University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Optical **S**ensor **P**ackage for **R**elative **E**xploration (OSPRE) Conceptual Design Document (CDD)

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1.0 PROJECT INFORMATION

1.1 PROJECT CUSTOMERS

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1.3 RELATED DOCUMENTS

Name	**Revision**
Customer Requirements Document: “LM Sponsored CU ASEN Senior Project: Customer Requirements Document (2016-2017 academic year)”	1 (02AUG2016)
ASEN4018 Course Assignment: “Conceptual Design Document (CDD)”	2016

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1.6 NOMENCLATURE

D	diameter
kg	kilogram
m	meter
px	pixel
R	range
s	second
α	angular diameter

1.7 LIST OF ACRONYMS

CONOPS	Concept-of-Operations
COTS	Commercial, Off-the-Shelf
CR	Customer Requirement
DR	Design Requirement
ECI	Earth-Centered, Inertial Reference Frame
FOV	Field of View
FBD	Functional Block Diagram
FR	Functional Requirement
GNC	Guidance, Navigation, and Control
IDE	Interactive Development Environment
IR	Infrared Light
LM	Lockheed Martin Corporation
MP	Megapixels, (1×10^6 Pixels)
OSPRE	Optical Sensor Package for Relative Exploration
RAM	Random Access memory
UV	Ultraviolet Light

2.0 PROJECT DESCRIPTION

2.1 OVERVIEW

Small satellites such as CubeSats have gained popularity as lower-cost and lower-risk platforms for science payloads and technology testing. While numerous options exist for small satellite attitude determination and control systems, the determination of vehicle position generally relies on ground-based tracking or on-board GPS receivers. In order to utilize small satellites for missions deeper into space and beyond the operable range of ground tracking or GPS, alternate solutions must be developed to determine the inertial position of the spacecraft while still satisfying the requirements for very limited mass, volume, and power. One such method is that of “angles-only” relative-navigation, whereby position is resolved from image data of nearby celestial objects acquired by one or more compact imaging sensors when coupled with a known attitude.

This project will develop and test a prototype navigational package, named Optical Sensor Package for Relative Exploration (OSPRE), to include the requisite hardware and software, which implements a technique of “angles-only” navigation. The OSPRE system will be designed with integration aboard a Lockheed Martin (LM) CubeSat vehicle in mind, and has physical and functional requirements to allow for this. The primary mission of this satellite overall is to serve as a remote sensing test platform while executing a lunar flyby. The navigation system developed herein will provide the vehicle Guidance, Navigation, and Control (GNC) computer with regular updates to its state vector, including inertial position, velocity, and their respective errors for at least the duration of the lunar transit.

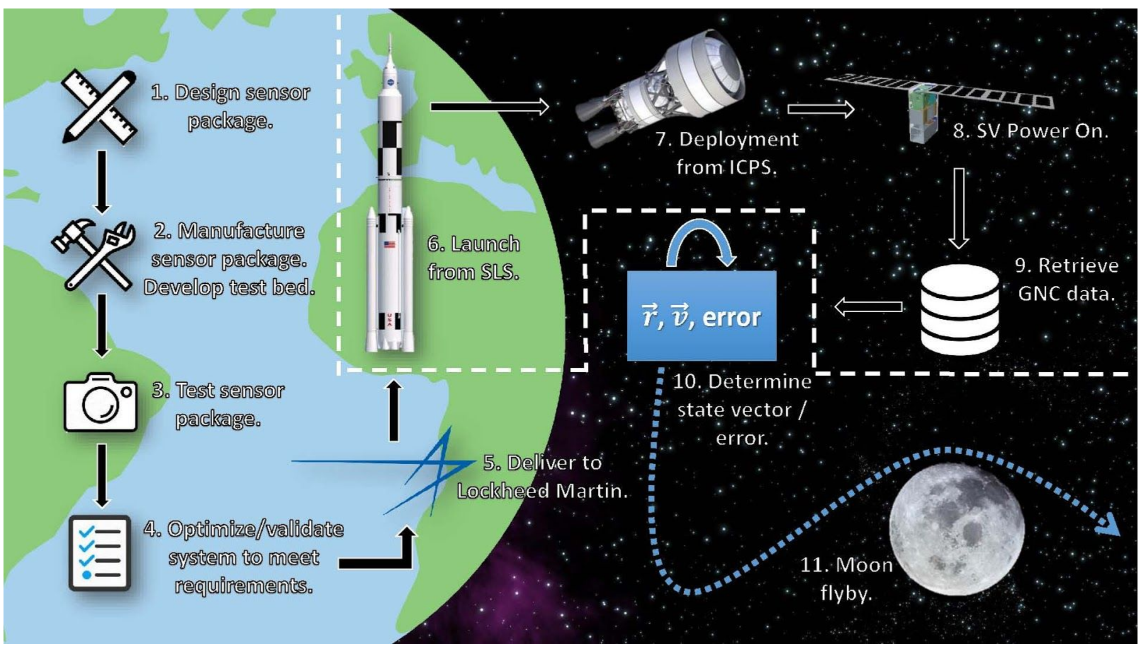

Figure 2.1 Mission Concept of Operations

The overall project and mission flow is illustrated in Figure 2.1 below. The OSPRE navigation package will utilize a Commercial-Off-the-Shelf (COTS) microcontroller to command sensor acquisition and process imagery of the Earth and Moon, measuring both their size and location within the field of view. Provided a known vehicle orientation in terms of quaternions from the vehicle GNC computer, the sensor package will then determine the angles to each target, and compute the spacecraft position in the Earth-Centered-Inertial (ECI) frame. Consecutive measurements will be utilized to compute velocities in the ECI frame and, together with the computed position and relative error, be passed to the vehicle GNC computer as a state vector update. Given the uncertainty that accurate initial conditions will be available upon vehicle deployment, the OSPRE system will not be designed with an over-reliance on these conditions for orbital propagation, but will instead rely primarily on its own relative solution and processing based upon direct measurement. When available, the imaging of other celestial objects such as sun angle and their respective angular positions may be utilized for error-checking and validation.

This document will provide a list of key design requirements with respect to functional requirements, detail and compare several high-level subsystem design approaches with respect to their satisfaction of those requirements, and ultimately select a baseline design approach for work moving forward.

2.2 CONCEPT OF OPERATIONS

The concept of operations for the OSPRE prototype to be designed, developed, and tested during the course of this project is illustrated in Figure 2.2. Initially, OSPRE will be placed in an initial location within the testing environment at which point it will power on and initiate its data acquisition script (1). Prior to any images being taken, OSPRE will receive an initial set of simulated data from a computer that the OSPRE team will provide, including a sun angle, attitude quaternion, J2000 time, and moon/sun ephemeris (2). OSPRE will then take an image of the simulated celestial body and process this image utilizing the chosen navigational algorithm (3). This will provide a position vector and position error which will subsequently be saved into OSPRE's memory. Given that two distinct positions and times are required in order to determine a velocity, an initial velocity cannot be calculated after the first image. Therefore, OSPRE will be physically moved within the testing environment to another exact location for which the OSPRE team has simulated data (sun angle, quaternion, etc.) (5). Steps (2) through (5) are then completed again; however, following the image capture, vectors for both position and velocity and their respective errors can be calculated. This process is repeated indefinitely until OSPRE's performance within the testing environment is deemed satisfactory.

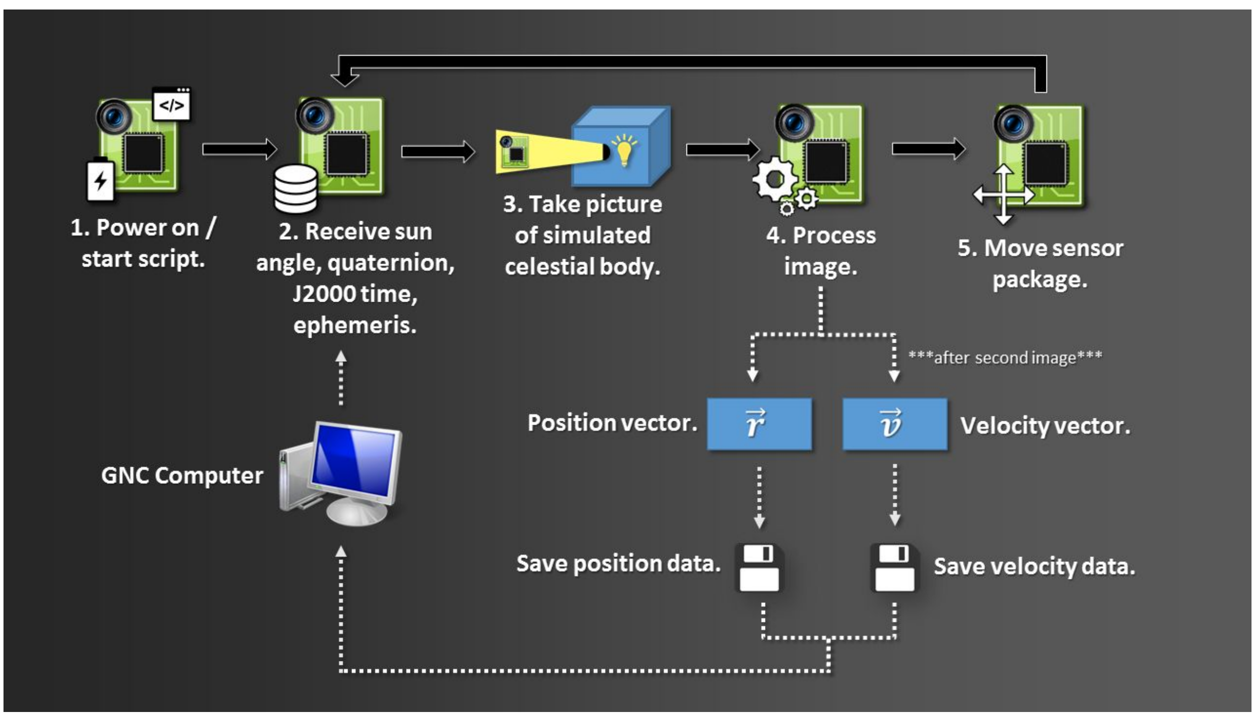

Figure 2.2 Concept of Operations for OSPRE Test

2.3 FUNCTIONAL BLOCK DIAGRAM

The OSPRE deliverables can be described in two main packages: the test bed and the sensor package. Contained within the sensor package is the image sensor, while the test package contains the microcontroller test console and any necessary peripherals. As illustrated in Figure 2.3, during testing images will either be simulated through calculating scale images in software, or captured directly by creating a darkroom environment with projected images. The simulated images will be used initially while the physical test environment is being created. These images are then passed to the ZedBoard test bed computer where they are post-processed and handled by the algorithm to return the state vector and state error. A more detailed functional flow diagram including only the OSPRE system appears in Appendix B.

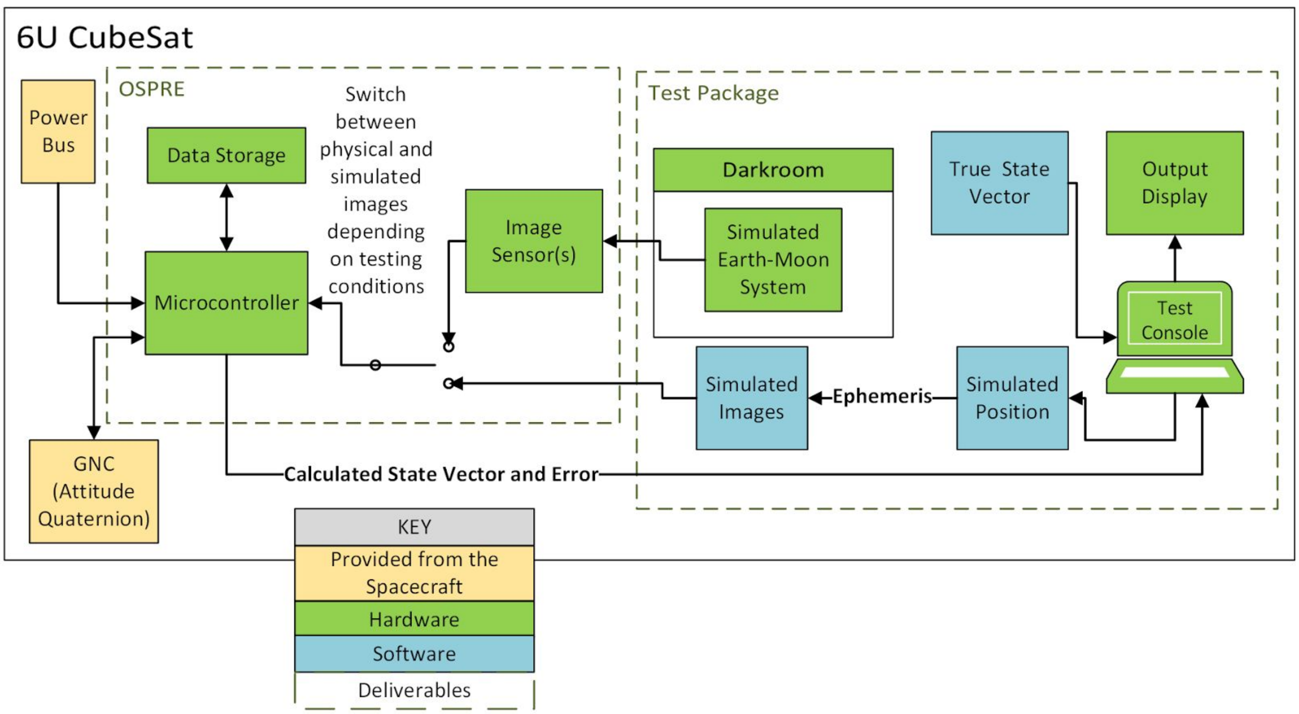

Figure 2.3 Functional Test Flow Diagram, OSPRE Prototype Test

2.4 FUNCTIONAL REQUIREMENTS

The Functional Requirements (FR) for the OSPRE system are largely customer-specified requirements for both the navigation package hardware and microcontroller software which will communicate with and control the navigation package. These include specific requirements concerning the operation of the OSPRE system, electrical and communication interfaces, and software input and output. The following list categorically identifies each of the high-level functional requirements for the OSPRE system, identifying the most high-level Functional Requirements with the prefix "FR". Design requirements derived from these functional requirements are listed in Section 3.

FR0.0 OSPRE shall provide relative navigation from an image sensor package for a Lockheed Martin CubeSat on a lunar trajectory.

FR1.0 OSPRE shall determine the state vector and state vector error of the simulated spacecraft.

1.1 OSPRE shall use a method of angles-only navigation to determine the state vector of the simulated spacecraft.

1.2 OSPRE shall determine the position of the simulated spacecraft to within 1000 km of the true position.

1.3 OSPRE shall determine the velocity of the simulated spacecraft to within 250 m/s of the true velocity.

1.4 OSPRE shall determine the angle between the earth, the spacecraft and the moon.

1.5 OSPRE shall determine validity of the solution.

FR2.0 OSPRE shall comply with all Lockheed Martin integration requirements in accordance with the "Customer Requirements Document" listed in Section 1.3, included below for reference.

2.1 OSPRE shall comply with all Lockheed Martin electrical integration specifications.

2.2 OSPRE shall comply with all Lockheed Martin communication protocols.

2.3 OSPRE shall be controlled with a ZedBoard development board.

2.4 OSPRE shall output telemetry for the simulated spacecraft.

2.5 OSPRE shall acquire image data for no more than one hour continuously and wait at least one hour between these acquisition periods.

3.0 DESIGN REQUIREMENTS

3.1 DESIGN REQUIREMENTS

The following Design Requirements (DR) were either derived from the functional requirements listed in Section 2.6 or specified by the customer. Design Requirements consist of requirements for the design of both the navigation hardware, referred to as the "OSPRE Navigation Package" and control software to be installed on the connected microcontroller, referred to as "OSPRE Software". Many Functional Requirements of the OSPRE Software correlate directly to Design Requirements. Each Design Requirement below is numbered within the list to match the functional requirement in Section 2.4 from which it was derived.

Table 3.1 Functional and Design Requirements Matrix

<table>
<tr><th>FUNCTIONAL REQUIREMENT(S)</th><th colspan="2">DESIGN REQUIREMENT AND VERIFICATION METHOD</th></tr>
<tr><td rowspan="3">FR0.0</td><td rowspan="2">DR0.0:</td><td>OSPRE Navigation Package shall include one or more image sensors and associated hardware capable of acquiring images of the Earth and Moon throughout the specified mission.</td></tr>
<tr><td>DR VERIFICATION: Hardware Inspection and Test</td></tr>
<tr><td colspan="2">FR VERIFICATION: Demonstration and Functional Test</td></tr>
<tr><td rowspan="3">FR1.0</td><td rowspan="2">DR1.0:</td><td>OSPRE software shall be designed to process acquired imagery and compute a state vector update.</td></tr>
<tr><td>DR VERIFICATION: Software Inspection/Review</td></tr>
<tr><td colspan="2">FR VERIFICATION: Software and Hardware Functional Test</td></tr>
<tr><td rowspan="8">FR1.1</td><td rowspan="2">DR1.1.1:</td><td>OSPRE software shall include the processing of imaging sensor data as a primary means of measurement to determine the direction to the Earth and Moon.</td></tr>
<tr><td>DR VERIFICATION: Software Review and Test</td></tr>
<tr><td rowspan="2">DR1.1.2:</td><td>OSPRE software shall receive as input the time in seconds past J2000, Sun and Moon ephemeris, Sun angle, and the simulated spacecraft's attitude quaternion.</td></tr>
<tr><td>DR VERIFICATION: Software Review and Test</td></tr>
<tr><td rowspan="2">DR1.1.3:</td><td>OSPRE software shall include the computation of the angles between the simulated spacecraft, Earth, and Moon in all phases by utilizing those inputs listed in DR1.2 and DR1.2.1.</td></tr>
<tr><td>DR VERIFICATION: Software Review and Test</td></tr>
<tr><td rowspan="2">DR1.1.4:</td><td>OSPRE software shall include the estimation of the range to the Earth and Moon from the simulated spacecraft by utilizing those inputs listed in DR1.1.1 and DR1.1.2.</td></tr>
<tr><td>DR VERIFICATION: Software Review and Test</td></tr>
</table>

	DR1.1.5:	OSPRE software shall output the computed state vector update and error in the ECI reference frame.
		DR VERIFICATION: Software Review and Test
	FR VERIFICATION: Hardware and Software Functional Test	
FR1.2	DR1.2:	OSPRE software shall include the computation of the position and the position error of the simulated spacecraft and be capable of achieving an error of less than 1000km from actual position.
		DR VERIFICATION: Software Review and Test
	FR VERIFICATION: Software Review, Functional Test, and Error Analysis	
FR1.3	DR1.3:	OSPRE software shall include computation of the velocity and velocity error of the simulated spacecraft and be capable of achieving an error of less than 250 m/s from actual velocity.
		DR VERIFICATION: Software Review and Test
	FR VERIFICATION: Software Review, Functional Test, and Error Analysis	
FR 1.4	DR1.4:	OSPRE software shall include computation of the angle between the Earth, spacecraft, and the moon
		DR VERIFICATION: Software Review and Test
	FR VERIFICATION: Software Review and Functional Test	
FR 1.5	DR 1.5:	OSPRE software shall include validation of the calculated position and velocity solutions
		DR VERIFICATION: Software Review and Test
	FR VERIFICATION: Software Review and Functional Test	
FR2.0	DR2.6:	OSPRE shall have a total system mass of less than or equal to 0.8 kg.
		DR VERIFICATION: Physical Inspection and Measurement
	DR2.7:	OSPRE shall have overall dimensions of 5 cm. x 5 cm. x 1 cm.
		DR VERIFICATION: Physical Inspection and Measurement
	FR VERIFICATION: Inspection, Functional Test, and Electrical Test	
FR2.1	DR2.1:	OSPRE electrical power distribution and instrumentation systems shall be designed or selected to comply with all Lockheed Martin electronic integration specifications.
		DR VERIFICATION: Inspection and Electrical Test
	DR2.1.1:	OSPRE Navigation Package electrical power distribution system shall operate

		nominally with an input voltage or voltages of 3.3, 5, and/or 12VDC. All components of the OSPRE Navigation Package requiring electrical power shall be designed or selected to utilize one or more of these voltage levels or some division thereof.
		DR VERIFICATION: Electrical Test, Inspection by measuring voltage
	DR2.1.2:	OSPRE Navigation Package shall be designed such that it does not exceed a peak current of greater than 500mA.
		DR VERIFICATION: Electrical Test, Inspection by measuring current
	DR2.1.3:	OSPRE Navigation Package shall be designed to require no more than 3W of power.
		DR VERIFICATION: Electrical Test, Analysis by using voltage and current to determin power
	FR VERIFICATION: Component Inspection and Electrical Test	
FR2.2	DR2.2:	OSPRE Navigation Package and software shall be designed to utilize Lockheed Martin specified communication protocols.
		DR VERIFICATION: Review/Inspection and Demonstration
	DR2.2.1:	OSPRE Navigation Package shall be designed to communicate with the microcontroller through SPI, I2C, and/or CameraLink protocols. Navigation Package components should be selected such that they are capable of interfacing with one or more of these protocols. However, the interface through which the OSPRE Navigation Package communicates with the microcontroller shall do so with only one of these protocols.
		DR VERIFICATION: Design Review
	FR VERIFICATION: Communications Demonstration	
FR2.3	DR2.3:	OSPRE's software shall be designed and OSPRE's operating system shall be selected to operate on a ZedBoard controller.
		DR VERIFICATION: Software Review
	FR VERIFICATION: Software Demonstration	
FR2.4	DR2.4:	OSPRE software shall be designed to output telemetry for utilization by the simulated spacecraft GNC system.
		DR VERIFICATION: Software Review and Demonstration
	DR2.4.1:	OSPRE software shall store position update telemetry relative to the ECI frame and associate it with a timestamp indicating the time in seconds past J2000 at which that computed position was valid. OSPRE shall provide position error update telemetry relative to the ECI frame and associate it with a timestamp indicating the time in seconds past J2000 at which that computed position error was valid.

		DR VERIFICATION: Software Review and Demonstration
	DR2.4.2:	OSPRE software shall store velocity update telemetry relative to the ECI frame and associate it with a timestamp indicating the time in seconds past J2000 at which that computed velocity was valid. OSPRE software shall store velocity error update telemetry relative to the ECI frame and associate it with a timestamp indicating the time in seconds past J2000 at which that computed velocity error was valid.
		DR VERIFICATION: Software Review and Demonstration
	DR2.4.3:	OSPRE software shall store the computed Earth-Spacecraft-Moon angle update telemetry and associate it with a timestamp indicating the time in seconds past J2000 at which that computed angle was valid. Each successive angle update determined to be valid by the OSPRE software shall not overwrite valid solutions at previous times.
		DR VERIFICATION: Software Review and Demonstration
	DR2.4.4:	OSPRE Navigation Package shall be designed to output telemetry providing the capability of monitoring the operational status of the OSPRE Navigation Package hardware and providing a means by which basic system faults may be diagnosed.
		DR VERIFICATION: Software Review and Demonstration
	FR VERIFICATION: Software Review and Demonstration	
FR2.5	DR2.5:	OSPRE Navigation Package and software shall be designed such that the image acquisition period necessary for an acceptable solution requires no more than one hour. The OSPRE system shall be designed to then wait at least an additional hour before attempting to acquire new imagery or request simulated spacecraft maneuvering to target.
		DR VERIFICATION: Software Review and Timed Functional Test
	FR VERIFICATION: Functional Demonstration and Test	

3.2 REQUIREMENT VERIFICATION METHODS

The method of verification associated with each of the preceding requirements is listed in Table 3.2 below. Each verification procedure is indexed by the Functional Requirement number or series with which both it and the particular Design Requirement to be satisfied are associated per Table 3.1. Those requirements whose satisfaction will be simply demonstrated without a functional test, analysis, or measurement are not included in this matrix.

Table 3.2 Requirement Verification and Test Matrix

REQUIREMENT(S)	VERIFICATION/TEST METHOD
FR0.0	The Earth and Moon will be physically simulated and imaged by the sensor package in a controlled environment to include lighting conditions and scale representative of those conditions specified by the mission profile. Execution of the corresponding test procedure will determine whether or not the sensor package has the capability to acquire imagery of these test targets of sufficient quality such that the computed position and velocity is within the maximum error specified by FR1.3 and FR1.4. This test procedure software will utilize the same algorithms as the OSPRE software to locate the target in the field of view with respect to elevation and azimuth, estimate its diameter, and compare those to known values measured independently during test equipment fabrication and setup.
FR1.0SERIES	OSPRE software will be be tested by providing known inputs corresponding to those listed in DR1.2 and DR1.2.1 and comparing the output of each software component (i.e. function or method) and the combined software to known, analytically-determined values.
FR1.2.SERIES	The OSPRE software image processing and measurement component will be tested by providing either simulated or real images of the Earth and Moon which have been resampled to match selected sensor characteristics. Software determination of target direction and size will be verified by manual measurement of the input images in Adobe Photoshop(R). The OSPRE software navigational and validation components will similarly be tested with known inputs and outputs, the latter of which will be compared to analytically or independently-computed values. The true error of each resulting state vector update and Earth-SC-Moon angle will be determined with the given input analytically in order to verify OSPRE compliance with the maximum allowable error listed defined by FR1.3 and FR1.4.
FR2.1SERIES	The OSPRE input to the OSPRE Navigation Package electrical power supply will be monitored with bench-top electrical test equipment during system start-up, operation, and shut-down to ensure compliance with this series of requirements.
FR2.4SERIES	The storage or output of accurate telemetry from the OSPRE software, to include all items listed in this series, will be verified by analysis of that data output or stored by the system following a functional test.

4.0 KEY DESIGN OPTIONS CONSIDERED

The OSPRE project can be conceptually broken up into a three major subsystem design spaces: the Imaging System design space, the Embedded Systems design space, and the Testing Methods design space. Each of these design spaces come with their own requirements that provide constraints that limit what may be considered to achieve the project objectives. In accordance with DR0.0 and DR1.0, as listed in Section 3.0, OSPRE shall contain and utilize an imaging sensor(s) to collect data to feed to the navigation algorithm which, in turn, limits the design space of the Imaging System. Per DR2.3, OSPRE must be capable of running on and interfacing with some sort of ZedBoard development board, which limits the Embedded Systems design space. A method of operationally testing the combined OSPRE software and hardware, to include a physical test setup, will also be required in order to demonstrate compliance with numerous requirements.

4.1 IMAGING SYSTEM OPTIONS

Containing and utilizing an imaging sensor is a hardware requirement provided by the customer. Consequently, this requirement limited the Imaging System design space to various imaging sensor-based designs rather than looking for alternative approaches such as laser ranging or using photodiodes. The team considered the impact these alternative options would have on the system in case they could be used in addition to the imaging system and/or if the customer requirements could be changed. Initial estimates indicated that the laser ranging approach would require an extremely high powered laser in order to travel the distances required for this application which would drive up costs and power requirements greater than permitted. On the other hand, the photodiode approach would not provide sufficient resolution to achieve the necessary accuracy. In the imaging sensor realm, the team evaluated options such as imaging at different wavelengths of light, at multiple focal lengths, and the use of more than one sensor. The three regions of light considered for the Imaging System's conceptual trade study were narrowed down to visible light, ultraviolet light (UV), and infrared light (IR) due to commercial availability as well as previous image-based navigation system designs. Each region of light has its own benefits and drawbacks that should be considered when considering design configurations.

Using visible light to image the Earth and Moon was the first region of light considered because it was the most familiar, had the greatest hardware availability, and offered the greatest simplicity in testing. Imaging in the visual spectrum also allows for the greatest number of camera lenses and sensors to be considered due to the commercial off-the-shelf (COTS) options available that fit in the required volume constraints. This meant that the OSPRE project could more readily select the option that best balances having a high resolution and/or high focal length while maintaining relatively low cost. Using visible light image sensors would also prove more cost effective in the testing phase of the project. Concerns for using visible light include the visible spectrum luminance of the Earth and Moon in different phases, the sensitivity of commercially available sensors, as well as the high focal length/ high resolution combination necessary to meet the accuracy requirements. A visible light camera would be relatively unhelpful in dealing with the different phases of the Earth and the Moon considering the dark sides of both celestial bodies don't reflect nearly as much visible light. As a result, the algorithm would have to analyze phased shapes instead of full circles, as shown in Figure 4.1a, which adds complexity to the software and potentially introduces additional error. Alternatively, the camera could take an image with a long enough exposure to resolve the dark side of the celestial bodies. As a consequence, that would over-saturate the light side of the moon and introduce additional noise, as seen in Figure 4.1b. Combining these two exposures using high dynamic range (HDR) software could offer optimal exposure but needs to be studied further to analyze the error it may introduce.

Figure 4.1a Crescent moon with low exposure[1]

Figure 4.1b Crescent moon with high exposure[2]

Using ultraviolet (UV) light to image the Earth and the Moon has the potential to provide a high contrast between the edge of the celestial body and the blackness of space; however, it was quickly discovered the drawbacks of using UV light greatly outweigh the benefits. Specifically, imaging in ultraviolet light would add a great deal of complexity and/or cost to the Imaging System, because 1) it would require filtering the light prior to reaching the sensor, 2) because most CCD and CMOS camera sensors have poor responsivity in the UV region, and 3) because it doesn't help in dealing with phases since the Earth and the Moon don't generate their own UV light (as shown in Figure 4.2).

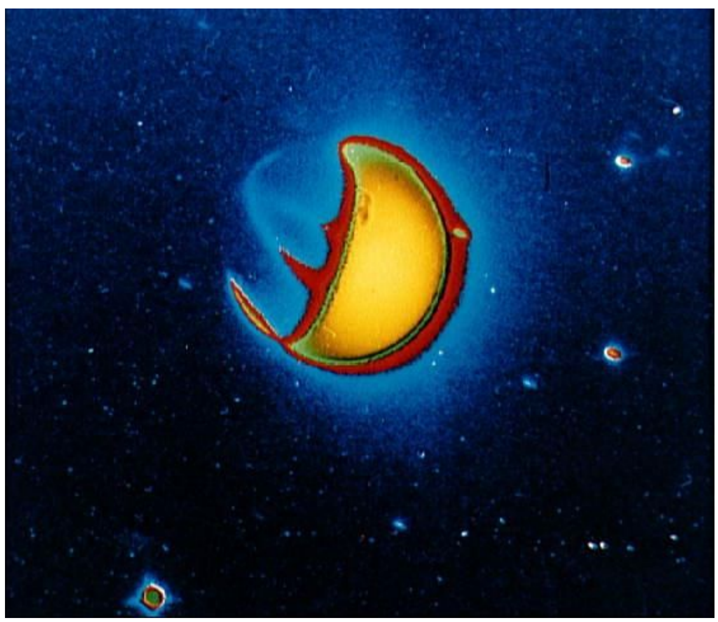

Figure 4.2 Image of the Earth in UV taken from the Moon[3]

Using infrared (IR) light to the image the Earth and the Moon is a popular technique because all celestial bodies emit infrared light, as well as reflecting the light from the Sun. Since both the Earth and the Moon emit light in the mid to far infrared (15 to 100 microns), it could prove easier to capture images of the entire disk regardless of phase (as seen in Figure 4.3). IR sensors are also very common for use in horizon tracking or for when the spacecraft is so close to the body that the camera can only image part of the disk. Some of the drawbacks in using IR light sensors include a decrease in sensor resolution (with respect to most visible wavelength cameras) that is common in IR cameras and the lack of available camera options due to limited commercial availability within the required volume constraints. Due to the limiting size of the volume envelope listed in the requirements, there are limited COTS options for IR camera sensors, which will either decrease the quality of the sensor or drastically increase the cost.

Some common metrics for all imaging sensors are the pixel resolution and the resulting field of view (FOV), which are dependent on the focal length of the lens being used. In order to be within the required position accuracy of 1000 km, either the resolution of the camera needs to be very high, the FOV of the camera narrow, or a combination of both. This design driver was realized by correlating the instrumentation error associated with the camera and how much physical space each pixel represents for a given image. For the sake of conducting a trade study on various imaging systems, the OSPRE team defined a standardized metric called the pixel-to-degree ratio which could be computed for any lens and sensor combination. Since the focal length of the lens and the physical size of the sensor can be used to calculate the resulting FOV of the camera (in degrees) and the imaging sensor has a set resolution (in pixels), the pixel-to-degree ratio for any camera can easily be obtained. By analyzing the position in flight where the instrumentation error will be the greatest, a required pixel-to-degree ratio that will keep the maximum position error within 1000 km can be determined and used to evaluate various imaging systems.

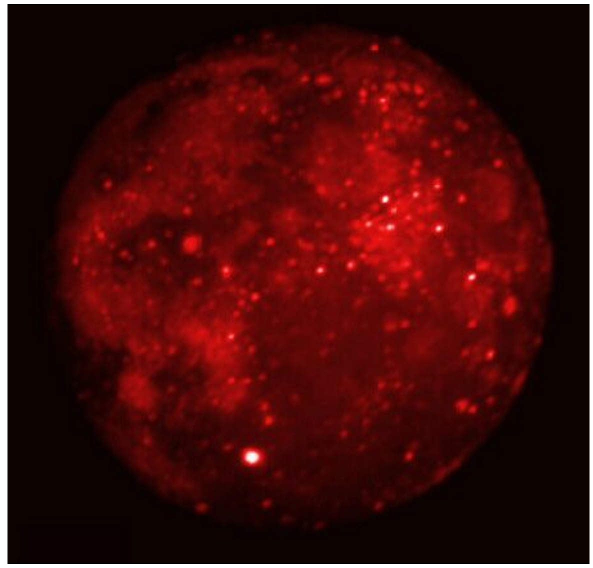

Figure 4.3 Image of the Moon in IR during a total lunar eclipse[4]

As seen in Figures 4.4a and 4.4b below, the approximate position with the greatest instrumentation error can be determined using a simple linear model for range, and the range error can be determined due to a limited number of pixels in a given image sensor. Using a simple model that assumes a linear flight path from the Earth to the Moon, the range (R) to both celestial bodies, with known diameters (D), can be computed and then used to estimate the apparent angular diameter (α) of each celestial body using Equation 4.1 The instrumentation error is implemented assuming that there is an error of one pixel on each side of the apparent angular diameter, which will either increase or decrease the apparent angular diameter by two pixels. Using the new angular diameter that includes the two pixel error, the range is then recalculated by solving Equation 4.1 for the range (R). This process is repeated at each location throughout the linear flight path in 1 km increments, for both the Earth and the Moon, in order to determine the approximate location at which the range error from both celestial bodies intersect and the location at which the spacecraft would turn to begin imaging the Moon. As seen in Figure 4.4a, it is at this location, not the location with the minimum apparent angular diameter (α_{min}), that the range error is a maximum. However, based on the camera selected, the angular span of one pixel changes depending on the camera's resolution and FOV. Since the maximum error is dependent on the angular span of two pixels being either added to or subtracted from the apparent angular diameter of the celestial bodies, the maximum error is also a function of the pixel-to-degree ratio of the camera. A camera with a small FOV and/or a high resolution would result in a high pixel-to-degree ratio, which would decrease the width of the two pixel error added to or subtracted from the apparent angular diameter of the celestial bodies, thus decreasing the resulting maximum error. This relationship can be seen in Figure 4.4b thus a high pixel-to-degree ratio will be desired by all of the imaging systems evaluated.

$$\text{Ang. Diameter } (\alpha) = 2\arctan(\tfrac{1}{2} D / R) \qquad \text{Equation 4.1}$$

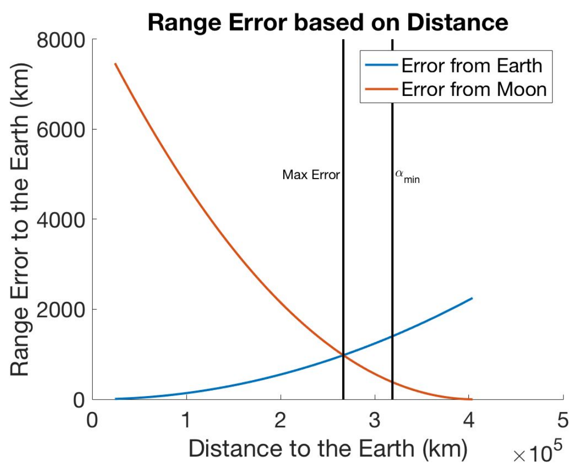

Figure 4.4a

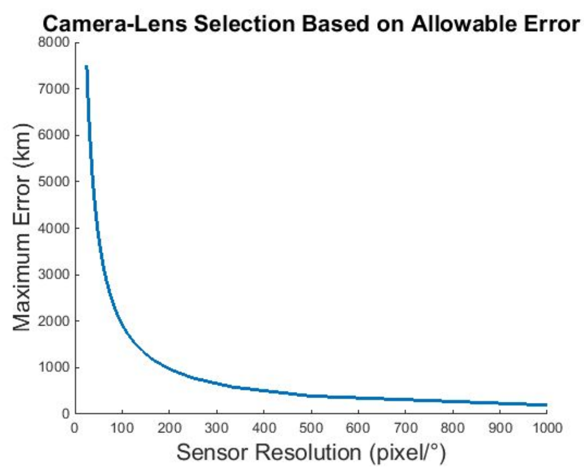

Figure 4.4b

4.1.1 One visual light camera

The simplest viable solution approach would be a single visual light camera. A single visual light camera would take up the least amount of volume, leaving more room for mounting mechanisms and other components, and would draw the least amount of power, leaving more wattage to be allocated to other components. This solution would be less expensive than other solutions because the cost would only have to cover a single sensor and there are a large range of visual sensors to choose from. The main design driver for this configuration is that the camera would need to have a high enough resolution to accurately analyze the Earth and Moon when both are very far away and thus small in the camera's field of view (FOV). This design driver must be balanced with having a wide enough FOV to image the entirety of the Earth upon deployment (about 20°). If this counterbalance is not achieved the image processing would have to work for partially imaged bodies which increases software complexity and error potential.

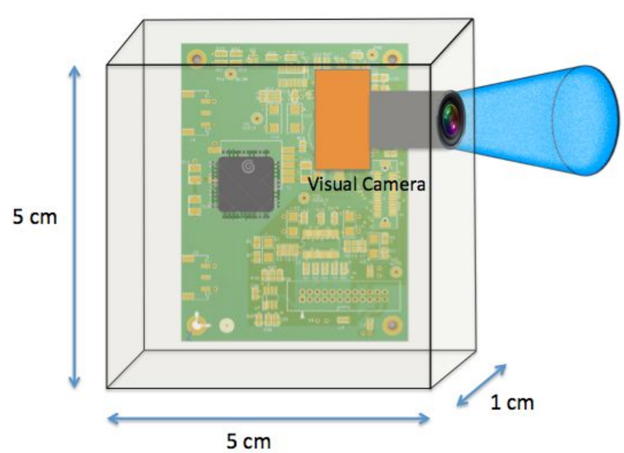

Figure 4.5 One visual camera configuration

Having a single sensor would only allow the sensor package to take data from a single piece of the sky at once, making it effectively impossible to view the Earth and the Moon at the same time. If the algorithm depends on comparing the relative angles of the Earth and the Moon, images of both would be required and thus the spacecraft would have to slew between image captures. This would increase the complexity of the algorithm and would introduce additional error inherent to the spacecraft estimating how far it moved between the two captured images. Thus, this configuration may be more appropriate if paired with an algorithm that depended on imaging a single celestial body during each data collection cycle.

The pixel resolution for these kinds of camera sensors that fit within the allocated volume have a range between 5 megapixels (MP) and 14 MP. The field of view typically lies around 50°, but could be decreased by increasing the focal length of the lens. However, adding a lens that will fit within the volume constraints could be difficult to find. These kinds of cameras usually cost several hundred dollars. The largest obstacle to this solution would be finding a camera with a high enough pixel-to-degree ratio to generate an accurate solution when the spacecraft is far away from the celestial bodies. In other words, having a single camera would require it to have both a large FOV for close proximity operations and a large pixel-to-degree ratio for far proximity operations, requiring an extremely high resolution.

PROS	CONS
Low complexity	Difficult to find sensor with adequate FOV and resolution that fits within volume constraint
Low volume	Limits viewing to a single piece of the sky at a time
Fairly easy to test	Having a single focal length/FOV will produce high error for some positions in flight

4.1.2 Two visual light cameras with one wide FOV and one narrow FOV

Adding an additional visual light sensor would slightly increase the complexity of the system. The system would still only have to deal with a single kind of sensor (i.e visual light), but would have to take into account differing FOVs. This configuration would utilize one camera with a relatively large FOV and a another camera with a smaller FOV. It would take up more power and more volume than the preceding solution.

When the spacecraft is very close to the Earth or the Moon, the celestial body will completely fill the camera’s FOV, making it very difficult to generate an accurate solution. The wide FOV camera would minimize the time that the FOV is completely filled, allowing a longer window to determine a solution. If the spacecraft is deployed near geosynchronous orbit (GEO), the FOV must be at least 20° to contain the entirety of the Earth. Thus, the wide FOV camera should have a FOV of at least 20°.

However, a wider FOV camera will have a smaller pixel-to-degree ratio, which will result in a less accurate solution. Therefore, as soon as the celestial body can fit inside the FOV of the smaller FOV camera, the system would switch to using the second camera. This would provide higher accuracy when the Earth and the Moon are both very far away and thus appear small in the camera’s FOV.

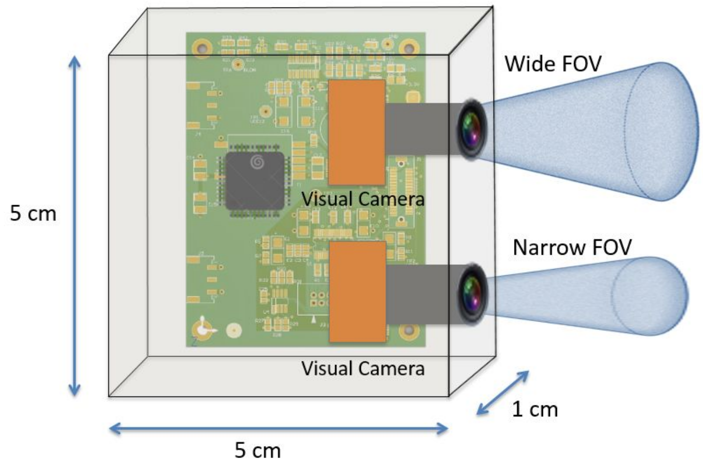

Figure 4.6 Two visual cameras configuration

This solution would allow more flexibility in camera choices. A single camera configuration would require a camera with an extremely high resolution, since it would need to have a wide FOV to deal with close proximity, while still achieving a high enough pixel-to-degree ratio to allow for an accurate solution at far proximity. A two camera configuration, however, would not require as high of a resolution sensor, since the wide FOV camera wouldn't have to deal with far proximity. The pixel-to-degree requirement for the wide FOV camera would be significantly lower, because the celestial body is much larger in the camera's FOV, and the pixel-to-degree requirement for the small FOV camera would be easier to achieve with the smaller field of view.

Similar to the preceding solution, the two visual cameras configuration would work best with an algorithm that depends on only observing a single celestial body at once. The primary obstacle for this solution is that it will be difficult to find a small FOV camera without violating the volume requirements, since a smaller FOV is achieved with a longer focal which requires a longer lens.

PROS	CONS
Flexible camera choices	Difficult to find small FOV camera that fits in volume constraints
Accurate at both near and far proximities	Limits viewing to a single piece of the sky at a time
Fairly easy to test	Doesn't help with addressing Moon or Earth phases

4.1.3 One visible light camera and one infrared camera

Adding an infrared (IR) camera would increase the complexity because, not only is there an additional sensor, but a separate type of sensor as well. The algorithm would have to have different protocols for dealing with the different types of sensors. Furthermore, an IR camera would be more difficult to test because it would be more difficult to create an uncontaminated test setup, since human bodies emit IR even when in the dark.

A single IR sensor is not a viable solution because the resolution on IR sensors is typically smaller than visual light sensors, and a single IR sensor would not be able to achieve the required pixel-to-degree ratio. However, IR sensors are often used for horizon detection since all celestial bodies emit IR at a predictable intensity. Using both a visual sensor and an IR sensor would allow for the sensor package to benefit from both the visual light camera's high resolution and the IR camera's accurate horizon sensing. An IR sensor would also simplify generating a solution for varying Moon and Earth phases, because it could still detect the dark side of the Moon and Earth.

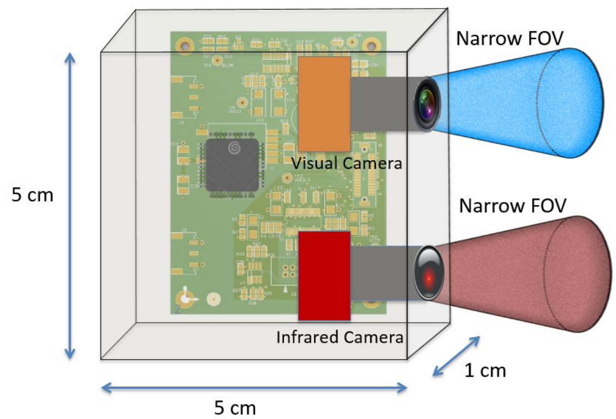

Figure 4.7 One visual and one IR camera configuration

Similar to the first solution, however, this configuration would require cameras with very high resolutions in order to function for both near and far proximity to the celestial bodies. Also, like the preceding solutions, the one visual / one IR configuration would work best with an algorithm that depends on only observing a single celestial body at once.

PROS	CONS
Would simplify detection for all Earth / Moon phases	Difficult to find sensor with adequate FOV and resolution that fits within volume constraint
Use in horizon detection	Limited options for IR sensor due to volume constraints
	Limits viewing to a single piece of the sky at a time
	Low resolution on IR sensors

4.1.4 Two visible light cameras with one wide FOV and one narrow FOV, and one infrared camera

A two visual light / one IR camera configuration combines the benefits of the second and third solution at the cost of added complexity, volume, and power. The IR sensor would make detection for all Earth/Moon phases much simpler and would easily detect the Earth and Moon horizons, while the two different visual light cameras would allow for an accurate solution at both near and far proximities without the need for extremely high resolutions. Like the preceding solutions, this configuration would work best with an algorithm that depends on only observing a single celestial body at once. It would also be more difficult to test the IR camera than the visual cameras.

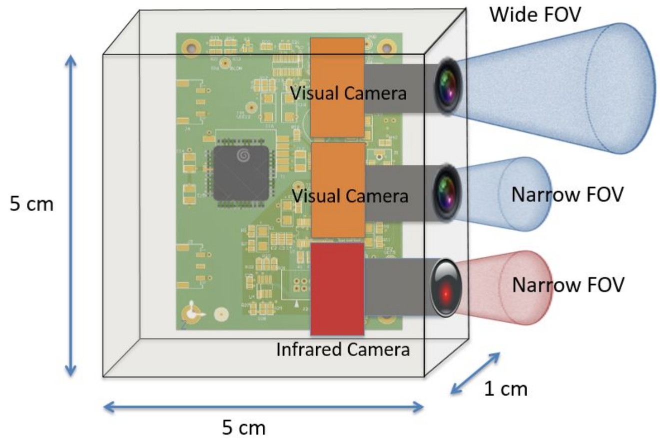

Figure 4.8 Two visual and one IR camera configuration

However, having three cameras, especially three cameras that do not all use the same type of imaging sensor or have the same FOV, greatly increases the complexity of the system. The algorithm would have to be more complex to account for each sensor, and the avionics would have to be more complex to deal with interfacing with each sensor. Three sensors would also take up more power and and more space, and since limited volume is a driving factor for this project, this could prove problematic.

PROS	CONS
Would simplify detection for all Earth / Moon phases	Very complex
Ease of horizon detection	Limited options for IR sensor
Flexible camera choices	Limits viewing to a single piece of the sky at a time
Accurate at both near and far proximities	Low resolution on IR sensor
	Large volume

4.1.5 Three visual light cameras with identical FOVs

Three three visual cameras configuration is different from all preceding solutions in that is it optimal for a different algorithm approach. Instead of having additional cameras to vary the wavelength or vary FOV, this solution aims to increase the FOV without sacrificing a high pixel-to-degree ratio. Three identical imaging sensors with medium FOVs would be aligned such that each would observe an adjacent section of the sky, thus increasing the FOV three-fold. This approach is beneficial to an algorithm that requires observing the Earth and the Moon at the same time and determining the angles between them to generate a state vector solution.

This solution could also be used in the same manner as the one visual camera configuration, but instead of necessitating a single camera with a wide enough FOV and high enough pixel-to-degree ratio, which could be very difficult to find, each of the three cameras could have a medium FOV that together amount to a much larger FOV that is adequate for close-proximity observations. In other words, the combined larger FOV can contain the entirety of the Earth or Moon at close proximity, but each camera will have a high enough pixel-to-degree ration to generate an accurate solution at far proximity.

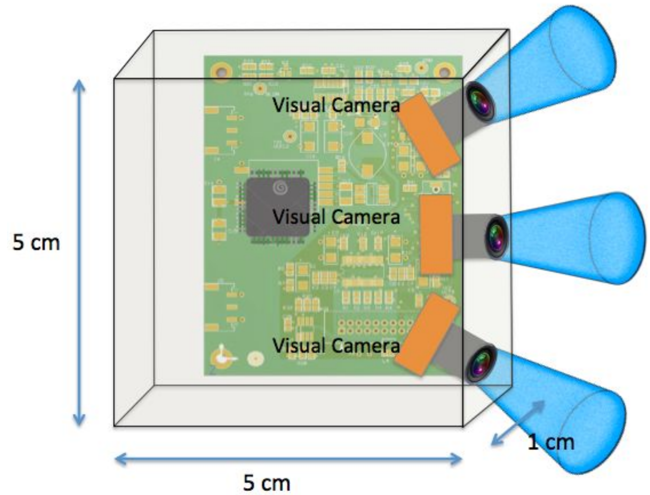

Figure 4.9 Three visual cameras configuration

This configuration is less complex than the previous solution in that, while it still requires three cameras, the cameras would all be identical. Therefore, the algorithm would only have to deal with one type of camera and one FOV. However, it would be more complex in that the algorithm would have to combine each image of the three images into a single image. It would also be difficult to align each camera so that their FOVs are perfectly adjacent to each other. Similar to the previous solution, this configuration would require a larger amount of power and volume.

PROS	CONS
Can view large portion of the sky at a time	Complex
Flexible camera choices	Large volume

4.2 EMBEDDED SYSTEMS OPTIONS

Using a ZedBoard as the microcontroller responsible for interfacing with the OSPRE sensor package is a specific requirement by the customer. However there are still various configurations of different ZedBoards, external memory devices, and operating systems that can meet OSPRE's requirements in regards to storing data, implementing and running the chosen algorithm, and interfacing with the chosen imaging system. There are 3 main types of ZedBoards: the standard ZedBoard, the MicroZed board, and the PicoZed board. All three options are considered in the following design solutions. There are also a small number of "carrier boards" available for each different ZedBoard that provide various different peripherals and I/O functionalities. All carrier board options appear in at least one of the following design solutions. The choice of operating system to run on the selected microcontroller has been intentionally limited to either running a version of Linux, or not using an operating system at all and loading pre-built applications onto the microprocessor. This design choice has been immediately restricted in this way to not include considerations towards other types of OS's because a majority of Linux systems are free, Linux systems are fairly standard in the microcontroller community, there are a large amount of online resources for help in this area, and the OSPRE team members have far more familiarity with Linux systems on microcontrollers than with other operating systems on microcontrollers.

4.2.1 ZedBoard Running Linux with No Carrier Board and No External Memory[6]

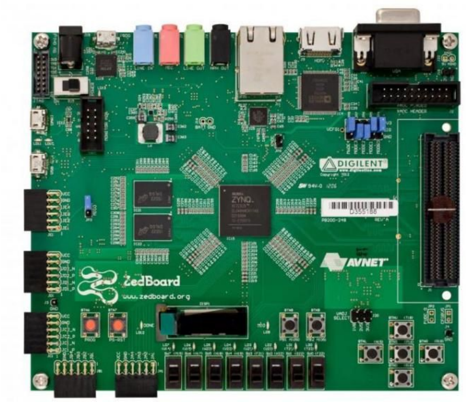

Figure 4.10 ZedBoard

Using a sole ZedBoard base allows the robustness of the Xilinx Zynq™-7000 system on a chip (SoC) while making use of the flexibility that linux offers. The ZedBoard has 512MB of DDR3 SDRAM useful for computational speed, 256 Mb of Quad-SPI flash that can serve as quick-access data storage, a 4GB SD card, and 5 Pmod connectors for general purpose input and output (I/O.) Because of all the on-board and SD card memory, this board would likely not need an external memory device. This board also has a multitude of interfacing options, including JTAG-USB, USB-UART, Ethernet, HDMI, and VGA interfaces, along with user-configurable LEDs and switches, that will likely lend their benefit further in the development process. Although this board will cost roughly $520 it has the additional benefit of not requiring a carrier board to be purchased. One potential downside for this option is that some of the interfaces, such as the audio output, will not be used and could potentially be replaced by a more applicable carrier board. This board is also very flexible in that it combines some of the functionalities of a traditional Field Programmable Gate Array (FPGA), useful for very quick and efficient data processing, and a traditional microcontroller/microprocessor, useful for user interfacing and developing and implementing mathematical algorithms.

PROS	CONS
Many different interface options	Expensive
No need for additional carrier	Only 5 PMod headers
Lots of data storage (512MB DDR3, 32MB Flash, 4GB SD Card)	
Dedicated Video Output Hardware (HDMI and VGA)	

4.2.2 MicroZed Running Linux with I/O Carrier Board[7]

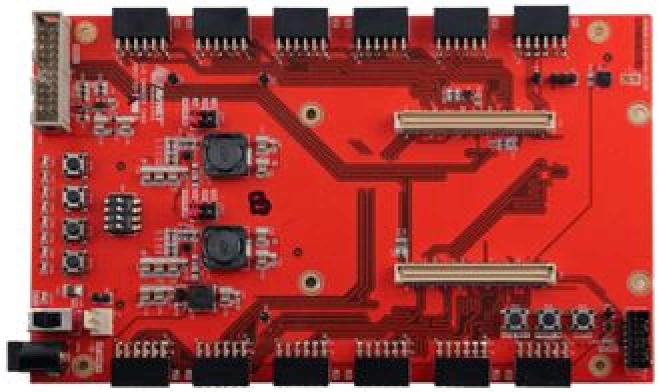

Figure 4.11 MicroZed I/O carrier board excluding the MicroZed

The MicroZed uses the same Xilinx Zynq™-7000 chip family but has 100 MHz slower clock speed, has 1GB of DDR3 SDRAM, and only 128 Mb of Quad-SPI flash. However, the carrier board adds 100 general purpose I/O (GPIO) ports at the cost of reducing the peripheral connections such as audio and VGA. This configuration would be useful for a system that requires many different electrical connections to the processor with a large computational buffer, but is not the best option for a system that needs to output visual data. Together with the carrier card this configuration would cost roughly $460.

PROS	CONS
100 GPIO pins	No dedicated video output hardware
1 GB DDR3 SDRAM and 16 MB Flash	Only 1 GB microSD card
Slightly cheaper than ZedBoard	Requires purchase of carrier card
	Interfacing with carrier card adds complexity

4.2.3 PicoZed 7Z020 Running Linux with FMC v2 Carrier Board[8]

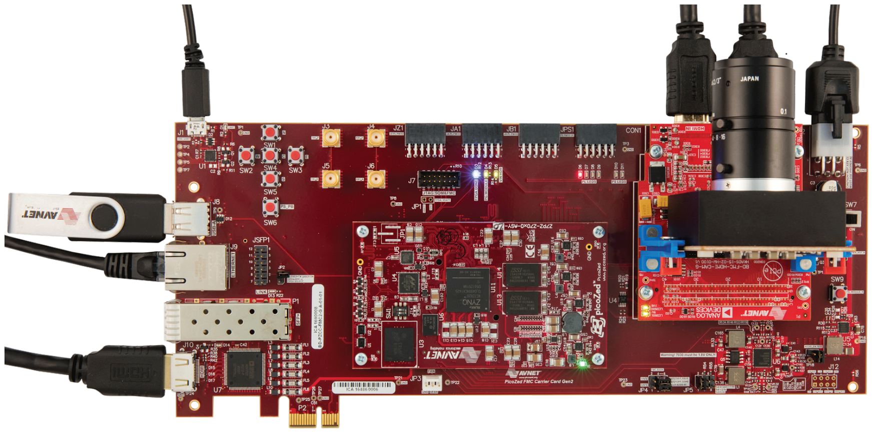

Figure 4.12 PicoZed FMC v2 carrier board with radio peripherals and PicoZed attached

The PicoZed family have different tiers based on the number of user I/O ports along with the number of transceivers contained on the board, and for this configuration the 7Z020 option was chosen as it has less RF components with a higher count of GPIO pins. The FMC carrier board then expands upon this with four SMA connectors for use with antennas, configurable switches and LEDs, along with other interfaces.

PROS	CONS
138 GPIO pins	More complex with a carrier card
Cheapest option	Less familiarity with FPGA programming aspects of carrier card
Plenty of memory (1 GB DDR3 SRAM, 8GB SD card, 16 MB Flash	
HDMI output	

4.2.4 PicoZed 7Z020 Running an Application with FMC v2 Carrier Card[9]

This solution used the same PicoZed board as mentioned above, and is seen in Figure 4.12, but instead of an operating system, it uses an FPGA programming approach or a development kit with drivers specific to the PicoZed board. This solution provides the option to create hardware that is specific to our problem or software that is specific to our hardware, which leads to faster more efficient computing. However, this may be more difficult to implement due to additional complexity and lower familiarity.

PROS	CONS
Faster computing performance	Team is unfamiliar with Vivado Suite necessary for programming the FPGA
Fairly inexpensive	Puts hardware requirements on LM when they decide to implement on actual system
Plenty of memory (1 GB DDR3 SRAM, 8GB SD card, 16 MB Flash	Added complexity with carrier card
HDMI output	

4.2.5 MicroZed 7Z020 Running a Linux with Embedded Vision[9]

This solution used the same MicroZed board mentioned above with the Embedded Vision package add on. The Embedded Vision package provides additional HDMI interfaces, memory and cables. This solution costs $549 which is not significantly more than the MicroZed board. The Embedded Vision package provides the interfaces required to display our image processing results and algorithm on an external video display.

Figure 4:13 MicroZed embedded vision carrier board without MicroZed

PROS	CONS
HDMI Input and Output connectors which will allow for output display	Slightly more expensive
Specifically made for interfacing with a camera	Requires use of a specific camera (+$500)

4.3 TESTING METHOD OPTIONS

One of the customer requirements for this project was to develop a physical test bed to validate the system performance and quantify the errors of the OSPRE navigation package. This meant that the team needed to begin the conceptual design process to determine if developing such a test bed would be attainable within this project's scope. The goal of the test was to allow the image sensor to capture images of a celestial body (or simulated body) in an otherwise dark environment. The test would, ideally, touch on many of the mission phases that OSPRE would likely encounter. Team OSPRE set to work conceptualizing several different tests, each utilizing a unique approach to simulating the expected mission environment. Each of the four tests are described in greater detail, justified, and compared in the following subsections.

4.3.1 Dark room with light box

This method involves utilizing a dark room and a point source of light emitted from a light box to simulate a celestial body. The light box will be a non-transparent solid structure that internally houses a simple light fixture. On the face of the box that is facing the camera there will be a removable panel with a hole laser cut to the desired shape. Several panels will be manufactured, each that correspond to a different light phase of the simulated celestial body. The camera will then be placed at an appropriate distance from the box to perform image capture. The following figure and table show a basic setup diagram of the test as well as the pros and cons of this specific test method.

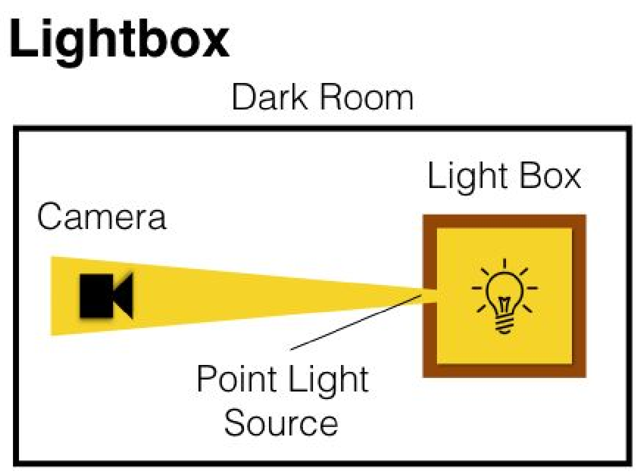

Figure 4.14 Lightbox Test Setup

PROS	CONS
Easily accounts for celestial body phases	Light diffusivity characteristics are difficult to model and thus the test may not behave as the celestial bodies this test is trying to simulate
Minimal stray light interference	Manufacturing the light box will require non-negligible time investment
Laser cutting panels allows for a high degree of manufacturing precision	Ventilation of the light source may complicate the design of the lightbox

4.3.2 Dark room with projector and screen

This method involves utilizing a dark room and projector to display a high resolution image of the celestial body on a half sphere mounted on a wall. The screen would be placed at a known location within the dark room and the image chosen would occupy an amount of the screen that properly scales the dimensions of the test to the desired environment. This would allow the OSPRE team to provide images to the camera of various celestial phases, distances, etc., only limited by the amount of quality sources than can be found online. This approach is somewhat of a synthesis between a simulated celestial body and an actual one because it implements physical images on a digital display. This results in a model that is both highly indicative of the actual operational environment and easily transformable to replicate various celestial scenarios. The following figure and table show a basic setup diagram of the test as well as the pros and cons of this specific test method.

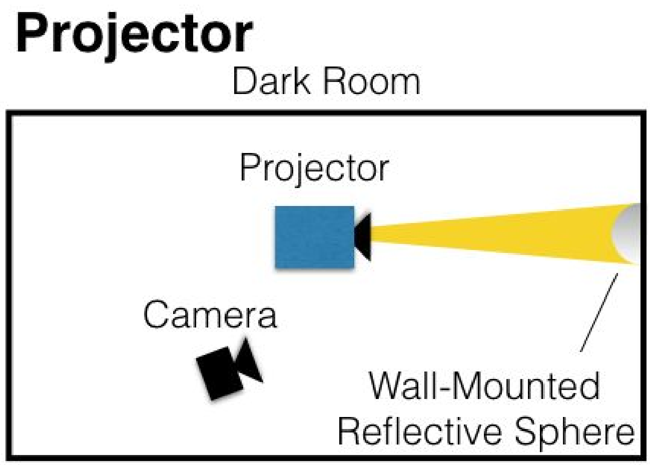

Figure 4.15 Projector Test Setup

PROS	CONS
Simple to setup and image multiple phases	Possible issues with stray light
Images contain colors and geographical features of the planets they are simulating aiding in test realism	Projector brightness may not fall within desired light intensity range
The reflecting sphere offers a light diffusion characteristics that is very similar to the celestial bodies it will be simulating	More difficult to find facility that meets test requirements. Ie - room size, projector, wall for mounting, etc.

4.3.3 Night time images of the moon

The most straightforward testing approach is to not simulate the celestial bodies at all but to photograph them directly. This test will simply take photos of the moon at night over the course of several days in order to capture the system performance during several phases. This test approach was included because it offers a unique design solution with very apparent pros and cons. The trade study will determine exactly how these characteristics compare to the other design options. The following figure and table show a basic setup diagram of the test as well as the pros and cons of this specific test method.

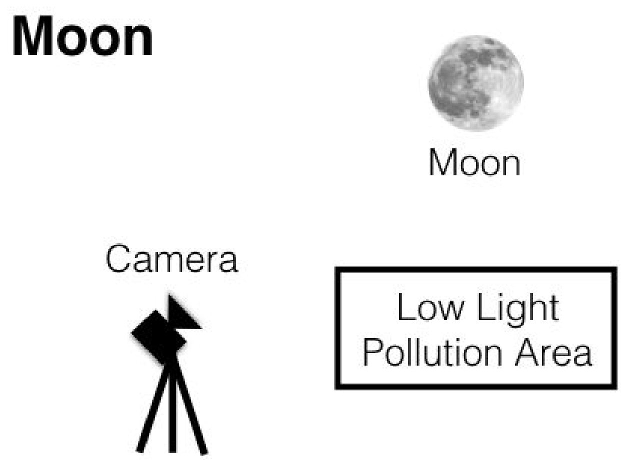

Figure 4.16 Moon Test Setup

PROS	CONS
Virtually no equipment, facilities, or cost required	No control over moon phases or weather
Most accurate representation of celestial body	Requires travel to suitable location to meet clarity requirements
Image sensor testing can begin immediately	The size of the moon will be much smaller than anything encountered during the Lockheed Martin mission

4.3.4 Dark room with 3-D celestial model

The final test method considered was an approach that improved the environment simulation quality at the downfall of increased complexity and cost. The test would utilize a simple sphere on a mount as the simulated celestial body and a light outside of the imaging sensor frame as the light source (ie - the sun). While this concept had known downfalls from the onset, the team posed that the simulation accuracy benefits may outweigh the cons and thus it should be included in the trade study. In addition, this approach is the only testing simulation that utilizes a full sphere, an approach that must be considered. This may allow the test to better simulate the different phase characteristics that will be encountered in the space environment. The following figure and table show a basic setup diagram of the test as well as the pros and cons of this specific test method.

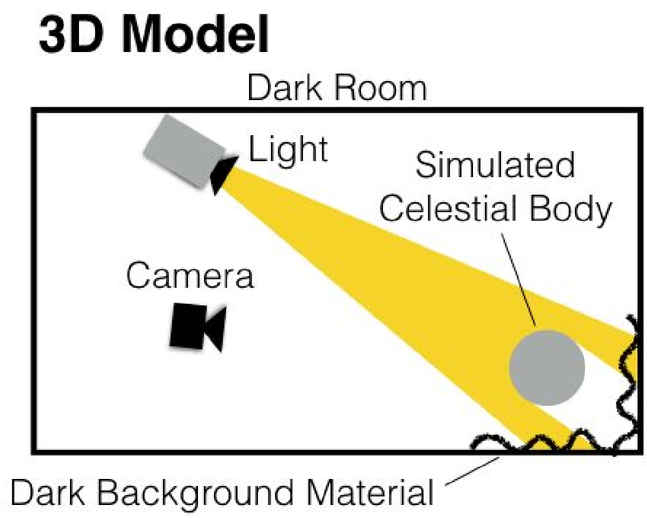

Figure 4.17 3D Model Test Setup

PROS	CONS
Realistic light diffusion characteristics of celestial bodies	High amounts of stray light interference likely
Source light is less constrained by size, thermal characteristics, brightness, and distance from the simulated celestial body	Complex design and assembly
Simple to scale sphere depending on facility constraints	Difficult to manipulate test environment for new phases

5.0 TRADE STUDY PROCESS AND RESULTS (30 pts)

5.1 IMAGING SYSTEM TRADE STUDY

5.1.1 Imaging System Evaluation Criteria

The imaging sensor trade studies looked at different methods for achieving the project definition of utilizing an imaging sensor to perform angles-only navigation. The differing solutions offered unique methods for obtaining images of the Earth or Moon that could be processed to produce the spacecraft state vector using various algorithm methods. This mainly came down to the number of sensors used and the type of imaging wavelengths. The metrics on which each solution is measured are described and justified below. The weights are also discussed for each criteria to better understand the impact on the project design.

Adaptability (25%): The adaptability of a given solution refers to the solution's ability to work well in many different scenarios. This includes the different scenarios the sensor package will see while being tested as well as the different scenarios corresponding to different design solutions for other aspects of the project. For example, if a solution works well for close proximity operations but well not for far proximity operations, it will be given a lower score than a solution that works well for both. Likewise, if a solution works well for multiple different algorithms or multiple different embedded systems, it will have a higher rating than one that doesn't. This metric is the most important because it directly corresponds to how well the system will work, so it is given a 25% weight.

Score	1	3	5	7	10
Adaptability	Works well in no situations and severely limits design space	Works well in few situations and slightly limits design space	Works well in some situations with minimal limits to design space	Works well in most situations without limiting design space	Works well in all situations without limiting design space

Complexity (20%): Complexity is referring to the foreseen difficulty of implementing a proposed solution. It is one of the largest driving criteria with 20% weight, because a more complex system introduces a larger time investment and more opportunities for failure. As the solution methods become more complex, the ability to successfully develop the required algorithms, interfacing, and/or structural layout become arduous and imperative to meeting the specified project requirements.

Score	1	3	5	7	10
Complexity	Too complex to possibly complete on schedule	Could complete on schedule but with no margin for error	Will most likely complete with some margin for error	Will certainly complete with enough margin for error	Will complete easily with lots of margin for error

Cost (15%): The cost of each solution must be considered when deciding on the approach to be taken. A strict requirement of a $5,000 budget was given to the team for the entirety of the project. There do remain options for additional funding if necessary, so cost was not treated as the leading design criteria. The team's initial research allowed us to believe that maintaining the $5,000 budget should be reasonable given that reasonably priced sensors were found on the order of several hundred dollars, or less than 10% of the allocated budget. Cost will still present some level of challenge, therefore the team decided on a weight of 15% to adequately represent the struggles foreseen involving funds.

Score	1	3	5	7	10
Cost	> $2000	~$1600	~$900	~$300	~ $50

Volume (20%): The OPSRE team is restricted to a volume envelope of 5cm x 5cm x 1cm for the entire sensor package design. The limiting depth of 1cm provides a challenge for sensor selection since it typically correlates to less resolution and wider FOV photos, resulting in a smaller pixel-to-degree ratio. Since the pixel-to-degree has been identified as a driving variable for increasing the accuracy of the results, a small depth presents a difficult obstacle for the design team. At this time in the team's research, the average volume found per visual sensor that meets our pixel density requirements is 1.795 cm^3 while the average for an IR sensor was 0.537 cm^3. Each additional sensor requires cables and excess space for installation that must be considered. Not to mention the spatial limitations imposed when adding the microprocessor and baseboard into the provided volume envelope. Thus, a weight of 20% was assigned so that the volume could be seen as an important factor when selecting an imaging system. Accounting for the estimated spatial limitations, a scoring factor from 1 to 10 was developed according to the percent of volume taken up by each sensor needed in the solution proposed.

Score	1	3	5	7	10
Volume	> 20% total volume	15% - 20% total volume	10% - 15% total volume	10% - 5% total volume	< 5% total volume

Testability (15%): The Testability criteria refers to the difficulty with which a solution could be physically tested. It was weighted based on the time and effort required for procedures to be performed as well as if the solution is feasible to test. Since the team contains precursory plans for testing and has found the means by which to replicate both visual and IR light, the team does not foresee this as the largest concern for each solution. A weight of 15% displays how testability is not seen as the driving critical project element but still remains important for project success.

Score	1	3	5	7	10
Testability	Impossible to test without very complicated facilities or equipment	Difficult to test, facilities or equipment may be difficult to obtain or operate	Moderately difficult to test, some facilities or equipment may be difficult to obtain or operate	Easy to test, though some facilities or equipment may be difficult to obtain or operate	Very easy to test without complicated facilities and equipment

Power (5%): The electrical power is the final evaluation criteria for the solution methods considered. Electrical power includes the power draw that the imaging sensor package will require for operation. The power draw of the system is a strict requirement provided by the customers which is why it must be included in the decision of a solution method. However, it is not an absolute driving factor because the type of sensors being investigated all have a power draw well within the limits. A weight of 5% was given to this criteria because it was seen as the lowest driving factor for imaging sensor design.

Score	1	3	5	7	10
Power	<100% total power	50% - 70% total power	30% - 50% total power	10% - 30% total power	>10% total power

5.1.2 Imaging System Trade Matrix

		One Visual	Two Visual	One Visual & One IR	Two Visual & One IR	Three Visual
Criteria	**Weight**	**Score**	**Score**	**Score**	**Score**	**Score**
Cost	15%	7	6	6	5	5
Volume	20%	8	6	7	4	3
Power	5%	7	6	6	5	5
Complexity	20%	6	6	5	5	4
Testability	15%	8	8	5	5	6
Adaptability	25%	6	9	7	9	6
Weighted Total	**100%**	**6.90**	**7.05**	**6.10**	**5.70**	**5.60**

5.2 EMBEDDED SYSTEMS TRADE STUDY

5.2.1 Embedded Systems Evaluation Criteria

In order to quantitatively determine which embedded systems design solution of the options listed in Section 4.2 above was the best, the OSPRE team first developed different metrics or evaluation criteria on which to rate the different solutions. These metrics were created by identifying which aspects of any particular design are most important to the overall success of OSPRE and to meeting the design requirements laid out in Section 3 above. They are: Cost, Interfacing, Memory, Complexity, and Familiarity. Once these key parameters of the embedded systems design solutions were identified, the OSPRE team then assigned a weight in terms of percentage to each of these metrics in order to identify which among them were more or less important than the others. Then each design solution can be scored on each metric and given an overall score based on the weighted result. This enables this OSPRE team to be able to quantitatively determine which design solution is the best. Descriptions of the metrics and their weights follow:

Cost 10%: Cost is a limiting factor for the OSPRE mission as funds are finite. Therefore it must be considered when selecting a design solution. It is also important because the embedded systems trade study only covers a small portion of the overall project and therefore the total cost allowable for the embedded systems design is even smaller than the overall limited funds allocated for OSPRE. However, this metric is not the most important factor driving the design because it is not expected that any of the design solutions will approach the limit on cost. Therefore it is weighed at an intermediate value of 10%.

Score	1	3	5	7	10
Cost	>$3,000	~$1,500	~$750	~$375	<$100

Interfacing 25%: Three of the primary functions of OSPRE's embedded systems platform are to be able to interface with the OSPRE team members working on developing it, to interface with the imaging subsystem, and to interface with a simulated spacecraft GNC computer. These can be quantified together under one metric as simply interfacing.

Interfacing with OSPRE team members involves accessibility of programming the ZedBoard and its peripherals including the available video outputs, and is important because a platform that is less accessible in interfacing will involve more time and effort in order to program it. This would be problematic considering a large amount of time is expected to be devoted to implementing the angles-only algorithm on the ZedBoard. Interfacing with the imaging subsystem involves controlling and communicating with the image sensor(s). The chosen embedded systems design must be able to control the image sensor and retrieve image data from it. This directly relates to several functional requirements. Interfacing with a simulated spacecraft GNC computer involves bidirectional communication with an external processor in order to receive all required inputs to the OSPRE system and to output all required outputs to the OSPRE system. This functionality also directly relates to several functional requirements. These metrics were further divided into the available connections that each solution may have, and although a particular solution may not have every connector within its category, the category represents the ideal. An interface protocol, SPI/I2C, is required but was not included within the metrics as the FPGA portion of the Xilinx Zynq allows pins to be configured to SPI/I2C. With this metric including considerations to three major aspects of the overall OSPRE system, it is weighed at the highest percentage of 25%.

Score	1	3	5	7	10
Interfacing	Lacks required interfaces (0 GPIO 0 Video Output JTAG 0 Quad-SPI 0 USB 0 Ethernet)	Lacks required interfaces but additional connections can be added with great difficulty (0 - 50 GPIO JTAG USB)	Lacks required interfaces but additional connections can be added with minor difficulty (50 - 100 GPIO JTAG USB Quad-SPI)	Lacks required interfaces but additional connections can be added with ease (100 - 150 GPIO JTAG USB Ethernet Quad-SPI)	Has all required interfaces (>150 GPIO JTAG USB USB-UART Ethernet Quad-SPI HDMI VGA)

Memory 15%: Memory is a limiting factor for the OSPRE mission because memory limits which operating systems can be installed, how many pictures can be stored and how much previous data can be used. Lockheed Martin has required our computation and image processing to not exceed a TBD amount of volatile memory and has given us TBD amount of non-volatile memory on the ZedBoard for algorithm use. It is important to have the maximum allowable amount of memory for algorithm usage on the ZedBoard, as well as extra memory to hold the OS and additional overhead. This trade study looks at both volatile and nonvolatile memory on the ZedBoard and additional memory that can be added to our 5cm x 5cm x 1cm sensor package. This metric is an important factor driving the design, but is given a weight of 15% because of the option of adding additional memory inside the sensor volume.

Score	1	3	5	7	10
Memory	No memory	Not enough memory	Just enough memory	Extra memory	Way too much memory

Complexity 25%: The complexity of the chosen solution will dictate the amount of time required to dedicate to development, and has the potential to dramatically delay the OSPRE project. The amount of complexity was determined on the basis of preliminary research into proper system setup, and combines the process of loading software to the development board, programming the algorithm and necessary subroutines, and the complexity involved with interfacing with the necessary sensors. As the OSPRE project relies heavily on image processing, open source packages such as OpenCV are highly appealing, however this may or may not be relatively harmless to install and compile. Another example of potential complexity is the interface of which the OSPRE team programs the development board. If a compiled application was chosen for the operating software then it would require the use of a specialized interactive development environment (IDE) which the team has learned from ASEN 3300 also has a steep learning curve associated with it.

Score	1	3	5	7	10
Complexity	Too complex to implement	Many points of failure/hard to debug/hard to design	Several points of failure/ expected debugging difficulty/ expected design difficulty	Few points of failure/easier to debug/easier to design	Trivial complexity

Familiarity 25%: The familiarity of the chosen embedded systems solution will influence OSPRE's ability to come up with creative and effective solutions. Team OSPRE will be able to produce a higher quality product on familiar hardware because more time will go into the design of the product versus learning to use the hardware. The amount of familiarity is determined from the team's prior experiences which is located in section 6 of the PDD. This metric is an important design driving factor so it is given a weight of 25%.

Score	1	3	5	7	10
Familiarity	All team members have no experience	Some team members have slight experience	Some team members are experienced	Some team members are very experienced	Multiple team members are experts

5.2.2 Embedded Systems Trade Matrix

		Zed/Linux	Micro/Linux/IO	Pico/App/FMC	Pico/Linux/ FMC	Micro/Linux/ Embedded Vision
Criteria	**Weight**	**Score**	**Score**	**Score**	**Score**	**Score**
Cost	10%	7	7	6	6	7
Interfacing	25%	9	5	7	7	8
Memory	15%	8	5	7	7	5
Complexity	25%	7	5	3	5	6
Familiarity	25%	6	6	4	5	4
Weighted Normalized Total	**100%**	**7.40**	**5.45**	**5.15**	**5.90**	**5.95**

5.3 TESTING METHODS TRADE STUDY

5.3.1 Testing Methods Evaluation Criteria

The metrics for the testing methods trade study were conceptualized by team OSPRE by identifying what aspects of the test bed design were most important. These metrics were created by brainstorming what the test needed to accomplish from a functional requirements perspective, the requirements associated with building/preparing the test bed, as well as the overall fidelity of the experiments. The goal of this trade study was to compare the different test bed concepts based on these metrics to see which design solution best met the criteria. In addition to identifying the key aspects of the test design, team OSPRE also weighed each metric based on how important it was on the design choice. To do this, the team identified three main categories based on importance: those that were integral to the test design, those that posed a large but lesser concern, and finally those that were of least concern. The weights were also delegated in such a way that even characteristics with the smallest weighting would still have a noticeable influence on the trade study results. This classification method helped to create an optimal weighting spread between the eight metrics. The description of each metric, why it was included in the trade, the reasoning behind its weight, and lastly the scale definitions are detailed below.

Cost (7.5%): The purpose of including a cost metric is straightforward: the budget of this project is a limiting factor to many possible design solutions and thus must be considered. Despite this importance, the cost was weighed relatively low when compared to the other metrics. The reasoning behind this decision was that while cost was important it didn't pose a significant concern when compared to the other metrics. Outside funding sources offer an opportunity to acquire more funds if the optimal test solution requires such. To mitigate the chances of any testing methods that have impractical expected costs, the scale was designed in such a way that these solutions would always be assigned a 1. The following table details how cost was weighed. The budget for testing must be kept to a minimum due to the strict budgetary constraints of this project so the following quantitative scale was developed. It was created around two values, what the team expected to reasonably spend developing the test bed (score 5) and how much was considered too much (score 1). In order to estimate the costs for each test method, the test was broken down into its most basic materials and components. The cost of the parts and materials were then found from known vendors to estimate the total cost.

Score	1	3	5	7	10
Cost	+$400	$200 - $399	$100 - $199	$50 - $99	$0 - $49

Time Investment (10%): Time was considered a key metric due to the strict and limiting timeline of the testing phase of this project. This metric includes the time required for design, manufacturing, preparing, as well as running the tests. Time investment was assigned a weight of 10% because of the relatively low importance it had on the design of the test method. At the same time, this weight was calculated such that the time investment score associated with each design solution would still play a pivotal role. The scale was defined by approximating the average (score of 5) as well as maximum (score of 1) time the team would devote to designing, manufacturing, and executing tests. The test execution metric was defined as the hours necessary to set up the test and collect data for 1 hour which results in units of hours per hour. Each test was broken down into these three stages, analyzed, and then assigned a time investment rating. If a test fell into multiple scores between the three stages, the scores were averaged and then rounded to the nearest whole number.

Score	1	3	5	7	10
Time Investment	**Design:** +8 wks **Manf:** +8 wks **Test:** +3 hrs/hr	**Design:** 6-8 wks **Manf:** 6-8 wks **Test:** 2.5 hrs/hr	**Design:** 4-6 wks **Manf:** 4-6 wks **Test:** 2 hrs/hr	**Design:** 2-4 wks **Manf:** 2-4 wks **Test:** 1.5 hrs/hr	**Design:** 0-2 wks **Manf:** 0-2 wks **Test**: 1 hr/hr

Facility Requirements (10%): From the beginning of test method development, it became apparent early on that each design solution would require different facility capabilities and specifications. The team realized that testing facilities on campus are limited and thus the facility requirements for each solution should be identified and considered when selecting the final test method. The team quantified this metric by calculating how large the room had to be based on a typical lens' minimum focal distance, the smallest practical size of the celestial body that could be constructed/captured, as well as the if the room needed any special equipment/characteristics such as projector, vaulted ceilings, dark walls, and/or no windows. The test methods were then scored based on how difficult it would be to acquire a room with the minimum specifications. The facility requirements was assigned a weight of 10% as this aspect of the test method design was of lesser importance than other metrics included in the study. This weight was not low enough though that the facility requirements would not play a significant role in the trade. The facility scale is qualitative. The reason behind this choice was that each test method may introduce unique facility requirements. Rather than try to encompass all of these requirements, the methods were merely scored on how practical/simple it would be to find a facility that met those needs.

Score	1	3	5	7	10
Facility Req.	Not attainable	Specialized room	Typical room (no special req.)	Very flexible	No facility req.

Accuracy (15%): The accuracy metric refers to the amount of error that is introduced into each testing method. If a sufficient amount of error is present in a test method, it will not be possible to utilize this method as a reliable validation tool, and it will not accurately represent the actual environment that OSPRE is intended to operate in. This was given a weight of 15% as this is one of the most important testing metrics. The purpose of utilizing a test bed simulation is to validate the performance of the system before its actual operation, and failing to develop an accurate test method leaves the system's performance essentially unknown. That being said, the OSPRE team believes the manufacturing and measurement precision to be the most important factors in the test accuracy. Since the moon model will be scaled to an incredibly small size (most likely smaller than 1 foot in diameter), the ratio at which distances scale will be incredible. As an example, using a moon equatorial radius of 1738.1 km and model radius of 3 in, 1 km corresponds to approximately 43.84 µm on the model. This requires the manufacturing and measurement tools that will be utilized to have extremely high precision if the model is to represent the moon to an acceptable likeness. Ultimately, the following scale has been made to represent the test models' accuracy in comparison to the moon.

Score	1	3	5	7	10
Accuracy	Precision < 100 km.	Precision >100 km, < 10 km	Precision > 10 km, < 1 km.	Precision > 1 km, < 0.1 km.	Precision < 0.1 km.

Mission Testing (20%): This metric reflects whether or not the testing method can be used to simulate every expected phase of the mission. The reason for including such a straightforward metric is that some of the test methods explored had a multitude of benefits but were extremely limited in which phases they could accurately simulate. It is important for the chosen test to be able to simulate all of the testing phases as the hardware must be validated in every anticipated phase. As a result, this metric was assigned a strong weight to reflect this importance. The scale was designed by breaking the mission down into four main phases of the mission the team anticipates testing will be necessary and then seeing how many of these phases the particular test method could realistically achieve. The four main phases are as follows: maximum distance capture, minimal distance capture, sun glare capture, and average mission capture. The scale is defined in the table below.

Score	1	3	5	7	10
Mission Testing	Can simulate none of the four phases	Can simulate one of the four phases	Can simulate two of the four phases	Can simulate three of the four phases	Can simulate all of the four phases

Simulation Fidelity (15%): This metric refers to how well the test simulates the lighting conditions expected in the space environment. These characteristics include sun glare effects, Earth/moon reflectivity characteristics and phases, as well as the ability to simulate all phases of the mission (close versus distant celestial body imaging). The test methods were rated based on how many of these characteristics were either inherently achieved in their design as well as how many could be simply integrated to the test setup if desired. This metric was assigned a high rating compared to most of the other metrics. The reason behind this decision was that the optimal test should capture many of the aspects of the lighting conditions expected in the space environment. The greater this similarity the greater the team can catch design flaws, fix them, and deliver a working product to the client at a higher level of success. The fidelity scale was designed based on a points system. As described above, each test method was rated by how many lighting characteristics they could achieve. The lighting characteristics are as follows: the test can simulate sun glare effects, has realistic light diffusion characteristics, has realistic light intensity differences between lit and unlit sides of the celestial body, and can simulate all phases of the celestial body accurately.

Score	1	3	5	7	10
Fidelity	Satisfied no lighting characteristics	Satisfied 1 lighting characteristics	Satisfied 2 lighting characteristics	Satisfied 3 lighting characteristics	Satisfied all 4 lighting characteristics

Stray Light (12.5%): The stray light metric refers to the amount of unintended light each test method can be expected to contain. If there is a sufficient amount of stray light present in the test environment, the accuracy of the algorithm may be limited due to stray light sources obscuring the simulated celestial body within the camera's field of view. This was given a weight of 12.5% as much of the research done for OSPRE's chosen test methods has proven most stray light effects to be negligible. However, unforeseen factors within these tests may require this metric to be brought to additional attention in the future. Although a quantitative expected illuminance for each test environment was found through simple calculations using factors such as hardware specifications, NOAA data sets, etc., the scale itself it qualitative in nature. It essentially ranks from 1, being completely unusable images, to 10, being usable image under all required testing scenarios.

Score	1	3	5	7	10
Stray Light	Excessive. Unusable images for all scenarios.	High. Unusable images for most scenarios.	Moderate. Usable images for some scenarios.	Minimal. Usable images for most scenarios.	Negligible. Usable images for all scenarios.

Assembly (10%): The assembly metric is rating how difficult the team expects each test method would be to construct and prepare for tests. This metric is important as some design solutions may offer a wealth of benefits but be near impossible to construct with the time, budget, tools, and other resources available to the team. The assembly metric was assigned a weight of 10% as it is not vital to the test method design but still plays a significant role in the final design solution. The assembly scale was designed qualitatively. The reason behind this decision was that each test method may introduce unique difficulty and/or complexity to its assembly score and thus a numerical scale was not practical. Instead, a standard difficulty scale was used.

Score	1	3	5	7	10
Assembly Req.	Possibly unattainable	Difficult	Neutral/Average	Easy	No assembly/ Extremely easy

5.3.2 Testing Methods Trade Matrix

		Lightbox	Projector	Moon Image Capture	3D Model
Criteria	**Weight**	**Score**	**Score**	**Score**	**Score**
Cost	7.5%	8	8	10	7
Time Investment	10%	6	6	7	4
Facility Requirements	10%	7	4	10	4
Accuracy	15%	8	7	9	7
Mission Testing	20%	10	10	1	10
Simulation Fidelity	15%	5	7	5	7
Stray Light	12.5%	7	9	8	4
Assembly	10%	4	4	10	3
Weighted Total	**100%**	**7.13**	**7.23**	**6.75**	**6.23**

6.0 SELECTION OF BASELINE DESIGN (20 pts)

6.1 IMAGING SYSTEM

In the imaging system trade study, the two-visual-camera configuration won with the one-visual-camera configuration in close second. The infrared configurations tied for third place, and the three-visual-camera configuration came in last. With this in mind, the IR and three-camera solutions were dismissed, having lower scores for cost, volume, power, complexity, and testability.

Between the two remaining options, the two-camera configuration was chosen as the baseline design. While having slightly lower scores for cost, volume, and power than the one-camera configuration, the two-camera configuration scored much higher on adaptability. This is because it will be much easier to find a pair of cameras that together fulfill all of the system requirements than it would be to find a single camera that can do the same. The single-camera configuration would require a camera with an extremely high resolution to achieve the desired pixel-to-degree ratio, since it would need a relatively large FOV to image the entire disk of the Earth upon deployment, while still being able to generate an accurate solution far away. The two-camera configuration would divide the responsibilities of functioning at close and far proximities between the two cameras. The larger FOV camera would not need an extremely high resolution because its pixel-to-degree requirement would be much lower, since it only needs to function at close proximity, while the smaller FOV camera would not require as high of a resolution to reach its desired pixel-to-degree ratio since its FOV could be smaller. This configuration makes the system much more robust with a minimal increase in cost, power, volume, and complexity.

6.2 EMBEDDED SYSTEM

A portion of the customer requirements dictated the use of a ZedBoard for testing development that is outside of the OSPRE volume constraints, and as seen from the Embedded Systems Trade Study in 5.2.2 the ZedBoard is the clear design decision. The trade study shows that the majority of the ZedBoard options researched are roughly the same cost at about $500, with differing costs influenced heavily by having to buy carrier boards. A few of the main design points that set the ZedBoard ahead of the other options was the amount of interfaces, memory, and lack of complexity. For interfaces there are 5 PMod™ headers that equate to a total of 60 GPIO pins, a Xilinx analog-to-digital (ADC) header, both USB and USB-UART, HDMI and VGA outputs, along with a multitude of user-definable switches and LEDs. Most likely not all of these interfaces will utilized, however, as the exact design solution is unknown the OSPRE team believes that having more options will result in better development down the road. A few of the other solutions offered greater number of GPIO pins at the cost of purchasing a carrier board, but generally the complexity and lack of other interfaces negated this particular benefit. The ZedBoard also has 512MB of DDR3 random access memory (RAM), 32MB of volatile flash memory, and includes a 4GB SD card that would otherwise need to be purchased. Relative to home computers the RAM may at first glance appear to be lacking, but when considering that our use of the ZedBoard platform will primarily consist of algorithm execution and light image processing, the 512MB is expected to be more than enough and for long term data storage the SD card can be upgraded.

Furthermore, the lack of an additional carrier board decreases the overall complexity through the lack of needing to interface with more peripherals than necessary. Running linux also decreases the complexity as the OSPRE team has more experience with linux than the required software to create a compiled application, and a compatible linux distribution is supplied by the company that manufactures the ZedBoard which eliminates the need to have to find a compatible operating system. Finally, through online research there is more public development support for the ZedBoard over the other options which increases the overall familiarity and decreases the complexity.[10] Conclusively, as the trade study shows, the ZedBoard running linux is the OSPRE team's chosen design solution moving forward with the project development.

6.3 TESTING

Establishing the baseline testing method was difficult as the lightbox and projector methods scored very similarly in the trade study. While the projector method may have won in the end, the lightbox method offers a similar number of advantages and disadvantages to the team. Considering how close the two scored the team decided to discuss the pros and cons of each method in further detail rather than just selecting the winner of the trade study. This discussion raised many important questions that would involve time for further calculations, models, as well as research to be conducted to truly rule out one option over the other. As a result, the team decided that between now and the critical design review, research and development could be conducted and a testing method selected. At this time, the baseline testing method cannot be selected but only narrowed in scope to the projector and lightbox methods. The team feels confident that leaving both options open at this time is far wiser than selecting a testing method based on insufficient knowledge.

7.0 REFERENCES

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APPENDIX A.

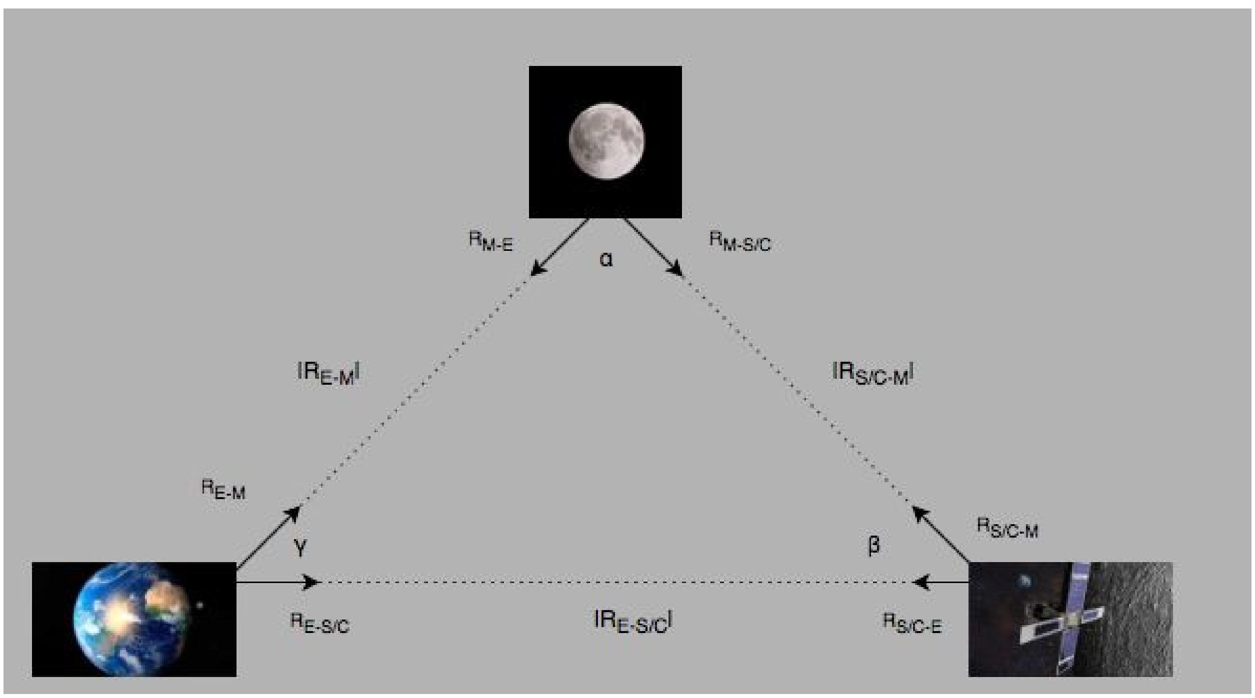
MODELS

Geometry

Output: The position of the spacecraft in the ECI frame ($R_{E-S/C}$).
Inputs:
$|R_{E-M}|$ - The distance between the Earth and the Moon
t_1 - The time at which the first quaternion is recorded
t_2 - The time at which the second quaternion is recorded
Q_1 - The 4x1 quaternion between the body frame and the ECI frame
Q_2 - The 4x1 quaternion between the body frame and the ECI frame
$\bar{c}$ - The outward normal vector pointing out of the lense of OSPRE's camera in the body frame

Assumptions:
1. Assume the moon and sun ephemeris, time, and quaternion are error free
2. Assume Perfect Pointing:
    a. We can point wherever we want to at 100% accuracy
3. Assume a maximum of 2 minutes of slew time between pointing at the earth and the moon

Free Body Diagram:



Instructions:
1. Command: Point OSPRE towards the Center of the Earth (Perfect Pointing Assumption) and pass quaternion Q_1 to OSPRE

2. Command: Point Ospre towards the Center of the Moon (Perfect Pointing Assumption) and pass quaternion Q_2 to OSPRE

Algorithm:

$\widehat{R_{S/C-E}} =$

$\widehat{R_{S/C-M}} =$

$\gamma = cos^{-1}(\widehat{R_{E-M}} \cdot - \widehat{R_{S/C-E}})$

$\alpha = cos^{-1}(\widehat{R_{M-E}} \cdot - \widehat{R_{S/C-M}})$

$\beta = 180 - \gamma - \alpha$

$\frac{sin(\beta)}{|R_{E-M}|} = \frac{sin(\alpha)}{|R_{E-S/C}|}$

$|R_{E-S/C}| = \frac{R_{E-M} sin(\alpha)}{sin(\beta)}$

$R_{E-S/C} = |R_{E-S/C}| \widehat{R_{E-S/C}}$

APPENDIX B.

OSPRE SYSTEM

FUNCTIONAL FLOW DIAGRAM