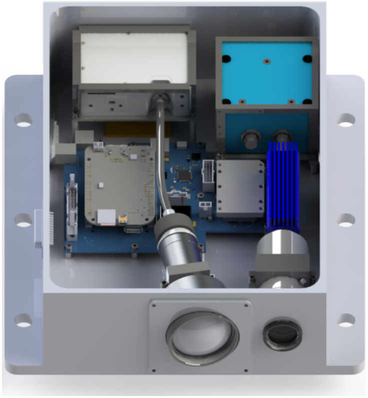
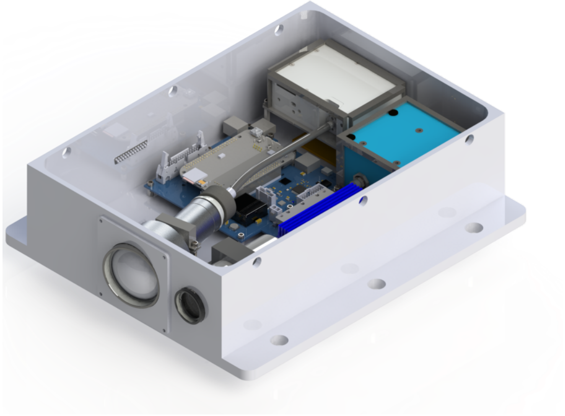
Instrument for Performing Laser-Induced Breakdown Spectroscopy (LIBS) in a Lunar Permanently Shadowed Region (PSR)

Technical Report





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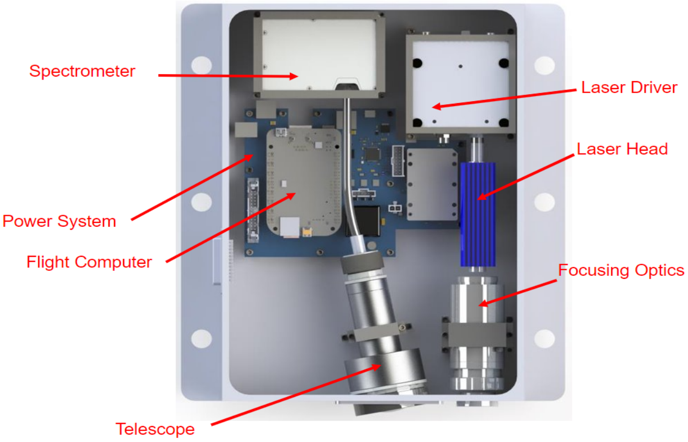
The Pennsylvania State University: Instrument for Performing Laser Induced Breakdown Spectroscopy in a Lunar Permanently Shadowed Region

Concept Synopsis: The Penn State Student Space Programs Laboratory (SSPL) is developing the Oasis instrument as part of the 2020 NASA BIG Idea Challenge. This instrument will perform laser-induced breakdown spectroscopy (LIBS) to survey for water in permanently shadowed regions near the Moon's southern pole. Laser pulses will be fired at the regolith from the rover-mounted payload, inducing a plasma that will generate an emission line spectrum corresponding to the elemental composition of the sample being tested. The elemental spectrum data captured by the spectrometer will be sent to the rover. This data will be analyzed to determine elemental concentrations present within the regolith and detect the presence of water.



Innovation: Many of the challenges of lunar exploration and habitation are driven by the need for water. Water is critical for supporting life, and can be split into its basic elements, further expanding its utility. While it has been established that water does exist on the moon, specifically in PSRs, its location is scattered non-uniformly. This, along with the costliness of mining water, creates the need for more detailed data, mapping specific locations of ice-water deposits. Oasis will serve this need, while also capturing data on general chemical composition. Knowledge of the chemical composition of lunar regolith and a more detailed map of ice-water deposits would be instrumental to future missions, such as the Artemis Program, going forward.

Proof-of-Concept Test	Results & Conclusions
Preliminary LIBS Test	Verified: • Laser's capability to ablate • Flight computer's ability to control laser and spectrometer Spectrometer data noise indicated need for further calibration.
Thermal Simulations	Verified thermal system's ability to maintain operable component temperature in a simulated PSR environment.
Instrument Sensitivity Test	Verified that spectrometer readings are sufficiently resistant to changes in temperature.

EXECUTIVE SUMMARY

The Penn State Student Space Programs Laboratory (SSPL) is developing the Oasis instrument as part of the 2020 NASA BIG Idea Challenge. This instrument will perform laser-induced breakdown spectroscopy (LIBS) to survey for water in permanently shadowed regions (PSR) near the Moon's southern pole. Laser pulses will be fired at the regolith from the rover-mounted payload, inducing a plasma that will generate an emission line spectrum corresponding to the elemental composition of the sample being tested. The elemental spectrum data captured by the Oasis spectrometer will be sent to the rover. This data will be analyzed to determine elemental concentrations present within the regolith. Identifying the concentrations of water at various locations will be crucial to future long-term lunar habitation. In addition to searching for water, the spectral data can be used to determine the concentration of various elements valuable for Artemis missions that seek to use regolith as a manufacturing or construction material.

A preliminary LIBS test took place in order to verify the LIBS system design. This test consisted of the laser, spectrometer, and flight computer being used to ablate and sample JSC-1A lunar regolith simulant in typical earth conditions (room temperature, non-vacuum, etc). This test was intended to verify overall LIBS functionality and measure the effects of laser pulse frequency and spectrometer integration time on collected data. The laser and spectrometer were successfully controlled through the flight computer, verifying software functionality. Furthermore, the laser successfully ablated lunar regolith generating a plasma, validating optical system design and demonstrating that the selected laser model is viable in this application. While data quality was low, the test presented multiple solutions that can be implemented in continued development.

This paper discusses the design of Oasis over the last year; analytical, simulation, and testing methods used to verify this design; and plans for continued development and path-to-flight.

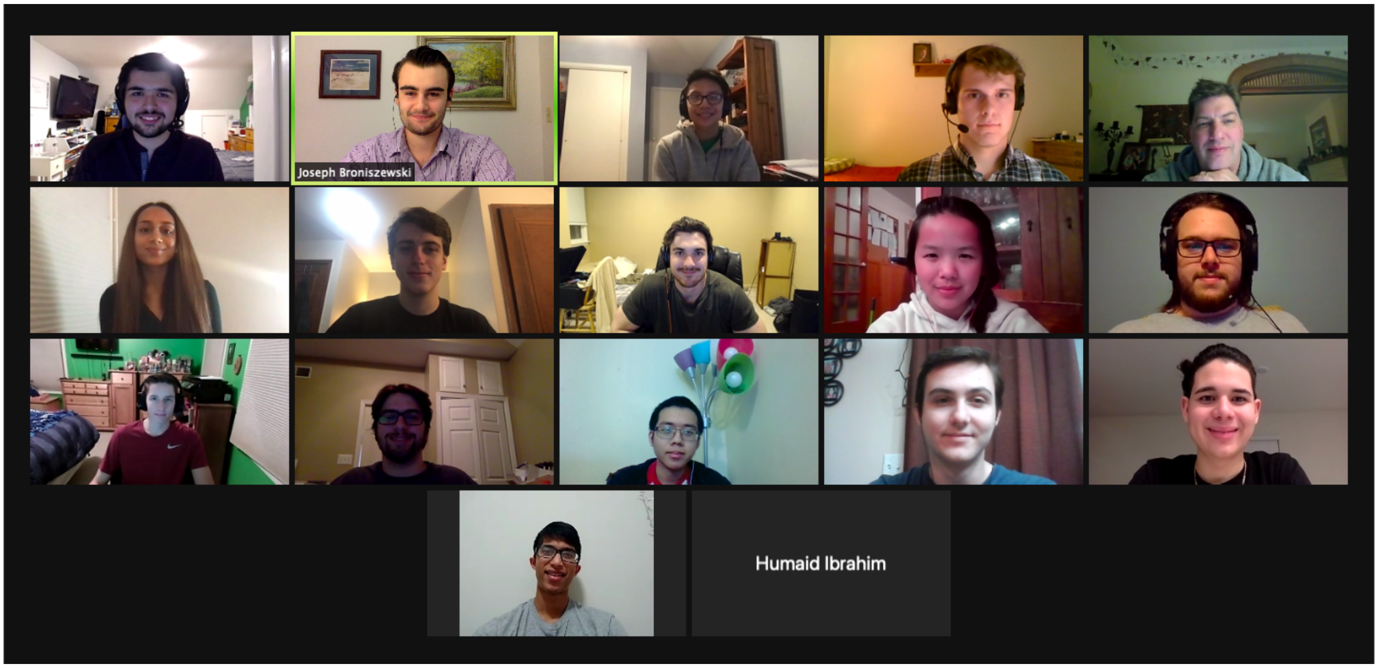


Fig. 1. The Penn State Student Space Program Laboratory 2020 NASA BIG Idea Challenge team.

I. PROBLEM STATEMENT

A. Artemis Context

According to NASA's Lunar Exploration Program Overview, the Artemis program is "focused on achieving the goal of an initial human landing by 2024 with acceptable technical risks, while simultaneously working toward sustainable lunar exploration in the mid-to-late 2020s." [1] The remainder of the Overview outlines the multi-step plan NASA has created to realize this timeline, along with some of the associated challenges that many engineers will dedicate themselves to solving. As part of the 2020 BIG Idea Challenge, a team of undergraduate researchers in Penn State's Student Space Programs Laboratory (SSPL) is developing Oasis, a rover-mounted spectroscopy instrument designed to search for water on the lunar surface.

B. Need for Water in Lunar Environment

Many of the challenges of lunar exploration and habitation are driven by the need for water. Water is critical for supporting life, specifically for drinking and growing food. The fact that water can be split into its elements, hydrogen and oxygen, further expands its utility, which include the production of breathable air and even rocket fuel. Although current technologies do not support cost-effective production of propellant [2], the creation of rocket fuel on the Moon holds great promise for later stages of the Artemis Program, such as using the Moon as a launch site to other terrestrial bodies like Mars [3].

Oasis is also able to measure the relative concentrations of other elements, which often have their own uses *in-situ*, including the construction of solar panels and 3D printed habitation structures [4]. Furthermore, these elements are also often required for the processes described in the previous paragraph.

An example in which secondary elements (in this case, carbon) are required to use water *in situ* is the Sabatier Reaction. The Sabatier Reaction is a chemical process currently used to make drinking water on the ISS. Conveniently, methane is a biproduct of this reaction, and a key ingredient in the creation of many rocket propellants. Due to an abundance of carbon in the atmosphere, the Sabatier Reaction is currently intended for Martian applications; however, it is a great example of how secondary minerals are often also needed to use water in extraterrestrial applications. [5]

To reiterate, the primary goal of Oasis is the detection of water. However the secondary goal of measuring general chemical composition of the lunar regolith is referenced throughout this paper as well.

Unfortunately, the benefits associated with the *in-situ* utilization of water come at a high cost. Lunar water is stored as permafrost ice trapped up to one meter in depth within lunar regolith [6], [7], which can make it difficult to detect visually from the surface. This permafrost ice is costly to mine because it is difficult to detect. There is very little light in PSRs, and the permafrost can be 1 m in depth. As a result, determining the precise locations of water deposits allows the mining operations to focus on areas that should yield significant quantities of water. This is similar to prospecting done for terrestrial mining operations.

C. Lunar Reconnaissance Orbiter

Entering lunar orbit in 2009, the *Lunar Reconnaissance Orbiter* spacecraft found evidence of water permafrost near the Moon's southern pole with its Lunar Exploration Neutron Detector (LEND) instrument [7]. This data (mapped onto the crater surface in Figure 2), in conjunction with research from Brown University [8], supported scientists' claims that water could be on the Moon, but also showed that water can generally be found in higher concentrations in permanently shadowed regions (PSRs).

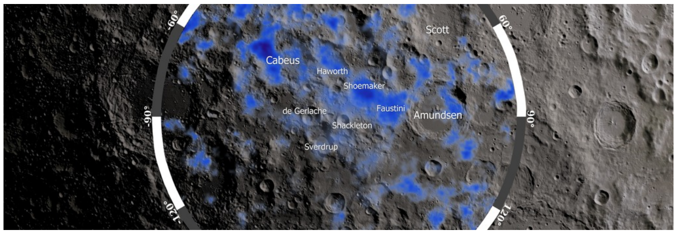


Fig. 2. LRO's LEND instrument measured neutron emission deficiencies in order to detect water on the lunar surface [7].

Unfortunately, these water-ice deposits are scattered non-uniformly throughout PSRs, making it necessary to collect density and concentration data *in situ*. A successful example of this kind of on-site sampling was the NASA LCROSS mission, which detected mercury, magnesium, calcium, silver, and sodium in the impact plume [9]. However, density measurements of these minerals were not collected. While recent discoveries indicate that water is much more common in sunlit regions than initially thought [10], reaching these high-density areas will still most likely be necessary. For this reason, Oasis has been designed for the exploration of PSRs.

II. BACKGROUND

A. Introduction to LIBS

Laser-induced breakdown spectroscopy (LIBS) is the measurement technique employed by Oasis to explore the regolith within these PSRs. LIBS operates by focusing a pulsed high-power laser onto a sample of interest, rapidly heating the sample and generating a localized plasma. As this plasma cools, the atoms of the sample emit light at characteristic wavelengths. Collecting and analyzing this light with a spectrometer allows for the identification of elements present in the regolith.

For over forty years, LIBS has been used for elemental analysis, and was initially proposed for planetary exploration in the 1990s [11]. Twenty-two years later, ChemCam became the first LIBS system to analyze a surface other than that of Earth.

B. ChemCam

NASA's ChemCam instrument (shown in Figure 3) is the first example of the use of LIBS on extraterrestrial bodies. Operated from the Mars Curiosity Rover, ChemCam has provided immense composition data from the Martian soil, including, but not limited to, rock type, relative chemical concentration, and even the detection of ice and aqueous solutions all from samples up to 7 meters away. It is a robust and versatile instrument that also houses a camera that collects visual information useful for both sampling of and traversing Martian soil [12].

C. LIBS on the Moon

ChemCam demonstrated that LIBS is a viable technique for *in-situ* analysis of the Martian surface. Although LIBS has yet to be successfully employed on the Moon, LIBS is a promising analysis technique for lunar regolith due to its ability to study a sample at a distance, which allows for data collection from rough surfaces that are present in PSRs. The ISRO Chandrayaan mission planned to utilize LIBS, the host craft collided with the lunar surface, destroying the payload [15].

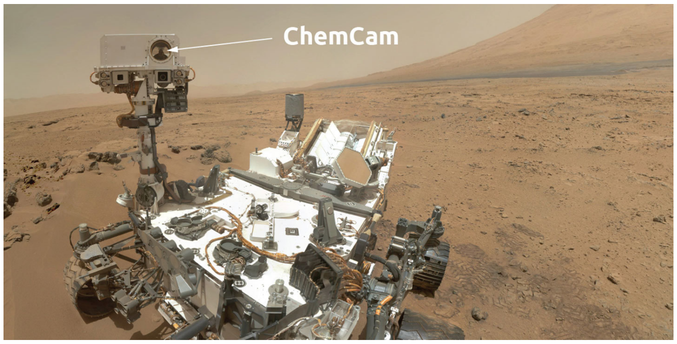


Fig. 3. NASA's ChemCam instrument on the Mars Curiosity Rover. Image from NASA.

The largest challenge is the Moon's lack of atmosphere, which results in negligible ambient pressure. As LIBS functions by analyzing an expanding plasma, the ambient pressure impacts the rate at which the plasma expands. In low pressure conditions, the plasma expands rapidly. Furthermore, low pressure results in a lower temperature plasma. These two factors greatly decrease the intensity of a plasma generated on the surface of the Moon compared to Earth or Mars [13].

D. Other Relevant Elements

In order to detect water using LIBS, it is important to understand what compounds are present in the resulting plasma and its emission spectra. The elemental forms of H, O, and OH appear when the water is ablated from the regolith (see Table I). The OH line is the most important for this mission because it is a distinct indicator of water, as H and O can be present without the presence of water [12].

While the main purpose of the Oasis instrument is to detect water using LIBS, it is also capable of detecting other elements. The most prominent elements present in lunar regolith are are shown in Table I. Identifying these elements will allow for the classification of the regolith in the largely unexplored PSRs.

III. PROJECT DESCRIPTION

A. System Requirements and Design Assumptions

The mission and system requirements for Oasis are derived from those explicitly provided by the

TABLE I
WAVELENGTHS FOR ELEMENTS AND COMPOUNDS OF INTEREST FROM NIST ATOMIC SPECTRA DATABASE [14]

Element	Wavelengths (nm)
Si	288.1, 390.5
Ti	308.8, 334.9, 376.0
Fe	259.9, 275.6
Mg	279.5
Ca	393.4, 396.9
Na	589.2
K	766.5
Mn	257.6, 294.9
Cr	267.2, 283.5, 312.0
P	253.5
H	656.3
O	777.4
OH	306.4

2020 NASA BIG Idea Challenge and instrument-specific requirements that were developed by our team. These requirements are provided in Table II and all requirements have been satisfied.

TABLE II
NASA BIG IDEA CHALLENGE REQUIREMENTS ARE MET BY THE OASIS DESIGN.

Item	Requirement	Result
Mass (kg)	< 15	7.84
Dimensions (cm)	None	$32\times21\times10$
Max Continuous Power Draw (W)	< 8	7.8
Max Peak Power (W) Draw*	< 40	33
Bandwidth (kbps)	< 380	250
Power Supply Voltage (Vdc)	28	met
Communication Protocol	RS-422	met
Adiabatic Mounting**	N/A	met

*Peak power draw is defined by the competition as no more than 5 minutes continuous

**Adiabatic mounting was assumed throughout development and analysis

Mission requirements mostly concern the nature of lunar regolith and the lunar environment. In order to ablate lunar regolith, a power density of 5 GW/cm^2 necessitates the use of an optical system to focus the laser [15]. Based on this property of the lunar regolith, and selection of the MicroJewel 1064 nm Nd:YAG laser, the optical system yields a focal length of 300 ± 15 mm.

To detect water, the spectrometer's required wavelength range must cover the emission lines for OH, H, and O, which is at least from 300 nm to 800 nm. To detect other elements that are expected in regolith, the necessary wavelength range increases to 250 nm to 800 nm. As a result, the spectrometer and the optics systems were designed to meet these requirements, which is covered in more detail in Section III-B.

The expected external temperature in the regions Oasis will be operating is 20–40 K [16]. Based on the temperature-range requirements of Oasis' internal components, a set temperature of 297 K is desired. This temperature was calculated as the average of the highest *minimum* and lowest *maximum* operable temperature of the components. The methods by which this temperature is maintained are described further in Section III-B.

It is assumed that during launch, flight, and landing, Oasis will be supplied power to moderate its temperature, or that the ambient temperature will be within the payload's tolerance. Convection heat exchange has been assumed to be negligible due to the lack of lunar atmosphere [17]. The design of Oasis assumes the payload will be mounted in such a way that lunar dust will not accumulate on the lens or significantly on the walls of the payload. Also, based on the variety of rover mounting ports, it is assumed that the host rover will allow for adiabatic mounting.

While Oasis has been designed with structural integrity in mind, analytical methods have not been used to verify that it can withstand launch vibrations. Developmental constraints necessitated this limit of scope prior to path-to-flight. The use of these analytical methods going forward, and the methods of testing to verify this analysis, are discussed in Section V.

B. System Design

1) System Summary: The packaged instrument is shown in Figure 4 and the general systems diagram of Oasis is provided in Figure 5. Per the requirements provided by the 2020 BIG Idea Challenge, Oasis communicates with its host craft through an RS-422 serial line, and is provided a 28 Vdc power source. The power system then converts that input voltage to those required by the individual components within Oasis. The BeagleBone Black Industrial flight computer controls the instrumentation (laser and spectrometer) in order to perform LIBS, and transmits collected data back to the host. The instrumentation has solid-state optics that are used to ablate and collect emissions from lunar regolith. The flight computer also communicates with the thermal logic controller (TLC). The TLC uses a closed-loop thermal control system to maintain temperatures within operable ranges inside the payload. All of these subsystems are described in further detail in the remainder of the this section.

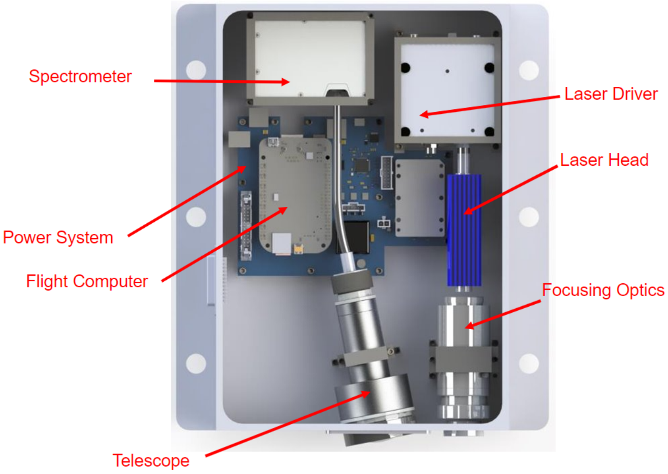


Fig. 4. General layout of Oasis.

2) Science: The science subsystem consists of the instruments needed to perform LIBS. Shown in Figure 6 during testing, a pulsed laser is used in combination with focusing optics to ablate the lunar regolith. A spectrometer with collection optics (labeled "Telescope" in Figure 4) to analyze the light emitted by this plasma.

Oasis neutilize a laser that is powerful enough to successfully ablate lunar regolith, while also staying compact. To satisfy these requirements, Oasis operates with Quantum Composer's MicroJewel laser. The MicroJewel is a diode pumped solid state Nd:YAG pulsed laser with the following specifications [18]:

- Wavelength: 1064 nm
- Pulse Energy: 11.5 mJ
- Pulse Duration: 4 ns
- Beam Diameter (Near field): 0.8 mm
- Beam Diameter (Far field): 1.7 mm
- Beam Quality (M^2): 4.2
- Max Repetition Rate: 30 Hz

The MicroJewel is compact, measuring 90 mm long and 16 mm in diameter, while also providing a large power per pulse making it ideally suited for a compact, low power LIBS system.

As stated in the previous section, the required power density to ablate the lunar regolith is 5 GW/cm^2. Without focusing optics, and assuming a far field beam diameter of 1.7 mm, the power density of the laser is 120 MW/cm^2, far under what is required.

To reach the minimum power density, the laser will need to be focused onto the regolith, necessitating the use of a beam expander and a 1-in plano-convex lens. As shown in Figure 7, the laser will fire into the beam expander then travel through the focusing lens, where the laser will be directed to the spot of ablation on the regolith. A beam expander is necessary before focusing the laser, because increasing the beam diameter will allow for a smaller beam waist at the focal length of the lens. This allows for the ablation of regolith at longer distances, increasing the modularity of Oasis onto other rovers.

The beam expander chosen for this payload is a 10X 1064 nm Vega Laser Line Beam Expander from Edmund Optics. The main requirements for the beam expander are a high damage threshold and a compact size. The energy density of the laser as it enters the beam expander is 0.415 J/cm^2, and the Vega beam expander has a damage threshold of 10 J/cm^2, which is significantly higher than what is required. The Vega beam expander measures 91 mm from end to end with a diameter of 40 mm, allowing for Oasis to stay compact.

The focusing lens is a 1-in UV-fused silica len, V-coated for 1064 nm, from Thorlabs, with a focal length of 300 mm. This lens also has a damage threshold of 10 J/cm^2, ensuring the lens will not be damaged during firing. The focal length was chosen because it was well below the maximum focal length required to stay over 5 GW/cm^2. As a result, there is flexibility with the range of albation, allowing for Oasis to be easily adapted to different rovers. However, changing the focal length of the system requires changing the focusing lens.

To analyze the laser-induced plasma, Oasis uses a Flame-T UV-VIS spectrometer by Ocean Insight. The Flame-T is compact (88.9 mm × 63.5 mm × 31.9 mm) and has a low power consumption of 1.25 Watts, making it ideal for a system like Oasis. Furthermore, the Flame-T has a wide wavelength range allowing for detection of critical wavelengths, from 306.4 nm to 777 nm. The Flame-T has the following specifications [19]:

- Wavelength Range: 200 nm to 850 nm
- Optical Resolution: 1.33 nm
- Integration Time: 3.8 ms - 10 s

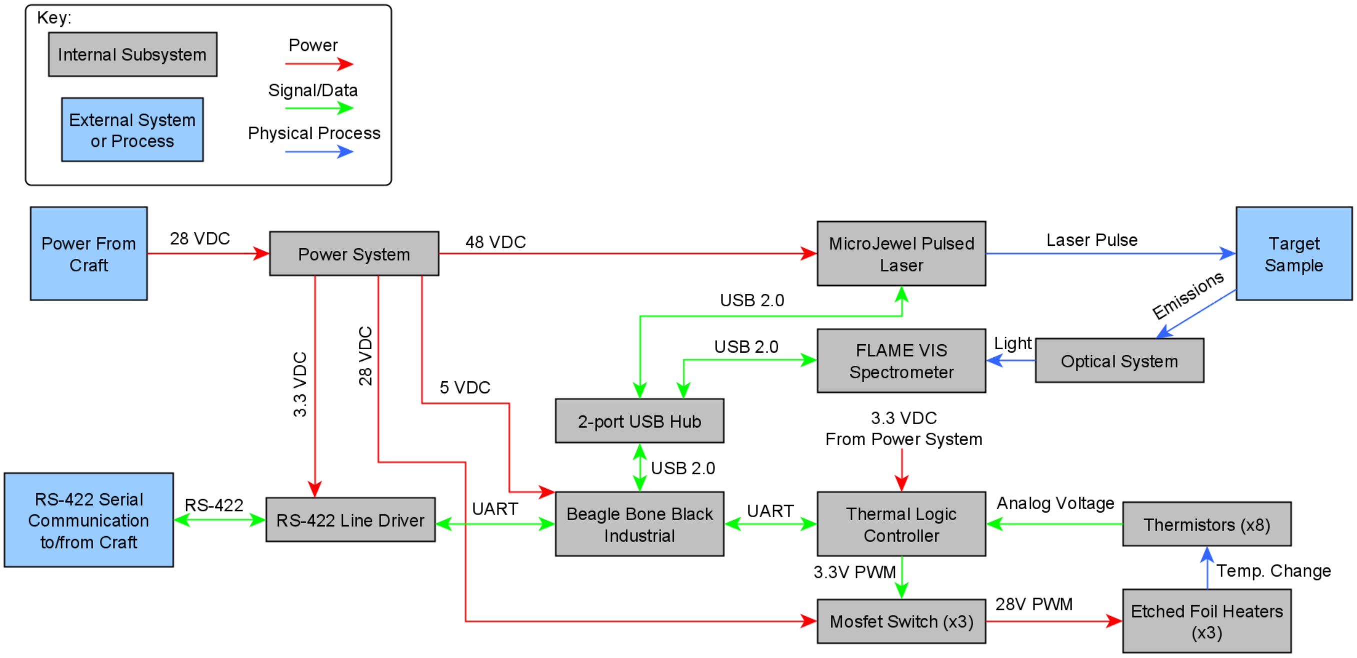


Fig. 5. Oasis systems block diagram.

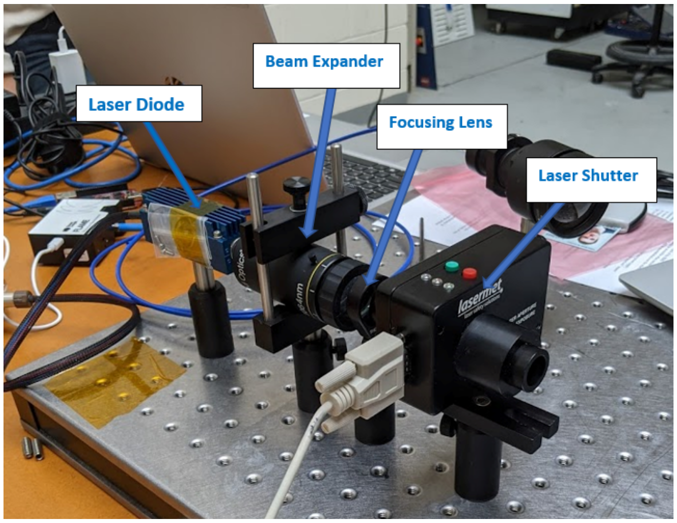


Fig. 6. Experimental setup of the laser system

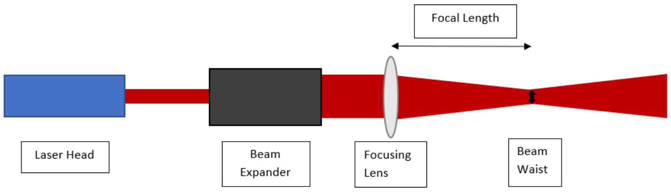


Fig. 7. Beam width variation as it passes through focusing optics

Oasis uses a telescope to collect the light emitted by the laser-induced plasma. The telescope, shown in Figure 8, consists of three UV-fused silica lenses from Thorlabs and a collimating lens from Ocean Insight. The largest diameter objective is used to maximise the light captured and analyzed. The objective chosen is a 2-in UV-fused silica lens with a focal length of 75 mm.

Then, a 1-in UV-fused silica plano-concave lens is used to collimate the incoming light from the objective, allowing for a filter to be used to block 1064 nm light from the spectrometer, which could damage the charge-coupled device (CCD) in the spectrometer. The light is then focused using a 1-in UV-fused silica plano-convex lens to the collimating lens, which connects to a fiber optic cable through an SMA 905 connection. Finally, the fiber optic cable connects to the spectrometer where the light is analyzed. When designing the telescope, the lenses and filters need to allow for the transmission of every emission line required. The three UV-fused silica lenses transmit wavelengths from 185 nm to 2100 nm and the collimating lens transmit wavelengths from 185 nm to 2500 nm. This meets the required transmission range of 250 nm to 800 nm.

After preliminary testing, it was found that the telescope needed to be realigned so the plasma light is collected by the spectrometer. As the laser focusing lens has a focal length of 300 mm, the telescope needed to be angled 11 degrees towards the spectrometer optical system so it is aligned with the point of ablation.

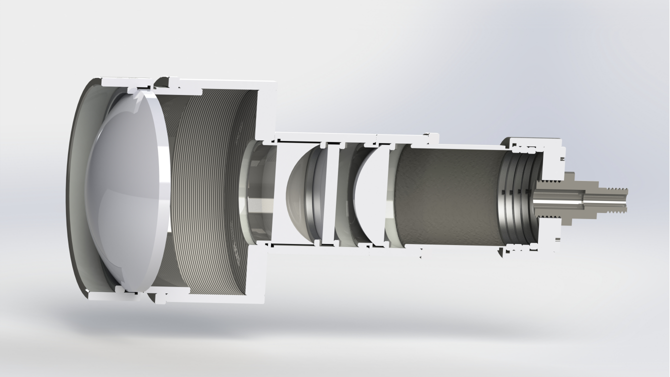


Fig. 8. Cross section view of telescope

3) Structures: The main housing for the Oasis payload consists of a 32 cm x 21 cm x 10 cm box of 6061-T6 Aluminum. It has two 3 cm fins on either side, each with 3 holes, to allow for mounting with the rover; yielding a payload footprint of 32 cm x 28 cm x 10 cm. The walls on the box are 0.5 cm thick in order to protect the interior components while also minimizing the weight. There are also holes in the walls of the housing to allow the laser and optical system to face the lunar surface. Additionally, there is a hole for a d-sub connector to connect to the rover. This hole is placed in an optimal location to allow the electronic system to communicate with the rover without it interfering with the payload's fins.

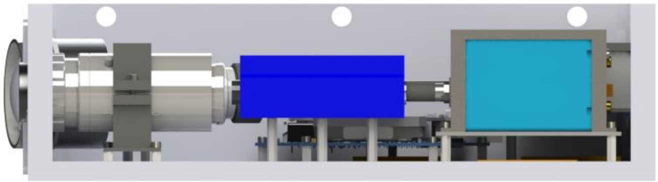


Fig. 9. Longitudinal cross section of Oasis, exposing component standoffs

There are a series of metric M3 tapped through holes on the bottom of the housing to which the standoffs for the components are attached. The spectrometer and laser driver are secured with brackets and base-plates to prevent them from moving or sliding. The optical system and beam expander are secured with brackets in order to ensure their stability. A plate mounts to the front of the housing to secure the optical system at its required angle.

The lid for the housing has an interior lip that is designed to fit inside of the housing cavity. This lip allows for the lid to be secured into place while allowing the lid to sit flush with the rest of the housing. The lid is then attached to the rest of the housing via button head screws placed on the sides of the housing. The screws go into the sides of the housing and are secured into the lip of the lid. By having the screws attach to the sides instead of the top of the lid, the overall thickness of the walls of the housing is minimized without compromising structural integrity.

Minimizing the payload's footprint was a priority throughout development. The intention was not only to use the given space efficiently but to make the overall dimensions of the project as small as possible, so that the payload can be used within a suite of rover mounted instruments.

Working remotely, 3D modeling became the primary method of structural design. Great effort was put into SOLIDWORKS in order to craft a CAD model of each component and its assembly in high detail. These efforts allowed for the creation of a shareable, visual representation of the project, while also setting up the foundations for manufacturing.

4) Thermals: The thermal control system for Oasis is based on both active and passive heating. Its function is to regulate the separate component temperatures towards a target temperature, within an acceptable operational range. As stated earlier, the thermal design assumes negligible convection, and negligible conductive heat exchange with the host vehicle. It also assumes an exterior temperature of 20 Kelvin.

To determine the ideal temperature for each component, the center temperature of the operating temperature range for each component, as specified on the manufacturer specification sheet, was used [20], [18], [19], [21]. Since the PCB includes both the BeagleBone Black Industrial and the Teensy 3.2 computers, the narrower temperature range of the two was used to determine the overall operational temperature range of the PCB. To determine the ideal overall target temperature, the average center temperatures of the PCB, spectrometer, and laser was taken and the outcome was a temperature of 296.5 Kelvin. The results of these calculations are shown in Table III.

For the passive heating aspect of the thermal control system, the exterior of the aluminum housing

TABLE III
TABLE OF OPERATIONAL TEMPERATURE RANGES FOR EACH MAJOR SYSTEM OF COMPONENTS, AND THE CENTER OF EACH RANGE

Component	Operational Temperature Range (K)	Center [Target] Temperature (K)
PCB (Overall)	233.15–358.15	295.65
Laser Driver	288.15–303.15	295.65
Spectrometer	273.15–323.15	298.15

will be polished to obtain an emissivity as close to 0.0425 as possible. Polishing the aluminum is an inexpensive and efficient way to achieve this desired emissivity [22]. During storage of the payload, a zero-residue plastic film will be placed over the polished aluminum to prevent the degradation of the surface optical properties from oxidation and other atmospheric effects. The plastic film will be removed for testing or any other use of the payload.

Other methods of insulation such as Multi-layer insulation (MLI) and single layer insulation (SLI) have been considered. Both surface insulation methods are potential options, but would provide an effective emissivity lower than desired. To best achieve a steady state at the desired target temperature, an emissivity close to the target is required.

To actively heat the payload, Polyimide heaters will be used. All Flex Flexible Heaters sells 2 inch by 2 inch pre-made Polyimide heaters that are well suited for Oasis' application. These heaters also have an attached pressure sensitive adhesive (PSA) that will make it easy to attach them to the components. At a size of 4 in^2, two heaters can be used to heat the spectrometer, laser, and PCB, respectively. The use of more than one heater allows for redundancy in case of failure. One heater will be attached to the top and bottom of both the laser driver and the spectrometer. This will allow for direct heat conduction into these components, for the most effective heating. Two more heaters will be attached to the bottom of the housing directly under the PCB. Since the PCB does not have any metal that a heater can be directly attached to, the heaters will act as a way to increase the temperature of the PCB standoffs, thereby decreasing the amount of heat that will leave the PCB through conduction. Since the components on the PCB use 2.84 Watts of heat and the PCB is designed to have an even distribution of heat through the use of internal copper layers, it was concluded that during normal operation, the PCB will not need any external heat supplied through heaters. The heaters under the PCB will only output a significant amount of heat in the event that the temperature of a component falls well below the target operational temperature.

There is a mass difference between the spectrometer and laser driver and the spectrometer has a continual power consumption during normal operation while the laser driver has no power consumption when not firing. Therefore, the heater output for each of these components needed to be different. Taking into account the power to mass ratio for each of these components during calculations, the laser driver heaters will have a continual output of 1.6 watts plus an additional 1.3 watts for every additional 1 watt of heater output for the spectrometer, in normal operation. This weighting is taken into account in the TLC code to give the heaters the correct amount of heat. A COMSOL Multiphysics simulation verifies this weighting with the temperature of the spectrometer and laser being within 1% of each other. During laser fire, all heaters will momentarily be shut off because there will be in excess of 30 watts of power consumption and dissipation during this time.

To moderate the temperature of the components, a thermal controller has been implemented. This controller must meet certain design objectives to maximize performance and provide information useful for system integration. These objectives are maintaining system stability, rejecting disturbance, promoting robustness, minimizing error, and tracking the error between temperature of the component and a determined reference point. A well-known solution to these design objectives is the three-term proportional-integral-derivative (PID) controller. These three terms perform specific scaling onto a given error value between the output and input of the system that can adjust parameters including temperature regulation and tracking. The proportional term is an adjustable parameter that helps to improve steady-state accuracy and reduce rise time of a system. The integral gain term scales with the amplitude and duration of the error; this improves the steady-state accuracy of the system and reduces its rise time. The derivative term is proportional to the rate of change of the error value and anticipates system behaviors. While this derivative term can help reach steady-state faster, it also accentuates noise. The derivative aspect is problematic in this thermal system because it could cause unwanted oscillation and decrease stability without offering significant benefit. Ultimately, it was determined that the use of a PI controller, without a derivative term, is sufficient to provide the necessary thermal control without excessive fluctuations. The controller is fully functional with PI gain coefficients and has been coded with a disabled D term that can be enabled if necessary. The P and I terms will be adjusted during cryogenic, vacuum testing as explained in Section V, and the decision to remove the D term will be verified.

The temperature of the components will be monitored by nine thermistors spaced inside the payload, with three thermistors on each component (laser driver, spectrometer, and PCB), for redundancy in case one fails. The TLC will monitor the error from the target temperature given by the thermistor values and output a pulse-modulated signal to gate drivers and MOSFETs controlling the heating elements. An anti-integral wind-up scheme will monitor the error between the target temperature and clamp the integral term to prevent excessive overshoot.

5) Electronics: The electronics subsystem consists of the hardware and software systems required to interface between the laser, spectrometer, flight computer, thermal logic controller, and rover.

The previously mentioned thermal logic controller (TLC) is a microcontroller, seperate from the main flight computer, embedded directly onto the PCB. The TLC is based off of a PJRC Teensy 3.2 and is devoted exclusively to temperature monitoring and heating through the use of a PI loop. Based upon the output from the PI loop, the TLC varies the duty cycle of a PWM signal which controls the amount of power delivered to the polyamide heaters. Having a separate microntroller for thermal control provides both redundancy with the flight computer and the ability for the payload to enter a low-power state while in transit to the mission area. In this low-power state, only the TLC needs to be powered on to maintain storage temperature, while the flight computer and other systems can remain off. This allows for the TLC to maintain the payload's temperature without the extra power draw from the other payload components.

In the beginning of the project, the electronics subsystem created a high level state diagram for the flight computer, laser, and spectrometer as seen in Figure 11. This high level state diagram helped guide the development of the flight computer software, and increased the resolution of the concept of operations. In ”flight” mode, the BeagleBone Black flight computer follows the following states under normal operations shown in Figure 11. Arrows protruding from the flight computer, labeled with commands, represent its control over the states of both the laser and the spectrometer independently. The laser is shown to follow a sequence of states prior to being able to fire. For coherent sampling data, the spectrometer is designed to integrate in sync with laser fire. The flight computer can also command the spectrometer to integrate independently of laser fire. The diagram displays how errors might influence the changing of states for each component. For example, an unexpected single latch-up event can cause the flight computer to be automatically restarted by the watchdog timer. The laser sampling sequence software represented in Figure 11 was successfully utilized in preliminary LIBS testing as described in the Section IV-B.

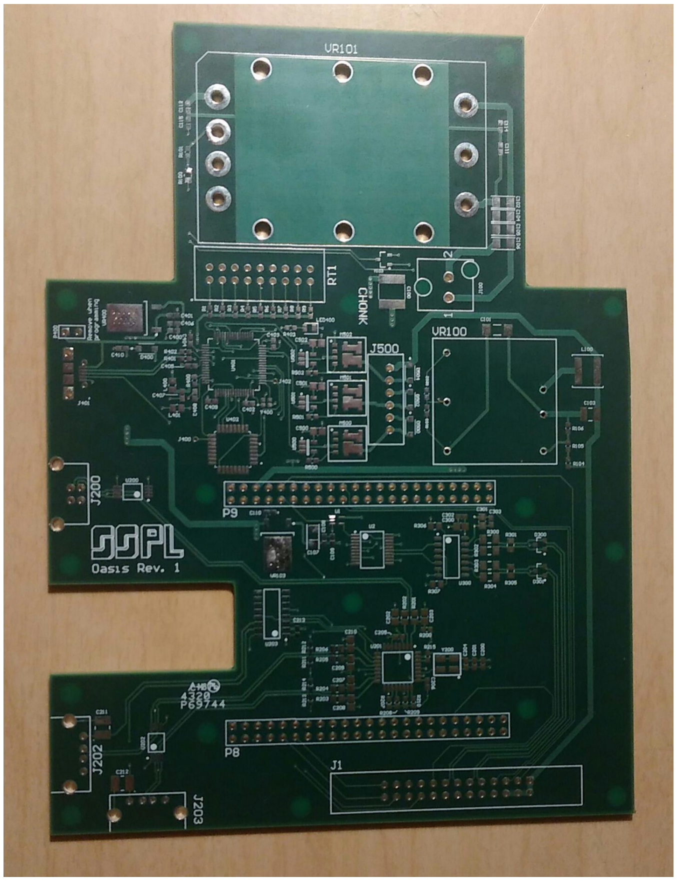


Fig. 10. The PCB design is manufactured and prepared to be populated by electrical components.

During development of the flight computer soft-

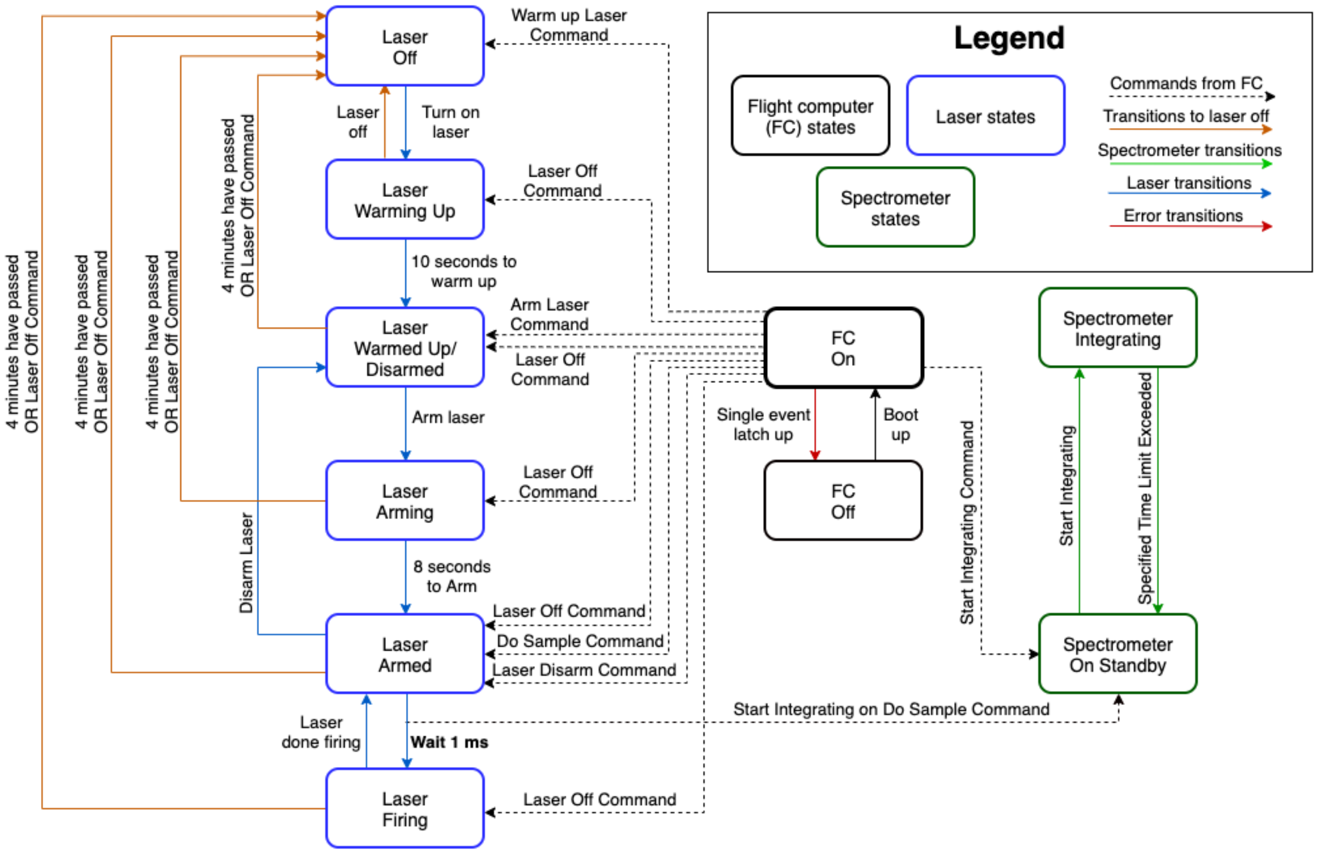


Fig. 11. State diagram of Oasis software

ware, the electronics subsystem developed a Python 3.5 library to control the MicroJewel DPSS laser [23]. The electronics subsystem also used the open-source Python 3 library pyseabreeze, which is a Python package to control the Ocean Insight spectrometer [24].

The power system distributes the 28-VDC input supply to a 48-V DC-DC converter, a 5-V DC-DC converter, and the polyamide heaters. Two 3.3-V linear regulators are supplied by the 5-V converter to power the thermal logic controller and communication components. The 48-V output is used by the MicroJewel laser, and the 5-V output is used to power the spectrometer and flight computer. The 3.3-V linear regulators are used to power the TLC and peripheral components such as the RS-422 line driver.

There are three power states of the payload: a low-power ”sleep” state as described above when only the thermal logic controller is active, a stand-by state when the entire system is active but the laser is not yet armed, and an active state when the laser is powered on and ready to fire. The total power draw of the Oasis payload in the latter two states is given in Figure 12.

The electronics subsystem began design and construction of the PCB to distribute the power as described and provide communication links amongst the systems. However due to COVID-19 delays, only an unpopulated PCB was manufactured, which can be see in Figure 10.

C. Major Changes Since Proposal

Initially, the proposed form of passive heating for the thermal control system was the use of aluminum foil as a low emissivity outer layer for the payload. This would have lead to many potential problems, such as conduction to the host craft. For these reasons, the passive heating portion of the thermal control system was initially changed to Multilayer Insulation (MLI). COMSOL simulations indicated that the emissivity needed to keep the components at the target temperature was closer to 0.0425, it

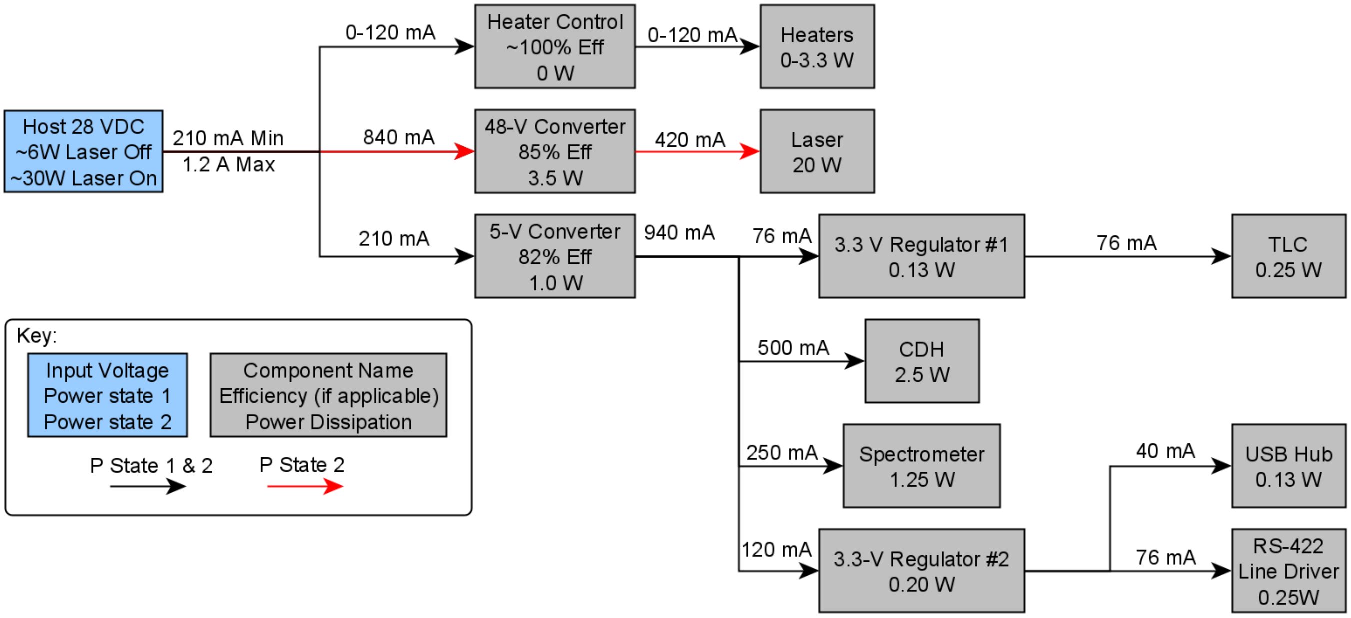


Fig. 12. Power draw diagram for Oasis power system

was determined that MLI would provide an emissivity too low for the payload. After coming to this conclusion, polished aluminum was chosen for the passive heating element of the thermal control system because of its emissivity being between 0.04 and 0.051 [22], along with the added simplicity over MLI.

The original structural design proposed had three adiabatic modules mounted inside a main housing. Each module was to be thermally controlled to allow for a power-efficient thermal design. However, it was determined that such a design would have consumed unnecessary amounts of power, and be cost inefficient. By combining all components into a single thermal module, the surface area and volume of Oasis significantly decreased. A smaller size and surface area minimized heat loss, reducing long-term power consumption.

Another change to the model is the location of the laser and spectrometer optical systems. Originally, they were fully inside the modules with holes for light to pass through. Instead, the optical systems were mounted into the wall of the housing with standoffs along the components to further support their weight. An angled hole bracket for the spectrometer's optical system was used to point the lens directly at the point of ablation.

The original design of the optical system did not include focusing optics at all, and the spectrometer emission collection optics have been considerably reworked. Originally, the laser was not focused so Oasis was not restricted to sampling at a fixed distance. This design was not possible because the laser is not capable of ablating the regolith without the use of focusing optics. Additionally, the collection optics have been redesigned by adding a larger diameter objective, and by connecting the telescope to the spectrometer via fiber optic cable.

The original design featured an ISIS on-board flight computer. The ISIS On Board Computer was replaced by a BeagleBone Black (BBB) Industrial (referred to as the ”flight computer” in this document) because the lead time required to receive the ISIS computer did not fit within development schedule. This change also allowed for more rapid prototyping throughout development of the PCB and software.

IV. PROOF-OF-CONCEPT TESTING

A. *Challenges*

Due to COVID-19 restrictions, the vast majority of the development of Oasis has been done remotely, so as to comply with state guidelines and ensure the health and safety of each team member. Through the use of online tools like Zoom and Microsoft Teams, the design of Oasis was significantly less affected by the shift to remote work than testing and verification was. Unfortunately, some planned tests had to be postponed to a path-to-flight situation due to limited access to facilities, very few researchers on campus, and months long delays in part acquisition due to vendors facing their own COVID-19 related challenges. Still, the tests conducted successfully validated breadboard development and integration of Oasis, increasing the technology readiness level (TRL) of Oasis from TRL-2 during proposal to between TRL-3 and TRL-4. This section describes the tests that were completed, whereas Section V discusses future testing plans.

B. Preliminary LIBS Testing

The Naval Research Laboratory (NRL) graciously provided us with the facilities and personnel to test the capability of Oasis to perform LIBS. The test utilized their class 4 laser safety certified lab, and their on-site safety protocols. Depicted in Figure 4, the test consisted of the laser and spectrometer, and a BeagleBone Black Industrial being used to ablate and sample JSC-1A lunar regolith simulant in typical earth conditions (room temperature, non-vacuum, etc). This test was not only intended to verify overall LIBS functionality, but also to measure the effects of laser pulse frequency and spectrometer integration time on collected data. The on-site users successfully controlled the spectrometer and laser in tandem through the BeagleBone Black Industrial, verifying the software that interfaces these components.

Additionally, the on-site users were able to see a glow generated from the laser-induced plasma during sampling shown in Figure 14. This glow could not have come from the laser itself, since 1064 nm is below the region of visible light. This indicates that the observed glow was from generated ablation. This was critical in verifying that calculations used in the design of the laser focusing optical system.

Although the laser-induced plasma was successfully generated, the spectrometer failed to detect any distinguishable peaks that are present in LIBS applications. This issue has several possible sources.

First, it is possible that misalignment of the optical system caused these issues. For example, calculations indicated that the telescope had to be tilted to face the point of ablation within one degree of accuracy. This issue would be accounted for in the integration of the LIBS system within the payload housing.

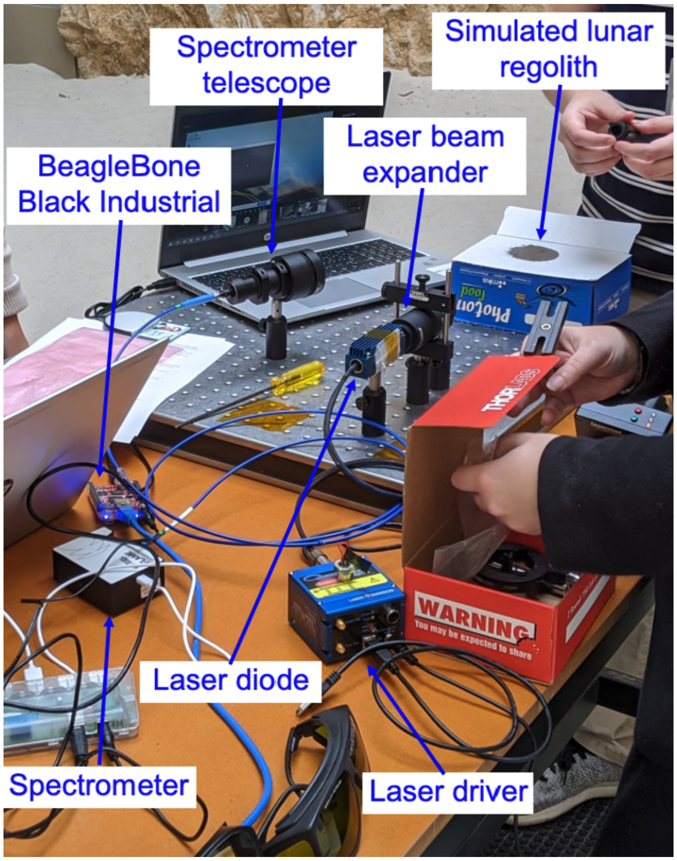


Fig. 13. LIBS testing setup at NRL

Fig. 14. The laser successfully ablates simulated lunar regolith.

Second, it is possible that imprecise timing between the spectrometer and laser could have lead to the collection of noisy data. The spectrometer may have either not sampled quickly enough to catch the ablation, or sampled for too long, effectively burying any detection data over time.

An external trigger which can simultaneously command the laser to fire and spectrometer to sample can be used to solve this issue. With this method, the laser has a delay option to ensure predictable latency between laser fire and spectrometer integration. Breadboard development of this external trigger has already begun with minimal changes to the current Oasis design.

Overall, the LIBS test performed at NRL provided valuable feedback that was otherwise unobtainable due to disruptions caused by COVID-19. It also significantly informed the design plans outlined in the Section V.

C. Electronics Testing

In order to test the design of the TLC, a small sub-circuit containing the MOSFET, line driver, and polyamide heater that would be used in the larger PCB was constructed. This sub-circuit tested the functionality of powering the polyamide heaters using a PWM signal from the TLC through a power MOSFET. The test shows that the TLC successfully controls of the power delivered to a polyamide heating pad through PWM output from the TLC.

Another sub-circuit was also designed to verify the functionality of the RS-422 communication link. The RS-422 line driver and appropriate peripheral components were included in the circuit. By connecting a RS-422 evaluation board to the sub-circuit, a rudimentary serial link was formed from one device to another through RS-422. This serial link was successful, which validated our RS-422 circuitry implementation.

D. Thermal Simulations

A simulation made in the COMSOL Multiphysics software was used to verify the design of the thermal control system. To verify the design, a basic model was made so that the outer emissivity of the payload and the heat input from the heaters in the spectrometer, laser driver, and PCB regions could be varied to show the relationship between the emissivity and heat input needed from the heaters to keep each component and the overall temperature within 1% of the target temperature of each component. A 3D temperature graph of the components, when the outer emissivity is set at 0.0425 and the total heater output is set at 1.6 Watts, can be seen in Figure 16. While an emissivity of around 0.0425 was the goal by polishing the aluminum housing, it was understood that the exact emissivity from polishing the aluminum may be higher than the target emissivity.

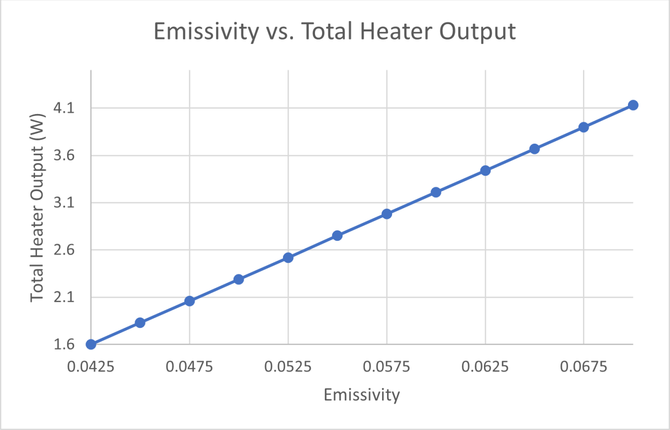


Fig. 15. The relationship between emissivity and total heater power input needed to keep payload components within 1% of the target temperature for each component.

The COMSOL model shows a direct relationship between the outer emissivity of the payload and the total heater power output. This model was able to confirm that even with an emissivity up to 0.06, the heater power input needed to regulate the temperature is still under the 3.3 Watt maximum power draw for the active heating system. This relationship can be seen in Figure 15.

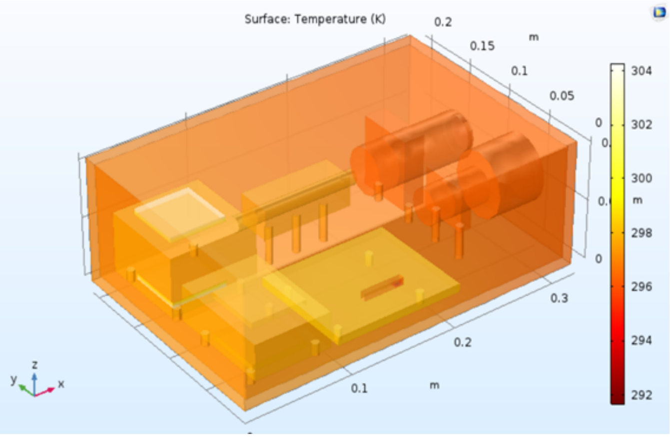


Fig. 16. Temperature distribution with an outer emissivity of 0.0425 and a total heater power input of 1.6 watts.

E. Instrument Tests

A test was conducted to ensure that the spectrometer would not have significant shifts in its readings with temperature shift within the operable temperature range. To do this test, spectrometer readings were taken starting at room temperature and incrementally as the instrument was being cooled.

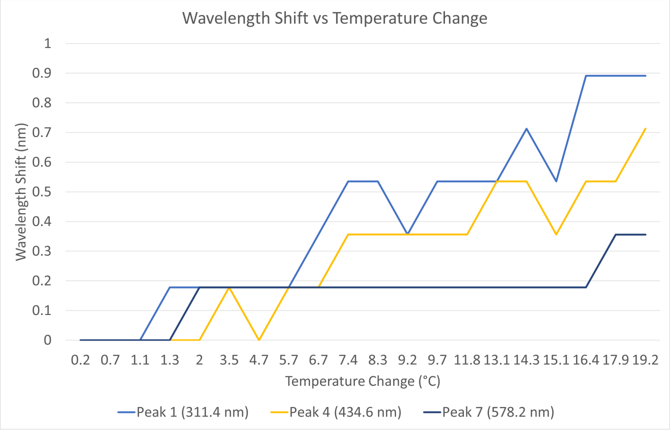


Fig. 17. Comparing plot of wavelength shift versus temperature for three peaks, 311.4 nm, 434.6 nm, and 578.2 nm

The data was gathered from a spectrolamp, which produced seven peak wavelengths ranging from 311 nm up to 578 nm, over temperatures ranging from 277.4 K to 296.6 K. The wavelength shifts were calculated relative to the peaks recorded at the minimum temperature, 277.4 K.

While the data indicated a clear trend that increasing temperature resulted in an increase in recorded wavelength, the maximum wavelength shift was less than 0.9 nm. Additionally, peaks at higher wavelengths shifted more than peaks at lower wavelengths, shown in Figure 17. At the lowest peak, for every increase in temperature there is a 0.049 nm shift in wavelength

From the data gathered, it was concluded that temperature change does affect the readings of the spectrometer. However, this change is too small to noticeably impact the data, as the resolution of the spectrometer is 1.33 nm, and the maximum change in wavelength was less than 1 nm.

V. PATH-TO-FLIGHT

A. *Overview*

The following plans are intended to raise the technology readiness level of Oasis from the current TRL level of 3 to TRL-6. Some are related to testing and system verification the Oasis team was unable to complete over the last year due to COVID-19 related difficulties, while others are related to design changes informed by analysis and verification that has already been completed.

B. *Future Testing*

1) TVAC: The payload will need to be tested in a cryogenic vacuum chamber, which can reach temperatures as close to 20 K as possible, to ensure proper operation of the thermal control system in a near-lunar environment. This has been planned with NRL staff, since they have offered access to their on-site thermal vacuum chambers. Tuning the gains of the PI loop would be found iteratively by analyzing the step response of the system for reaching the setpoint temperature. This can be done by first setting the integral term to 0 and starting with a small proportional term. The goal of this process will be test different gain values to determine the largest coefficient that does not produce overshoot to the step response, and as a safeguard choosing a smaller value by about 5-10%. Once setting this as the proportional coefficient, a similar process will be performed for finding the integral term: starting with a small integral coefficient, the step response will be tested at different integral gains to find a value that does produce overshoot to the system. From these design choices, the time constant of the system can be estimated for modeling the PI controller.

After successful tuning of the coefficients, the temperature of each component will be recorded, during normal operation of the payload without laser fire. If any component exceeds its operational temperature range, the heater weighting coefficients will be adjusted to account for the temperature difference.

2) Shake Test: During transportation to the surface of the Moon, the Oasis payload will endure a multitude of forces. It is crucial that the structural design of the device can withstand these forces, thus a shake test is required to verify analysis. In order to perform the shake test, the payload and all its components would first start out with a gentle shake, then observe the device to check for signs of damage or structural weakness. The intensity of the test would gradually increase and data would be recorded to observe how the payload behaves. This shake test would take place in Penn State facilities.

3) Integrated Test: An integrated test had been planned to test the Oasis system. The objective of the integrated test to verify functionality of the LIBS system in a relevant environment. This ensures the thermal subsystem, electronics subsystem, and mechanical components can successfully work during a laser fire in a cryogenic vacuum environment. Furthermore, an integrated test will verify that the LIBS system is sensitive enough to detect laser plasma in a low pressure.

The integrated test will also confirm that the thermal control system functions properly and keeps components within operational temperature range during normal operation of all components, including laser fire. Upon completion of the integrated test, the TRL level of Oasis will be raised to 5. This test would require an ablation proof thermal vacuum chamber large enough to house our system, and the lunar regolith 300 mm from the front payload wall.

C. Design Changes

1) Electronics: A path-to-flight situation would require multiple hardware and software changes related to radiation hardening and redundancy such as a transition to a real time operating system and a lower-level programming language. In particular, various space tolerant flight computer boards that can be adapted to replace the current flight computer - a BeagleBone Black Industrial - and thermal logical controller - a Teensy 3.2 design - have been explored. Some options, such as the ISIS flight computer [25] or the Pumpkin Space flight computer boards [26], have been considered which could fit the current power, dimension, and output budgets. These flight computers are of technology readiness level (TRL) 9, space-flight-proven, and “state-of-the-art for highly integrated on-board computing systems for small spacecraft” [27]. In fact, the Pumpkin Space flight computer board is a flight-hardened BeagleBone Black, which decreases complexity of transiting from the current design. These flight computer boards provide proven radiation-tolerant, single-latch-up resistant CPUs and memory storage capabilities.

Many electronics connections and components would also need to be replaced. For example, the USB plug-in cables for the laser and spectrometer would be integrated into the PCB, and the SD card storage would be switched to radiation tolerant EEPROM and Flash NAND memory for the code and data storage respectively. Each electronic component and solder joint must also be radiation tested, shake tested, and off-gassing tested, prior to integration and flight.

2) Structures: If given path to flight, the structures subsystem will make adjustments to create a lighter, flight ready payload. The usage of flight certified 3D printable plastics would be pursued in order to manufacture parts that would prove difficult to create via conventional subtractive manufacturing methods. The brackets on the spectrometer and laser driver will be 3D printed in order to minimize the overall weight of the payload, without compromising any of its structural integrity. The use of polyetheretherketone and polyamide-imide is being researched due to the lightweight properties and flight heritage [28].

A support structure would also be added to the fiber-optic cable connecting the spectrometer and the optical system. Due to the length of the cable, there are concerns that the oscillations induced by the vibrations experienced at launch could cause the cable to dislodge. To prevent this from happening, the fiber-optic cable will be threaded through a low outgassing, structurally sound pipe that will hold the cable into position. This would ensure the cable will stay connected and in place during flight.

One concern that arose during development was lunar regolith dust accumulation on the system exterior, especially optical surfaces. Based on these concerns, Oasis may require active or passive dust mitigation. Electrodynamic-Dust-Shield (EDS) technology has been considered for implementation within Oasis. EDS generates an AC electric field that would ”wash” away charged dust particles. Using transparent ITO electrodes, EDS can be used on the spectrometer telescope optical surface to prevent dust-related aberrations in data.

EDS has been tested by NASA among other international space organizations and holds great promise for use in multiple applications. Some of these applications may be further developed in the 2021 NASA BIG Idea challenge, which is entirely centered around dust mitigation. The Oasis team eagerly awaits submissions to this year’s competition and is hopeful that proposed technologies can be utilized with the instrument.

Vibrational forces have been an overarching concern during the entire development of the Oasis payload. As discussed in the Section V-B2, there are plans to conduct a shake test on our entire payload as part of the path to flight process. This shake table test is designed to obtain valuable data about the current state of the design of Oasis. As part of the data obtained through these tests, important design changes could be made, such as reorganizing the location of components, or changing specified materials entirely. These tests are an integral part of the structures path to flight plan and the data provided will be invaluable in the success of the payload as a whole.

3) Thermals: No design changes to the thermal control system would be needed for a path to flight scenario, unless different components are used. The thermal control system is very adaptable if changes to components cause a change to the power draw, and therefore the heat produced, by components.The same main procedure used to determine the current active and passive heating elements of the payload can still be used to adapt the payload. After an acceptable operational temperature range and target temperature for each component has been determined, the thermal model can be easily altered to reflect the changes to the design. The COMSOL model can be modified with different sizes to elements, different power outputs form each component, and even the addition or subtraction of components, to reflect the modified payload. After changes to the main model design, the same graph showing the relationship between emissivity and heater power needed to regulate to the target temperature can be made and used to confirm that, with the target emissivity, along with some shift from this emissivty, the target temperature can be easily reached. If the emissivity needed becomes lower than that possible from polished aluminum, the thermal subsystem team has conducted extensive research into MLI, which could easily be implemented, instead of the use of polished aluminum, for the passive heating element of the thermal control plan.

One helpful test that the thermal subsystem did not have time to run would be a COMSOL simulation to determine how long the payload could last in a sun lit region, while traveling to the Permanently shaded region of the Moon. A more detailed simulation could also be run once the location of initial deployment on the Moon is known.

Another helpful simulation would be one that determined the maximum pulse rate, and how long the payload can sustain shooting of the laser, before overheating. This simulation could also be conducted in COMSOL Multiphysics, and it could be used to determine how cooldown time needed before firing again.

4) Science: One change that would need to be implemented in a path to flight scenario would be the inclusion of 1064 nm notch filter. If the telescope captured the laser light, it could oversaturate the spectrometer's CCD, possibly causing permanent damage, and the use of a notch filter would mitigate this issue. Furthermore, the optics system was designed to allow for a 1-in diameter filter, meaning the filter can be added without change to the telescope. While temporary filters have been used in testing, a custom 1064 nm notch filter is needed as the wavelength range is too wide for commercially available filters. One company that is considered for this custom filter is Omega Optical.

Furthermore, while the current spectrometer covers the full wavelength range and has an acceptable optical resolution, it is only able to integrate over milliseconds which is too slow for lunar applications due to the low pressure. The Ocean FX UV-VIS spectrometer by Ocean Insight covers the same wavelength range, 200 nm to 850 nm, and has comparable resolution to the Flame-T, however the Ocean FX is capable of integrating down over microseconds, with a minimum of 10 μs.

Finally, testing has shown that the current collections optics and focusing optics are functional, but flaws with their current design have been found. Such flaws include chromatic aberrations, telescope alignment, and durability of the optics systems. To address these issues the natural step would be to redesign the optics system to focus both the laser and the spectrometer using a Schmidt-Cassegrain telescope. Using a reflecting telescope will remove concerns of chromatic aberrations. Furthermore, using a Schmidt-Cassegrain telescope with a beamsplitter will allow for the laser pulses to be collinear with the collected plasma light, removing the need to align off-axis collection optics and focusing optics. Mirrors also allow for easier mounting as the back of the mirror can be used while only the edges of lenses can be used, making the optics system stronger during time of intense acceleration.

VI. CONCLUSION

The Oasis instrument has made significant progress since its proposal in the fall of 2019. Each subsystem, and by extension the system as a whole, has been significantly developed. The laser and spectrometer optical systems have been designed, assembled, and verified through preliminary LIBS test. The development of the housing and structural components has progressed past full scale prototypes into designs ready for manufacturing. The components are organized to minimize the footprint of Oasis, allowing it to function within a suite of instruments and to be compatible with various host platforms. Both the active and passive thermal control systems have been verified with extensive analytical calculations and thermal simulations. Results indicate that the thermal system is able to maintain operable component temperatures. Also, testing has demonstrated that the spectrometer readings are negligibly affected by expected temperature variance and that the heat radiated by the laser will not exceed the capability of the thermal control system. The Oasis power and communications systems have been developed, manufactured, and tested, resulting in a custom PCB to interface the flight computer, thermal logic controller, spectrometer, laser, and to the host craft. Oasis software has been written and tested extensively, resulting in its successful use in the preliminary LIBS test. This software gives the flight computer full and reliable control of the laser and spectrometer and the ability to transmit data to the host craft successfully. The increase in TRL from Level 2 to Level 3–4 during this design, analysis, and verification is a promising start to future development and a potential path-to-flight.

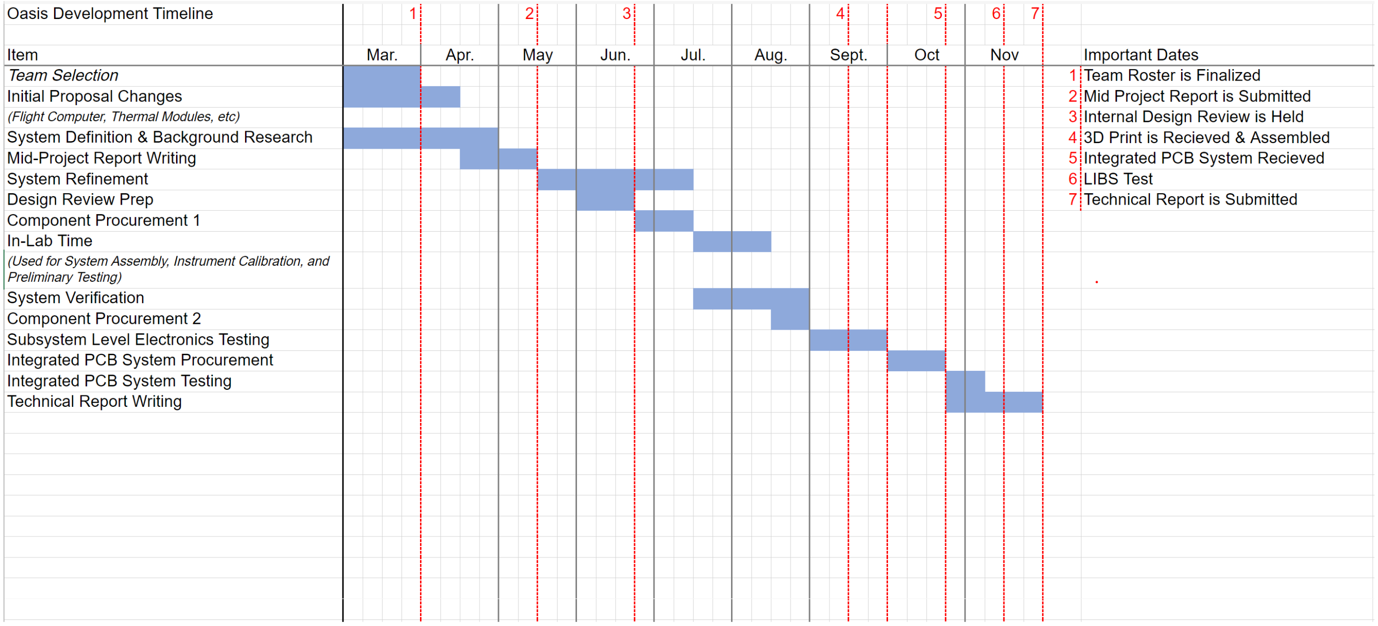
The engineers on the Oasis team have gained valuable experience throughout this project. The team of predominantly sophomore undergraduate engineering students now have technical experience in optical design, CAD, design for manufacturing, thermal analysis and simulation, control systems, command and data handling, and PCB design and manufacture, among other areas. These skills have been cultivated over a year of working within a systems-engineering environment. Industry standard project management practices were followed, including but not limited to subsystem-based team organization, design reviews with external experts, lean management, unit testing, and requirements documentation. Now equipped with both critical technical knowledge and an understanding of how this knowledge is utilized professionally to develop complex systems, the members of the Student Space Programs Laboratory (SSPL) are well equipped for continued Oasis development and other future projects. The Oasis instrument and the 2020 NASA BIG Idea Challenge have been extremely successful in inspiring the next generation of innovative engineering leaders.

VII. TEAM MEMBERS

- Ralph Quartiano, Sophomore in Aerospace Engineering, Project Manager and Systems Engineer
- Normen Yu, Sophomore in Computer Science, Electronics Subsystem Lead
- Drew McConnell, Sophomore in Physics, Science Subsystem Lead
- Adam Mladenetz, Sophomore in Aerospace Engineering, Structures Lead
- Joseph Broniszewski, Sophomore in Mechanical Engineering, Thermal Subsystem Co-Lead
- Samuel Luttringer, Sophomore in Mechanical Engineering, Thermal Subsystem Co-Lead
- Drew Binkley, Sophomore in Aerospace Engineering, Thermals
- Noah Chaffin, Sophomore in Computer Science, Electronics
- Lia Formica, Sophomore in Aerospace Engineering, Structures
- Miles Greene, Senior in Electrical Engineering, Science
- Humaid Ibrahim, Senior in Electrical Engineering, Structures
- Cade Ingram, Senior in Electrical Engineering, Electronics
- Alan Kwong, Senior in Electrical Engineering, Thermals
- Edwin Lu, Sophomore in Electrical Engineering and Computer Science, Electronics
- Sonali Nagpal, Sophomore in Aerospace Engineering, Structures
- Tyler Sengia, Sophomore in Electrical Engineering, Electronics
- Kieran Sweeney, Senior in Electrical Engineering, Electronics

VIII. TIMELINE

The timeline depicting Oasis development is shown in Figure VIII.


Oasis Development Timeline

Item

Team Selection

Initial Proposal Changes

(Flight Computer, Thermal Modules, etc)

System Definition & Background Research

Mid-Project Report Writing

System Refinement

Design Review Prep

Component Procurement 1

In-Lab Time

(Used for System Assembly, Instrument Calibration, and Preliminary Testing)

System Verification

Component Procurement 2

Subsystem Level Electronics Testing

Integrated PCB System Procurement

Integrated PCB System Testing

Technical Report Writing

Important Dates

1 Team Roster is Finalized

2 Mid Project Report is Submitted

3 Internal Design Review is Held

4 3D Print is Recieved & Assembled

5 Integrated PCB System Recieved

6 LIBS Test

7 Technical Report is Submitted

Fig. 18. Timeline of Oasis development.

IX. SPONSORSHIPS & THANK YOUS

Throughout this one year journey, we would like to thank many partners for helping us along the way. Per competition request, the financial award amount is listed at the end of each thank you message.

The Naval Research Laboratory (NRL) and Assurance Technologies Corporation (ATC) provided tremendous help to our team by sponsoring several additional teammates to work on this project, while also providing all team members with training in GitHub utilities, unit testing, and other industrial practices. NRL was also immensely helpful by allowing us to test the LIBS system at one of their facilities. Throughout the journey, they brought the input of laser, electronic, and software experts to guide us in the design, integration, and testing of Oasis. We thank them again for their generous support. Financial Award: approximately $6000 total for 3 members

The PA Space Grant also provided additional stipend support to team members, allowing additional members to receive stipend support and work on this project over summer. Financial Award: $8000 total for 4 members

We have also been sponsored by Blue Origin with a financial award and access to technical mentorship. We thoroughly appreciate this support. Financial Award: $1000

We would like to thank Astrobotics for their help in providing sample documentation for rovers that the payload could potentially be attached to.

We would finally like to thank The Pennsylvania State University for allowing us to use their facilities for development and testing where possible.

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Detailed Phase 1 Budget

Budget categories:	03/01/2020-10/31/2020
1. Salaries and Stipends	
a. Lead Faculty Advisor- Dr. Sven Bilen	$1,298
b. Project Advisor- Dr. Jesse McTernan	$3,696
c. Design Advisor- Joseph Portelli	$4,388
d. Student Stipends (10 students)	$78,000
2. Fringe Benefits	$3,551
3. Lab Supplies	$5,000
4. Capital Equipment Fabrication of Payload Brassboard	$35,000
5. Travel to the BIG Idea Forum	
a. Faculty Advisor	$1,000
b. Students	$14,000
6. Indirect Cost (F&A) Waived	$0
TOTALS	**$145,933**

BUDGET JUSTIFICATION
The Pennsylvania State University

Personnel - The principal investigator is budgeted at the percentage of time shown using his/her actual salary in the calculation. The principal investigator's time includes both technical and project management functions. Any other individuals/positions shown are technical staff with the percentage of time shown and actual salaries used. For project time occurring after July 1 of any given year, the salaries have been adjusted at the University approved rate of 2.5%.

Faculty Salary:

- **Sven Bilen, Faculty Advisor** - 2% effort over 3 months (0.06 summer month). Project PI and interface with Penn State administration, faculty director of SSPL, provide direction and student training.
- **Jesse McTernan, Faculty Advisor** - 15% effort over 3 months 0.45 summer month). Project co-PI, associate director of SSPL, engage with students during design, fabrication, and testing.

Other Personnel:

- **Joseph Portelli, Designer** - 10% effort over 8 months (0.80 calendar month). Provide guidance on circuit designs and fabrication, review student designs for manufacturability.

Fringe Benefits - Fringe benefits are computed using the fixed rates of 37.85% applicable to Category I Salaries, 13.00% applicable to Category II Graduate Assistants, 7.86% applicable to Category III Salaries and Wages, 0.25% applicable to Category IV Student Wages, and 23.52% for Category V, Postdoctoral Scholars and Fellows, for fiscal year 2020 (July 1, 2019, through June 30, 2020). If this proposal is funded, the rates quoted above shall, at the time of funding, be subject to adjustment for any period subsequent to June 30, 2020, if superseding Government approved rates have been established. Fringe benefit rates are negotiated and approved by the Office of Naval Research, Penn State's cognizant federal agency.

Student Stipends/Participant Support - budgeted @ $78,000. To support Spring and Summer 2020 stipends for 10 students (10 @ $7,800 each).

Materials and Supplies - budgeted @ $5,000. To support early stage prototyping, lab costs to support testing effort.

Equipment – budgeted @ $35,000.

XPart	Estimated Price
Flame VIS-NIR Spectrometer FLAME-T-VIS-NIR	$3,555.00
ISIS On Board Computer	$4,892.00
MicroJewel DPSS laser	$9,900.00
MicroJewel Control Board and Power Supply	$1,900.00
Spectrometer Optics	$5,000.00
Housing - Aluminum & Machining	$2,000.00
Housing - Thermal Coating	$1,000.00
Thermal System Electronic Components	$2,500.00
Cables & Connectors	$1,000.00
Power System	$1,000.00
Contingency	$2,253.00
Total	$35,000.00

Travel - budgeted @ $15,000, $1,000 for a faculty advisor and $14,000 for student team. All travel will be in accordance with University travel regulations and mileage will be charged at the current rate on the date of travel. Travel estimates are based on costs that were incurred on previous projects of a similar nature for federal and state agencies. To attend the BIG Idea Forum for 10 students. As travel location is not defined, assume four-night hotel stay, airfare, per diem, and a registration fee of $300 per attendee.

Facilities and Administrative Costs - F&A is waived for this proposal.

F&A rates are negotiated and approved by the Office of Naval Research, Penn State's cognizant federal agency. Penn State's current provisional on-campus rate for research is 58.05% of MTDC from July 1, 2019, through June 30, 2020. New awards and new competitive segments with an effective date of July 1, 2020, or later shall be subject to adjustment when superseding Government approved rates are established. Per 2 CFR 200 (Appendix III, Section C.7), the actual F&A rates used will be fixed at the time of the initial award for the duration of the competitive segment.

Detailed Phase 2 Budget

Budget categories:	**05/12/2020-10/31/2020**
1. Salaries and Stipends	
a. Lead Faculty Advisor- Dr. Sven Bilen	$1,298
b. Project Advisor- Dr. Jesse McTernan	$3,696
c. Design Advisor- Joseph Portelli	$4,388
d. Student Stipends (10 students)	$78,000
2. Fringe Benefits	$3,551
3. Lab Supplies	$5,000
4. Capital Equipment Fabrication of Payload Brassboard	$35,000
5. Travel to the BIG Idea Forum	
a. Faculty Advisor	$1,000
b. Students	$14,000
6. Indirect Cost (F&A) Waived	$0
TOTALS	**$145,933**

BUDGET JUSTIFICATION
The Pennsylvania State University

Personnel - The principal investigator is budgeted at the percentage of time shown using his/her actual salary in the calculation. The principal investigator's time includes both technical and project management functions. Any other individuals/positions shown are technical staff with the percentage of time shown and actual salaries used. For project time occurring after July 1 of any given year, the salaries have been adjusted at the University approved rate of 2.5%.

Faculty Salary:

- **Sven Bilen, Faculty Advisor** - 2% effort over 3 months (0.06 summer month). Project PI and interface with Penn State administration, faculty director of SSPL, provide direction and student training.
- **Jesse McTernan, Faculty Advisor** - 15% effort over 3 months 0.45 summer month). Project co-PI, associate director of SSPL, engage with students during design, fabrication, and testing.

Other Personnel:

- **Joseph Portelli, Designer** - 10% effort over 8 months (0.80 calendar month). Provide guidance on circuit designs and fabrication, review student designs for manufacturability.

Fringe Benefits - Fringe benefits are computed using the fixed rates of 37.85% applicable to Category I Salaries, 13.00% applicable to Category II Graduate Assistants, 7.86% applicable to Category III Salaries and Wages, 0.25% applicable to Category IV Student Wages, and 23.52% for Category V, Postdoctoral Scholars and Fellows, for fiscal year 2020 (July 1, 2019, through June 30, 2020). If this proposal is funded, the rates quoted above shall, at the time of funding, be subject to adjustment for any period subsequent to June 30, 2020, if superseding Government approved rates have been established. Fringe benefit rates are negotiated and approved by the Office of Naval Research, Penn State's cognizant federal agency.

Student Stipends/Participant Support - budgeted @ $78,000. To support Spring and Summer 2020 stipends for 10 students (10 @ $7,800 each).

Materials and Supplies - budgeted @ $5,000. To support early stage prototyping, lab costs to support testing effort.

Equipment – budgeted @ $35,000.

XPart	Estimated Price
Flame VIS-NIR Spectrometer FLAME-UV-VIS	$4,300.00
Flight Computer (BBB Industrial & Thermal Logic Controller)	$300.00
MicroJewel DPSS Laser	$11,800.00
Personal Protective Equipment for Class 4 Laser Operation (10 people)	$2,000.00
Spectrometer Optics	$2,000.00
Housing - Aluminum & Machining	$2,000.00
Housing - Multi Layer Insulation	$2,500.00
Thermal System Electronic Components	$1,500.00
Cables & Connectors	$1,000.00
Power System	$2,000.00
Contingency	$5,600.00
Total	$35,000.00

Travel - budgeted @ $15,000, $1,000 for a faculty advisor and $14,000 for student team. All travel will be in accordance with University travel regulations and mileage will be charged at the current rate on the date of travel. Travel estimates are based on costs that were incurred on previous projects of a similar nature for federal and state agencies. To attend the BIG Idea Forum for 10 students. As travel location is not defined, assume four-night hotel stay, airfare, per diem, and a registration fee of $300 per attendee.

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