |
| Name: Benjamin Vidaurre, Systems<br>Email: benjamin.vidaurre@colorado.edu<br>Phone: (303) 919-7671 | Name: Elliott Tung, Electrical, Finance<br>Email: elliott.tung@colorado.edu<br>Phone: (650) 722-7894 |
| Name: Katherine Nyland<br>Email: katherine.nyland@sbcglobal.net<br>Phone: (847) 373-2021 | Name: Marlin Jacobson, Integration & Test<br>Email: marlin.jacobson@colorado.edu<br>Phone: (813) 765-8249 |
| Name: Jacob Weiner, Integration & Test<br>Email: jacob.a.weiner@colorado.edu<br>Phone: (330) 949-3521 | Name: Davis Peirce, Software<br>Email: davis.peirce@colorado.edu<br>Phone: (303) 847-7400 |
| Name: John Hugo<br>Email: john.hugo@colorado.edu<br>Phone: (702) 286-1565 | Name: Vinay Simlot, Finance<br>Email: vinay.simlot@colorado.edu<br>Phone: (703) 943-6508 |

# I. Problem Statement

As of April 1, 2020, 2,666 satellites orbit the Earth[2], with the global satellite industry generating almost $280 billion 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.

The Spacial HEO Autonomous Detector and Evaluator (SHADE) project will continue the design and development of the partially unfinished and untested WRAITH system from last year's senior design group. This project will enable the existing orbit tracking sensor to track LEOs, MEOs, GEOs, and HEOs and will improve upon its autonomy, weather resistance, and portability. This project will deliver software upgrades to the previous system for autonomous operation, an updated modular system with an overall reduced system mass, upgrades to the weather protection system, and robustness for off-road system transportation. Additionally, the system will operate at full power autonomously for at least 12 hours and be deployed by one person in less than 30 minutes. The hardware will survive through a safe mode status in adverse climate conditions through a weather protection system. Finally, the project will operate on a budget of $5000; thus, the project will provide and economical solution for the SSA community to accurately predict the reentry trajectories of HEOs.

# II. Previous Work

SHADE is a continuation of two previous senior design projects. The first iteration was the Ground-Based Hardware for Optical Space Tracking (GHOST). GHOST was designed to autonomously detect space objects in GEO, MEO, and LEO, and make orbital predictions based on the tracking images. The second iteration was WRAITH, which sought to build upon GHOST by tracking objects in HEOs, operate autonomously for 12 hours, and be deployed by two people in less than 30 minutes. Due to the Coronavirus pandemic in March of 2020, the team was unable to test the full WRAITH system or complete the project.

The previous WRAITH senior design team ended their project on March 13th, 2020. Many objectives were completed; however, many requirements were left unfinished. In terms of software, completed items include commanding software for the iOption actuation stage, Zwo camera, and lid actuation motor, infrastructure for the scheduler to take advantage of commanding software in an autonomous manner, and self-calibration software for right ascension and declination. Incomplete items include software for the closing of the weather protection system lid due to weather detection, GPS integration, scheduler reruns, scheduler mission objects, image processing for missing objects, and scheduler HEO commands. In terms of hardware, all manufacturing and assembly of the previous WRAITH system is complete; however, overall system testing and weather-proofing are incomplete. Lastly, in terms of the environmental suite, the testing of all sensors individually and suite assembly are complete. Incomplete items include anemometer testing, testing of core code with the fully constructed and installed sensor suite, testing of UART communications, testing in various weather conditions, and the code for cellular communications.

Spacefaring or not, governments will always have an interest in space situational awareness to protect their investments in satellite technologies or intelligence capability. The United States has the largest network of sensors to track satellites, the most important being the 'space fence', a radar system with a 6 GW fan beam. The Department of Defense uses a system of optical telescopes called the Ground-based Electro-optical Deep Space Surveillance System (GEODSS) to track satellites. Because of its optical nature, GEODSS is able to track the movement of satellites across the sky by taking multiple pictures of a given location, providing more information than the space fence design [1]. In total, the US government alone has spent an average of 1.03696 billion dollars each year over the past five years on SSA [3]. The Russian government also has SSA capabilities with their Military Space Surveillance Network, while the European Space Agency is developing their network. Other groups with SSA capabilities include the International Scientific Optical Network, and other militaries and civilian groups [4].

# III. Specific 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, once the capabilities of the system are determined, those levels of success may be amended.

**Table 1 Levels of Success**

| Category | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Scheduling | Accept list of SatIDs and sort based on FOV, time, and visibility constraints. Capability for up to 6 objects per hour. | Prioritize objects according to human input or probability of image capture. | Adjust schedule to search for a missing or manuevered object, and issue an alert when this occurs. |
| Image Processing | Extract endpoints of streaks at photometric SNR of 30 or less. | Level 1. | Determine missing space object or manuever. |
| Orbital Determination | Accurate orbit determination using Batch filter. | Level 1. | Predicting possible orbits for missing objects. |
| Pointing | Tracking HEO orbits near apogee (GEO). | Tracking HEO orbits near perigee (LEO). | Search for missing objects using predicted possible locations. |
| Environmental Control | Retract environmental protection in accordance with onboard sensors. Safety hardware will protect against moderate weather conditions including light rain, wind, and a limited temperature range. | Level 1. | Retract environmental protection in accordance with remote override from operators. Updates ground station with environmental state and safety hardware status. |
| Durability | Withstand up to 7 g in any direction[6]. | Withstand up to 7.42 g in any direction. | Withstand up to 8.1 g in any direction. |
| Modularity | One operator is able to deploy the modules toollessly, each weighing 50 or less pounds[5]. | Level 1. | Each module weighs less than TBD lbs. |
| Power Efficiency | Reduce power consumption by TBD. | Level 1. | Reduce power consumption by TBD such that the system can be deployed for N nights. |

# IV. High Level Functional Requirements

### A. 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 as defined by the Standard Operating Conditions document with no human intervention for 12 hours.
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 be able to image targets with an apparent magnitude less than 10 and process the images within 10 seconds
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 deployable and packable within 30 minutes by one operator.
8) The system shall withstand vibrations resulting from off-road vehicular transportation.

## B. Concept of Operations

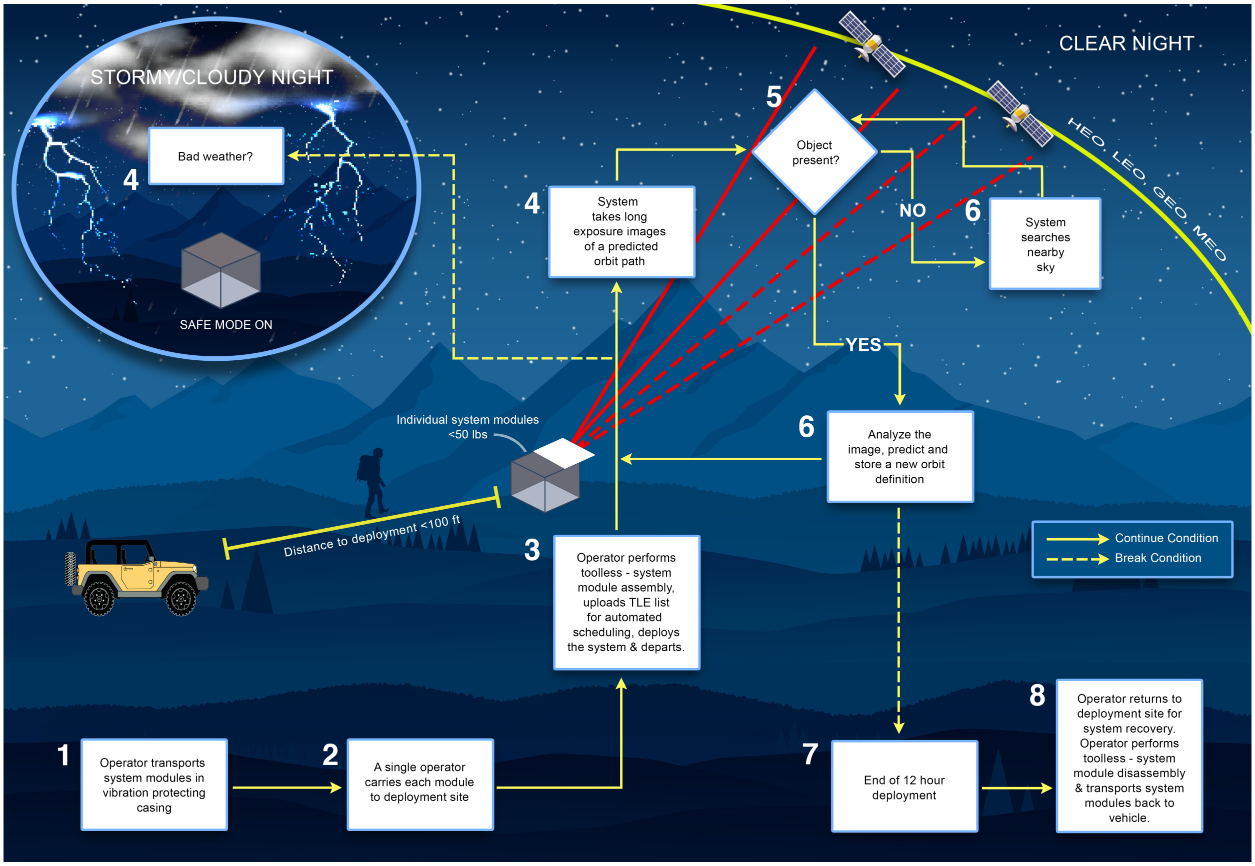


**Fig. 1 Mission Concept of Operations**

## C. Functional Block Diagram

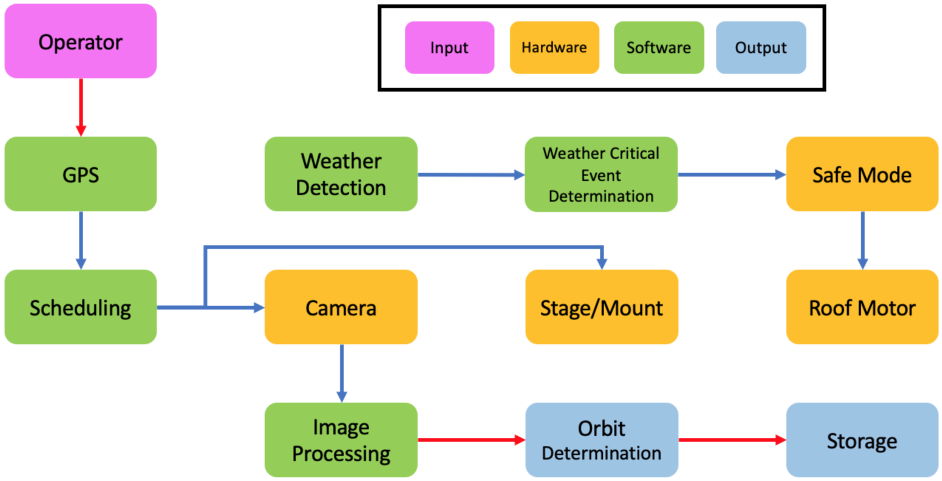


**Fig. 2 SHADE Functional Block Diagram**

## V. Critical Project Elements

### A. Scheduling Software

The scheduling algorithm will use on-board computing resources to determine up to six object visibility windows per hour while factoring in weather constraints. The software accepts sets of two-line elements (TLEs) and output the azimuth, elevation, and time stamps for each object's visibility window.

### B. Image Processing Software

SHADE will conduct real-time image processing to determine whether the target object is in frame and being tracked. If the target object is not in the frame, SHADE shall perform a search routine during which the target object should be located within one minute using only on-board computing resources.

### C. Environmental Protection System

The Environmental Protection System (EPS) shall be tested for full system functionality and interface with the on board hardware to determine safe operating conditions. The EPS sensors shall be modular in nature to allow for solderless replacement of individual components.

### D. Power System

The power system shall be able to provide full electrical power to the object tracker, roof actuator, and EPS. The electrical system is a carryover from WRAITH and will be studied to determine whether an increase in the total system endurance can be achieved.

### E. Optical Hardware

The existing optical hardware from WRAITH/GHOST will be tested and validated to ensure SHADE can meet existing functional requirements. It shall also be able to identify objects at altitudes between 300 and 36,000km.

### F. Orbital Determination and Tracking

SHADE will validate WRAITH's ability to determine an object's orbit after tracking the object. The orbit and track information are saved to on board storage for user access. SHADE shall also be able to track objects that are not in their expected location at the start of a visibility window.

### G. System Portability

SHADE shall be transportable by a single operator through the use of a modular design capable of deployment within 30 minutes without the use of tools. Each module shall weigh less than 50lbs and transportable for a minimum of 100ft.

# VI. Team Skills and Interests

**Table 2 Skills and Interests Table**

| Team Member | Skills/Interests | Critical Project Area |
|---|---|---|
| Quinton Dombrowski | C/C++/Java/MATLAB, ARM architecture and embedded software design, N-body physics simulation, UNIX, electronics/soldering | A,B,D,E,F |
| John Hugo | CAD in Solidworks and Autodesk Fusion 360, simulation and data analysis on MATLAB, systems engineering, Microsoft Excel, electronics/soldering | C,D,E,F |
| Marlin Jacobson | Software development used for simulation and data analysis in MATLAB and C++, systems engineering, thermal analysis, image processing, design in Solidworks and AutoCAD, soldering, hardware testing | A,B,D,F,G |
| Katie Nyland | Requirements Development, Project Management, Thermal and Vibration Testing, Sensor Testing, MATLAB/Arduino, 3D Printing, soldering, laser cutting, systems engineering, Microsoft Office, DOORs | C,D,E,G |
| Davis Peirce | Simulation and data analysis using MATLAB, thermal and structural analysis, orbital design and analysis, electronics/soldering, rapid prototyping, human factors engineering, | A,B,C,F,G |
| Robert Redfern | CAD In Solidworks & OnShape, STK Analysis, Arduino Programming, Project Management, Quality Management, PCB design/manufacturing, MATLAB/C++ Programming, Laser Cutting, Soldering, 3D Printing | A,C,D,F,G |
| Vinay Simlot | SolidWorks, AutoCAD, MATLAB/C++, Hardware, Machining | B,C,D,E,G |
| Elliott Tung | MATLAB, C++, Python, Electronics hardware wiring | A,C,D,E,G |
| Benjamin Vidaurre | Statistical modeling & analysis, MATLAB programming/simulation/optimization, systems engineering, astrodynamics, thermodynamics, quality management, technical writing | A,C,D,F,G |
| Jacob Weiner | Bread board prototyping, Soldering, Machining, 3D Printing, Data Analysis using MATLAB, RF communications | C,D,E,G |

# VII. Resources

### A. Heritage Equipment

Aerospace Corporation and the University of Colorado Boulder aerospace lab have provided the previous WRAITH hardware and software package to continue to build upon.

### B. WRAITH Team Members

Two of WRAITH team members are in contact with this team. Their knowledge of the previous WRAITH system will be helpful and critical for SHADE's understanding of the system for future planning.

### C. Aerospace Building Labs

The Aerospace Building has various resources, including materials and manufacturing centers, that may be of use for the team. The machine shop, specifically, will be a useful workspace for groups of team members. Additionally, the electronics lab will be of use for testing of electronic equipment.

**D. Team Member Houses**

Various team members' houses can be used as workspaces for the team while COVID restrictions are in place on campus in the event that access to campus resources are restricted.

**E. Space-Track.org**

All TLEs used for the system will come from the website above. The TLEs will be estimates based on the latest time the desired object was tracked. SHADE will then determine whether the estimate is still accurate for tracking.

**F. NOAA Weather Reports**

Weather reports will be used during the scheduling process to ensure that visibility requirements are met for the system. Additionally, these reports will be used by the operators to determine if adverse weather environments will be an issue before deployment of the system.

**G. NIST Timing Data**

The NIST timing data will be compared to the timestamps on output images by SHADE. These comparisons will help to validate the GPS-based timing data.

**H. University of Colorado Boulder Aerospace Faculty**

Many aerospace engineering professors and faculty at CU will be of great help to the team. Many members of faculty have expertise in manufacturing, electronics, orbital mechanics, and computer science. Their knowledge will be useful for the team when creating algorithms, completing testing, and manufacturing system parts.

**I. Mark Stakhiv & Jonathan Aziz**

Mark Stakhiv is the primary point of contact from Aerospace Corporation and is a member of the Mission Analysis and Operations Department. Jonathan Aziz is the secondary point of contact for the team from Aerospace Corporation and is a member of the Astrodynamics Department. Their expertise and experience will be useful for the team throughout the duration of the project.

| Critical Project Element | Resource/Source |
|---|---|
| Scheduling Software | Heritage (GHOST) |
| Image Processing Software | Heritage (GHOST) |
| EPS | Heritage (WRAITH) |
| Power System | Heritage (WRAITH) |
| Optical Hardware | Heritage (GHOST) |
| Orbit Determination & Tracking | Heritage (GHOST) |
| System Portability/Modularity | Aero. Labs & Off-the-Shelf Components |

## References


[1] Kennewell, John A, and Ba-Ngu Vo (2013). An Overview of Space Situational Awareness. Institution of Electrical and Electronics Engineers. *http://Ba-Ngu.vo-Au.com/ ba-ngu.vo-au.com/vo/KV_SSA_FUSION13.pdf.*

[2] UCS Satellite Database. (n.d.). Retrieved September 07, 2020, *from https://www.ucsusa.org/resources/satellite-database*

[3] United States Government Accountability Office. (n.d.). Retrieved September 08, 2020, *https://www.gao.gov/products/gao-16-6r*

[4] Libre Space Foundation. (n.d). Retrieved September 08, 2020, *https://libre.space/2020/03/02/space-situational-awareness/*

[5] OSHA procedures for safe weight limits when manually lifting. (2013-06-04). Retrieved September 08, 2020, *https://www.osha.gov/laws-regs/standardinterpretations/2013-06-04-0*

[6] Grzesica, Dariusz (2018). Measurement and analysis of truck vibrations during off-road transport. MATEC Web of Conferences *https://www.researchgate.net/publication/328194182_Measurement_and_analysis_of_truck_vibrations_during_off-road_transportation*