Spectral Forest

Final Design Report

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Fall 2023-Spring 2024

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DISCLAIMER

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EXECUTIVE SUMMARY

This is the Final Design Report for Team 10: Spectral Forest from the capstone group of Fall ‘23 – Spring ‘24. This report will detail the full process, start-to-finish, of the original design of an optical spectrometer. Our project is a shared capstone project, the ME team paired with an EE team both working on different areas of the project that will join in the finished product. This project has two purposes, one for each of our clients. Alexander “Allie” Shenkin wants to use this device for ecology application in a stationary position on the forest floor as well as attached to a drone. Our other client, Carlo da Cunha, will use this device in a lab setting to look at semiconductors and how they absorb or reflect light and how the light energy is transferred across and through the surfaces. While in all these situations the device will collect light data through a single aperture and transmit through a series of lenses it will be directed into a linear array which can decipher the light and record it to the on-board memory card. Once the device has been retrieved from the field, the user can plug in a single USB and transfer the data off the device and onto a computer. This light data is used in simulation models to predict the health of the forest, by viewing water concentrations in the soil, leaves, and trunks. The EE team is designing a custom PCB used to collect data and store it on an on-board SIM card (internal computer). They are going through the entire process of selecting resistors, capacitors, LEDs, and a battery. They are also tasked with selecting an appropriate linear array that is sensitive to the wavelengths that our client is interested in which is 350-1000 nm which is a little bit of UV, all the visible, and some IR. Our main task as the ME team is to protect all these components from the outside environment by creating a robust, waterproof, and durable enclosure that will keep all ingress out to the degree that a NEMA 3X rated enclosure would accomplish. A robust design will be simple as our device will not experience much stress under normal operation, but we must design for a fall to occur before drone flight take off and ensure the integrity of our device will not be compromised. Material selection for the enclosure will be crucial to its strength and life in the field. We have decided on Onyx and carbon fiber reinforced nylon that has great strength capabilities and we can 3D print it on campus at the engineering building. Waterproofing to the standard of a NEMA 3X enclosure will just require the accurate 3D printed dimensions of the top and bottom pieces of our design to mate smoothly together and implement a high-quality O-ring to provide the seal to block anything from entering at that access point. The other access points will be the USB port, solar bulkhead connector, photo sensor hole, indicator LED hole, aperture, and vent. The USB port, solar bulkhead connector, and vent are equipped with a rubber seal that will block dust and water from entering the device. The photo sensor and indicator LED will be sealed in place with a layer of RTV. The aperture will be sealed along its edge with RTV to provide a weather resistant seal. The optical design includes two aperture lenses aligned in opposite orientation followed by a diffraction grating and focusing lens before hitting the detector. The approximate 45-degree field of view allows a light range of 330-2400 nm to enter before the diffraction grating, which is a collection of thousands of tiny prisms that will split the light up by wavelength to create a rainbow, will cut the transmitted light range down to 330-1100 nm. The split light will then move through a focusing lens that allows a transmission of 400-1000 nm that focuses the light onto the detector. The detector will be mounted on a custom PCB along with a temperature sensor and 10-pin ribbon cable connector that will be sent through the dividing wall to the main PCB. The device will be equipped with two vents to ensure pressure and temperature equalization within the device. One will be between the outside and the electronics and the other will be between the electronics chamber and the optical chamber.

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1 BACKGROUND

In the background section of this report the project description will be summarized based on the proposal that was provided by the client at the beginning of the project, along with the meetings that we had with the sponsor to gain insight to their vision and desired outcome of this project. Why the project is important, along with the budget we are provided with, and the fundraising that we will conduct will be discussed. Secondly, the major deliverables that have been completed throughout this course will be described. Lastly, success metrics will be shown describing how the team was successful and how it was proven with calculations, tests, and design requirements.

1.1 Project Description

A hyperspectral VIS-NIR (Visible to near infrared wavelengths) solar CCD spectrometer to be used to analyze forest health. Composed of a series of optics to focus and isolate individual wavelengths for detection enclosed in a polycarbonate 3D printed enclosure. The final design incorporates a field of view of 45 degrees and allows for focused light in the wavelength range of 400-1000nm. Weighing just under 3 lbs and being smaller than 10x10x5in, this allows the final product to be mounted on a UAV for aerial data collection. This device is capable of operating in standard weather and temperatures including heavy rain/snow as well as an operating temperature range of 0-50 °C. The enclosure protects the internal components (both optical and electrical) from liquids and dust. Design software's used include Zemax, Onshape, and MATLAB.

1.2 Deliverables

Fall semester:

<u>Team Charter:</u> within is the team purpose, team goals, members personalities, roles, and responsibilities, ground rules, and potential barriers combined with coping strategies were discussed.

<u>Presentation 1:</u> The first presentation was all about defining our customer needs/ requirements and engineering requirements. Other sections that were included were project description, background & benchmarking, literature review, math modeling, budget, and schedule. All of which are linked to a different section of this report where it is gone into more detail.

<u>Presentation 2:</u> The focus of the second presentation was concept generation and evaluation. The other notable sections include project description, functionals decomposition, black box model, engineering calculations, Pugh chart, decision matrix, schedule, BoM, and budget updates.

Spring semester:

<u>Hardware status updates, 33%, 67%, and 100%:</u> These informal presentations showed the team's progress in assembling the product.

<u>Initial and final testing plans:</u> More informal presentations discussing the testing plan and subsequent results found form said tests

<u>UGRADs poster and presentation:</u> These two important deliverables were the creation of the poster and presentation shown at UGRADs. Special care was taken to ensure all the necessary information would be included concisely to satisfy the 15-minute time limit for the presentation and the size limitations on the poster presentation.

1.3 Success Metrics

This project was a success because a device was created that can withstand typical outdoor weather while continuing normal operation, the internal components are easily accessible and adjustable, and light data is accurately taken. The budget was increased to $5600 thanks to the NASA Space Grant Consortium and Chris Edwards, this allowed the upgrade of all the optical components within the system. The sealing of the device is integral to it surviving in the wild. The device successfully survived full submersion for ~10 seconds which is more extreme than the device will naturally experience. It was also discovered that the device floats so if it were to land in a body of water it would float. The device also kept blowing dust out of the internal chambers. The fall survivability of the device was also investigated, and it was found that the external housing will survive if it were to fall from observation height. The optics will need to be realigned but from ~20ft the mounts shifted slightly but were still attached to the device. The purpose of the device is to accurately record light data which is partially on the EE side but we are responsible for aligning the mirrors and linear arrays in a way that it is repeatable and adjustable so it can be calibrated and tuned. As for the ME team goals, we accomplished all we set out to do.

2 REQUIREMENTS

Contained in this second chapter are the requirements laid out by our client in the form of customer requirements which are goals that the client would like to achieve with this device. Along with constraints due to the nature of components that are necessary to include. The customer requirements are then translated into engineering requirements and are worded in such a way that they are quantifiable and testable so we can verify that our design does in fact meet that requirement. These two styles are then compiled into a House of Quality and the technical requirements are ranked based on how well they meet each customer's requirements. Their goals, values and units are shown in the HoQ as well.

2.1 Customer Requirements (CRs)

- Durable (CR1) - Needs to be able to withstand weather conditions and potential impacts from drops going as high as 100 m.
- Semi-constant internal conditions (CR2) - The inside components could produce heat when operating which can cause problems in the functionality of the design. There are also temperatures (both high and low) from the outside that can affect the model and must be accounted for.
- Ease of access (CR3) - The inside of the device can be access within 60 seconds.
- Environmentally sound (CR4) - The device can survive and protect the internal components against typical weather conditions including rain, wind, dust and snow.
- Spectral range between 400-1000nm (CR5) - The device accepts the desired wavelength range of 400-1000nm.
- As light as possible (CR6) - The weight must be less than 3.3 lbs. at a maximum as that is the max payload that the drone can carry but we will shoot for less than 2 lbs.
- As small as possible (CR7) - The size we must fit into is a 100x120x200 mm area (0.0024m3) that is constrained by the dimensions of the drone that our client will be using to fly the device around with.
- Drone mountable in operation (CR8) - The device can maintain functionality when being securely mounted on a drone in flight.
- Ambient operating range of 0-50°C (CR9) - internal and the external ambient temperatures should be in a range of 0-50 °C when the device is running.

2.2 Engineering Requirements (ERs)

- Long lifespan (ER1) – The device should be able to last 5 years or more.
- Internal temperature control with vents (ER2) –With proper ventilation, the internal and the external temperature should vary no more than 2 degrees in either direction.
- Easy to access data in EE side (ER3)– The shell should allow for easy accessibility to the internal components in case of possible damage or failure in the design.
- Water and dust proof (ER4) – The device should be water and dust proof to the degree of a

NEMA 3X which is rated for rain, sleet, and ice. No water should be present when exposed to these conditions.

- Optics designed for full range (ER5) – The optics successfully accepts and delivers the full desired range of light to the detector.
- Drone can fly while carrying (ER6) – Device weighs less than the given constraint and the drone can still operate when mounted.
- Fits within drone payload space (ER7) - The device fits within payload space beneath the drone when in operation.
- Optics secured during flight (ER8) – The optics stay secured and do not become dislodged during flight or potential impacts.

Table 1: ER Target Values

Engineering Requirement	Target	Tolerance	Measured/Calculated Value	ER Met?	Client Acceptable
ER1 - Long lifespan	5 years	± A few months	PC has a life of 10-20 years, everything else can be replaced/re-aligned	✓	✓
ER2 - Internal temperature control with vents	0-50℃	± 5℃	Ambient = 50C, Internal Ambient = 48.26 C	✓	✓
ER3 - Easy to access data	<5 sec	0 sec	Just plugs in, USB (needs 3 tries to get correct orientation)	✓	✓
ER4 - Water and dust proof	0 ml/ 0 mg	±0.01 ml/ 0.01 mg	Ingress after 10 sec of full submersion	✓	✓
ER5 - Optics designed for full range	400-1000 nm	± 0 nm	Based on Zemax Calculations, 400-1000nm fit within the CCD chip space	✓	✓
ER6 -Drone can fly while carrying	<2 lbs	+1lb	2lb 7oz	✓	✓
ER7 -Fits within drone payload space	10in*10in *5in	+ 0.5in	9.976in*8.238in*4.5in	✓	✓
ER8 - Optics secured	0 in of movement	0 in	Per greater than 5 ft drop, it moves. Will fix upon next iteration	✓	✓

2.3 House of Quality (HoQ)

The House of Quality is an integral piece of the concept generation as it draws connections to the ER-CR correlations and gives ranking on importance to the project. In the QFD provided below in **Figure 1**, the technical, engineering, and customer requirements are all weighted and compared according to their significance in the design. Each technical requirement is provided with a target that the team wants to be under or meet and consists of their own units. The three pre-existing state of the art (SOTA) designs were then ranked according to the customer needs. This step is useful in concluding which requirements are more valuable in testing than others as well as getting a baseline on how to test which design concepts are better or worse. This process can be redone in the future with later designs or iterations as well as individual components.

System QFD

Project:	Spectral Forest
Date:	Spring 2024

Correlation Legend	
++	Strong positive
+	Moderate positive
-	Moderate negative
--	Strong negative

Legend	
A	**APEX Imaging**
B	**ASD FieldSpec 4**
C	**NASA HyMap**

#	Technical Requirement	1	2	3	4	5	6	7	8
1	**Long Lifespan**	++							
2	**Easy to access data in EE side**	--	++						
3	**Water and Dust Proof**	+	--	++					
4	**Optics Designed for Full Range**	-	--	+	++				
5	**Drone can fly while carrying**	-	-	--	-	++			
6	**Fit within drone payload space**	-	+	--	+	+	++		
7	**Optics Secured During Flight**	+	-	+	-	+	+	++	
8	**Internal Temperature Control with Vents**	+	--	+	-	-	-	-	++

#	**Customer Needs**	**Customer Weights**	**Long Lifespan**	**Easy to access data in EE side**	**Water and Dust Proof**	**Optics Designed for Full Range**	**Drone can fly while carrying**	**Fit within drone payload space**	**Optics Secured During Flight**	**Internal Temperature Control with Vents**	***1 Poor***	***2***	***3 Acceptable***	***4***	***5 Excellent***
			Technical Requirements								**Customer Opinion Survey**				
1	**Durable**	4.5	9	2	5				8					AB	C
2	**Semi-constant internal conditions**	3.5			6					8			B	A	C
3	**Ease of access**	4		9	4			5					C		AB
4	**Environmentally Sound**	5			9					7				AB	C
5	**Spectral Range Between 400-1000nm**	5			5	9		2	6	3			B	AC	
6	**As Light as Possible**	4.5					9						C	A	B
7	**As Small as Possible**	4.5				2		9					C	A	B
8	**Drone Mountable in Operation**	3.5					8	8	9				BC		A
9	**Ambient operating range of 0-50 °C**	3.5			7					9				AB	C
	Technical Requirement Units		years	time in sec (to enter)	mL	nm	lbs	ins*ins*ins	Hertz	°C					
	Technical Requirement Targets		5	<60	0	400-1000	<2	<331	+/- 50	0-50					
	Absolute Technical Importance		40.5	45	154	54	68.5	98.5	97.5	109.5					
	Relative Technical Importance		8	7	1	6	5	3	4	2					

Figure 1: QFD

3 Research Within Your Design Space

3.1 Benchmarking

To begin the design process, the team must first consider the pre-existing models and consider how they function as well as the subsystems contained within each. The state of the art (SOTA) designs being presented utilize spectrometers that capture spectral data ranging from 350-2500 nm. The 3 pre-existing models use remote sensing to study forest ecosystems through biophysical and biochemical variables.

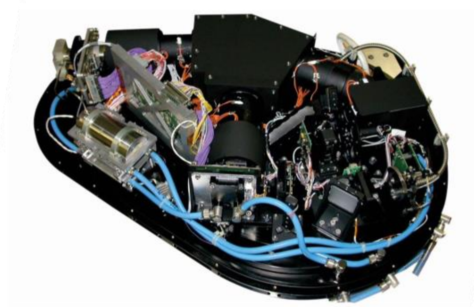

Figure 2.1: Airborne Prism Experiment (APEX) Imaging Spectrometer

The APEX imaging spectrometer records hyperspectral data in 300 bands with a spectral range of 380-2500 nm and at a spatial ground resolution of 2-5 m. It is also able to be mounted on drones. The image provided shows the layout of the internal components within the design and how they are tightly compacted to fit within one another.

Figure 2.2: ASD FieldSpec 4 Standard-Res Spectroradiometer

The ASD FieldSpec 4 is a portable, handheld spectrometer with a spectral range of 350-2500 nm. It comes with a plethora of interchangeable contact probes and mug lights for recording data by hand.

Figure 2.3: NASA HyMap Sensor

The NASA HyMap Sensor utilizes four spectrometers in the interval of 450-2450 nm. The design consists of two major atmospheric water absorption windows and an on-board bright source calibration system. This model is used in planes and helicopters when surveilling different environmental variables over large regions.

3.2 Literature Review

3.2.1 Tyler Lerew

[1] NEMA Enclosure Types - Website

This website describes the ratings for what environments electrical enclosures can safely be used in. They are based on the amount of ingress allowed to enter the enclosure, meaning dust and water. We must match the rating to the conditions that our unit will be experiencing. The rating that matches our operating conditions is the NEMA 3X.

[2] Electronic Enclosures, Housings and Packages, Woodhead Publishing, Chapter 4 - Book

This book chapter contains information about operating conditions, aesthetics, safety, internal fits, structural robustness, materials, maintenance. This information about these important topics will help us design a robust housing that conforms to the industry standards for electronic housings designed for external use when exposed o strong UV, rains, wind, sleet, and ice.

[3] Electronic Enclosures, Housings and Packages, Woodhead Publishing, Chapter 6 - Book

This book chapter contains information about IP ratings (Ingress protection), condensation, corrosion, gaskets, and extreme conditions. This information will help us with designing our enclosure in a way so it will not fail in the field under extreme conditions when exposed to harsh weather conditions. And it will help us design in a way to avoid or at least limit corrosion and condensation on an in our enclosure.

[4] Geometric optimization of an accurate cosine correcting optic - Paper

This peer reviewed paper discussed insights about optimizing the cosine corrector, so all the light that enters our devices makes its way to the chips in the correct orientation. This will help us in our design because it is essential that the light is as spectrally flat as possible, so we get an accurate reading from the linear array.

[5] Multispectral bidirectional reflectance of northern forest canopies with the advanced solid-state array spectroradiometer (ASAS) - Paper

This peer reviewed paper discusses the use of a linear array inside of a spectrometer used to survey the forest. This will aid in the design because this is exactly what we are trying to achieve, and the information presented here will help move us in the correct direction to achieving this task.

[6] Micro actuators for aligning optical fibers - Paper

This peer reviewed paper explains potential solution to misalignments of optical fibers during transit and data collection. There is technology that will mechanically adjust the optical fibers to ensure they are always perfectly aligned but this technology is of course expensive. Still, it is interesting and if we receive one of the large grants that we applied for this could be relevant but with our current budget allotment, it is not possible.

[7] Understanding Fiber Optic Splitters and How They Work - Website

This website aids in understanding how fiber optic splitters work so we can accurately design around it for optimal performance. Since we are taking a single aperture and splitting it into 3 chips, we will use this information to help us split the light effectively. It is interesting and if we receive one of the large grants that we applied for this could be relevant but with our current budget allotment, it is not possible.

[22] How did they make iPhone waterproof - Website

This Google search yields a few websites and videos that take iPhones apart and describe how they are sealed so well and can remain submerged at a depth of 6 meters for a claimed 30 minutes. This time limit has been proven to be much longer by independent users. This will help us in our design because we can use the same strategies that Apple uses to seal their products and implement those strategies into our device as well.

[23] The Benefits of Fused Silica & Quartz - Website

This webpage shows the versatility and usability of fused silica and quarts glass in spectral application. This will help us in our design because with their large range of transmissibility their application in optical situations is unmatched.

[24] Spectrometer Introduction, Tear-down, and Data Analysis for Plant Phenotyping - Website

This YouTube video shows the internal structure of a spectrometer that uses a linear array. This video is what we will be basing our initial design off has been a good source of inspiration for design.

3.2.2 Torrey King

[8] Handbook of Optical Design - Book

The handbook is a valuable resource in the field of optical design. It covers a wide range of topics related to optical design, making it an essential reference for professionals and researchers in the field of optics and optical engineering. The book explores various aspects of optical design, including principles, techniques, and applications, providing in-depth knowledge for those working on optical systems and optical device design.

[9] Fiber Optic Sensors: Fundamentals and Applications - Book

This book provides a detailed exploration of the fundamental principles of fiber optic sensors. It offers an extensive examination of the theory and practical aspects of fiber optic sensor technology, covering their design, operation, and applications in various fields, including spectrometry. This book dives farther into this topic than necessary for this project. The book serves as an invaluable resource for researchers, engineers, and anyone seeking a deeper understanding of fiber optic sensors.

[10] UAV-based Measuring Station for Monitoring and Computational Modeling of Environmental Factors - Paper

This paper presents a UAV-based measuring station designed for the monitoring and computational modeling of environmental factors. The authors discuss the utilization of UAVs equipped with advanced spectroscopic sensors for various environmental monitoring applications, such as vegetation analysis and pollution detection. The paper offers insights into the innovative use of UAV technology to collect essential data for environmental research, demonstrating its potential to contribute to the fields of environmental science and remote sensing.

[11] Research and application of UAV-based hyperspectral remote sensing for smart city construction – Paper

This journal article explores the research and application of UAV-based hyperspectral remote sensing in the context of smart city construction. Hyperspectral imaging, a form of spectroscopy capable of capturing a wide range of wavelengths, is a central focus of the study. The paper examines the various applications of UAV-based hyperspectral imaging in fields that are separate but conceptually comparable to the project at hand. It delves into how this technology can be harnessed for enhancing urban planning, environmental monitoring, and the development of smart cities, offering valuable insights into the potential integration of hyperspectral remote sensing in urban development and management.

[12] UAV-based multispectral remote sensing for precision agriculture: A comparison between different cameras - Paper

This journal article provides a comprehensive comparison of various cameras used in UAV-based multispectral remote sensing for precision agriculture. The study focuses on optimizing crop management through the application of UAVs and spectroscopic sensors. It offers insights into the benefits and limitations of different camera technologies in the context of precision agriculture. The research findings contribute to the enhancement of agricultural practices, enabling more efficient and sustainable crop management by harnessing the capabilities of UAVs and multispectral remote sensing.

[13] 1x4 Polarization-Maintaining Fiber Optic Splitters at Thorlabs - Website

Thorlabs, Inc. offers 1x4 Polarization-Maintaining Fiber Optic Splitters, which were considered for application. However, their suitability may be affected by cost constraints and the potential need for adjustments based on chip type changes.

[14] Cosine Correctors at Ocean Insight - Website

Ocean Insight is a reputable manufacturer offering a diverse range of cosine correcting lenses, essential for optimizing light filtration prior to its entry into the fiberoptic and chip components. This source serves as a potential vendor for procuring these essential items.

[31] Fundamentals of Heat and Mass Transfer - Textbook

Textbook that provides a comprehensive exploration of the essential principles governing heat and mass transfer. It offers a thorough foundation for understanding the fundamental concepts and applications in the field. Used in the MATLAB model making for heat within the encasing.

[32] Estimation Methods of Heat Generation from a Lithium-Ion Battery - Paper

A study on lithium-ion battery behavior. The researchers propose an equivalent circuit-based approach to meticulously estimate heat generation throughout charge and discharge cycles. The article has valuable insights into understanding the thermal dynamics of lithium-ion batteries, a crucial aspect in enhancing their performance and safety. Used to estimate the heat produced by the electronics during use.

[33] Zemax Knowledgebase - Website

The most valuable website used recent on this project. The Zemax Knowledgebase is a repository of information on all things Zemax. This Source has been critical in the learning process in how to use the software and understand the concepts of optics and optical systems. Within this source there are countless articles that explore specific questions on how to use the software.

3.2.3 Derrick Doan

[15] Imaging Spectrometry for Soil Applications, in Advances in Agronomy - Book

This book shows how spectrometers work and how they detect differences in soil through biophysical and biochemical properties such as light, precipitation, temperature, etc. This will aid the team in understanding how a spectrometer functions in different applications as well as the properties being recorded.

[16] Designing Plastic Parts for Assembly – Book

This book provides an overview of the design and manufacturing process of plastic parts within an assembly. Some key information included in the book is the process of material selection, fasteners, hinges, and techniques for assembling the model. The team can use this information when having to decide on different methods of design or selection over parts for the model and have references to previous designs.

[17] eoPortal - Website

This website provides pre-existing designs, specifications over parts, sub-units/subsystems, and figures to demonstrate how the models operate as well as record various types of data. The team can use this website for comparison over designs and reference for internal subsystems.

[18] Malvern Panalytical - Website

This website offers pre-existing design comparison and provides key applications, specifications, and accessories such as probes and lights. The team can use these models in state-of-the-art reviews and benchmarking of the current design.

[19] "Fusion of imaging spectrometer and LIDAR data over combined radiative transfer models for forest canopy characterization" - Paper

This peer reviewed journal covered remote sensing signal of imaging spectrometry and large footprint LIDAR to derive comprehensive canopy characterization of forests. This paper can be used to understand the different imaging methods and provides previous tests results to help base our design on.

[20] "Remote sensing of forest biophysical variables using HyMap imaging spectrometer data" - Paper

This peer reviewed paper demonstrates hyperspectral image data using HyMap sensor and linear predictive vegetation models. These models and recorded data are used to predict future outcomes in plant life in specific regions. This paper can be used to show methods of recording the data and analyzing trends in plant life.

[21] "Simulating imaging spectrometer data: 3D forest modeling based on LiDAR and in situ data" - Paper

This peer-reviewed paper provides information on key biophysical and biochemical variables and insight on photosynthetic processes, plant health, plant functional types, and species composition.

[28] Four Forces During Flight – Website

This website provides the forces applied on a vehicle when flying and ratios to find the climb rate as well as the acceleration. This can help the team understand the effects and consider these forces when having to mount the system to a drone in future applications.

[29] Cosine Correction, Lux and Light Meters – Website

This website explains what cosine correction is as well as how it works and is used within light meters while providing figures to help further explain. It can be used when potentially designing our own cosine corrector along with showing how the cosine correction will apply within the model.

[30] Spectrometer Design Guide - Website

This website introduces multiple methods for mirror layouts found within simple spectrometers. These methods include figures along with equations that use set parameters to solve for the focal lengths and diffraction angles of the mirrors in the system. This can be used to compare and validate the model's mirror layout dimensions as well as giving base parameters for the design.

3.3 Mathematical Modeling

3.3.1 Free fall off a table - Tyler Lerew

The equations that were used in this mathematical modeling were the impact for a falling object. F=mghd [25] and the stress equation σ=FA. The total force incurred by the box from the fall is 120 N found by a height of 1.8 m, a mass of 0.34 kg, and a bounce distance of 50 mm. The stress was found to be .5 MPa by the force of 120 N and an area of 253 mm^2. The ultimate strength of the material of choice, Onyx, is 69 MPa so there will be no yielding to worry about, but the shifting of internal components will be of some concern.

3.3.2 FEA on mounting system - Tyler Lerew

There were no equations used when analyzing the mounting system because I used FEA through the cloud-based software, Sim Scale. I set up the boundary conditions and force locations and ran the simulation and analyzed the results. There was only one place with a high stress concentration and that was because of the sharp corner that resulted in a tiny area and caused a super high stress to occur there. This is because there was a gap between the sleeve nut and the casement. When constructing this there will be some type of fastening glue to connect these two locations so the area will be large and the stress small.

3.3.3 Electronic and Environmental Heat Disbursement - Torrey King

One major design constraint that must be overcome is the temperatures the housing unit and internal electronic components may be exposed to. Major concerns stem from a few sources. First, the heat produced by the variety of electronics must have a way to dissipate and not overheat itself. The second major cause will be from the sun when operated during the daytime in the field. The third major concern is the overall external environment temperature that the unit will be operating in. To do some brief calculations for these there are some equations. Fourier's law of heat conduction which defines the heat transfer due to conduction through materials specifically temperatures within the internal environment to the external environment. Essentially exploring the heat transfer of produced heat inside to how it will cool off depending on some different materials we are looking into and simple guesses at proposed geometry of the unit. That equation is as follows $Q = -k \cdot A \cdot \Delta T \Delta x$. Assuming the final design will contain an air vent to assist in pressure differentials during flight we can use that to assist in keeping the internal components cool. Newtons Law of cooling can assist in that: [Equation]. For the radiation from electronics and the sunlight. Stefan-Boltzmann equation helps represent that: [Equation]. This is just a rough breakdown, and more exact calculations will be done later as the project scope narrows.

3.3.4 Vent Flow and Temperatures - Torrey King

To continue calculations on the topic of heat transfer and general material transfer through a vent to assist in dealing with pressure differentials and temperatures that may harm the sensitive electronics within the unit there are two general equations and an example of a potential vent. The vent chosen to estimate what can be achieved in the final design was a general vent that gore produces. It is a “weather-resistant” vent that allows 4000 ml/min at 70 mbar. Using the mass flow rate equation: m. = ρAV and the ideal gas law: ρ = PRT it can be calculated that the chosen option of a vent will work fine per our assumptions. Based off these equations, this level of vent will be more than adequate for the final design.

3.3.5 Forces applied when mounted to a drone - Derrick Doan

When mounting the design to a drone, it will be faced with the same forces as the drone itself. These forces include mass (m), acceleration (a), gravity (g), thrust (F) and weight (W). The mass was estimated by adding the mass of a drone, 2 kg, and the approximate mass of the design, 0.34 kg, to get 2.34 kg. The acceleration was also estimated using the average speed that drones travel, 45 mph or 20.13 m/s. With these variables we can calculate the thrust (F) using the equation F=ma to be 47.1 kg-m/s and weight (W) using W=mg to get 22.93 kg-m/s2. Putting the variable thrust over the weight variable, we get the ratio F/V which represents acceleration and climb rate. The higher the ratio, the higher acceleration and climb rate the design will experience. In our example the calculated ratio was 2.05 which means it will experience high levels of forces. It is important to understand these forces to not allow for the design to fail when facing them.

3.3.6 Cosine Correction - Derrick Doan

Cosine correction is needed in the design because the light aperture needs to be spectrally flat to produce even data across the spectrum. Without it, most apertures can only see approximately 25 degrees of the area exposed and can receive a plethora of energy levels when coming in at different angles. Cosine correction also expands the view of the aperture, allowing for a full 180-degree spectrum that emits light evenly across. This is based off Lambert's Law: $L_\theta=L_0\times\cos\theta$, which states the light intensity on the reflected surface, L_0, times the cosine of the angle, $\cos\theta$, being reflected is the light intensity being received on the other end, L_θ. The top angle reads as 0 degrees and goes down to 90 from all sides because light becomes more intense as the angle becomes more obtuse.

4 Design Concepts

4.1 Functional Decomposition

The design is simple with zero moving parts and limited function per sub-system. It is helpful to confirm this and clarify the functions of the housing unit and internal parts. For the housing unit, based on the design criteria which come from technical requirements. These are the following in no particular order: Long lifespan (ER1), Internal temperature control with vents (ER2), Easy to access data in EE side (ER3), Water and dust proof (ER4), Optics designed for full range (ER5), Drone can fly while carrying (ER6), Fits within drone payload space (ER7), and Optics secured (ER8). Some of these criteria are more critical than others which helps in ranking design qualities. However, they are all used in determining necessary functions. This list generated the following black box model.

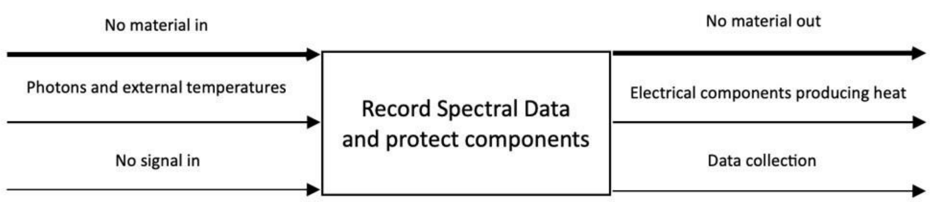

Figure 3: Black Box Model

In this black box model, it states that there is no material change in or out of the unit at any point during the process of the unit being used. There is also no signal input, and the only output signal is internally in the process of data collection as well as a USB port that allows for the off-loading of the data collected to be analyzed afterwards. Energy transfer is a little more complicated as there are photons entering the aperture and then also radiation. This causes the production of heat to occur as well as the electrical components to do their thing.

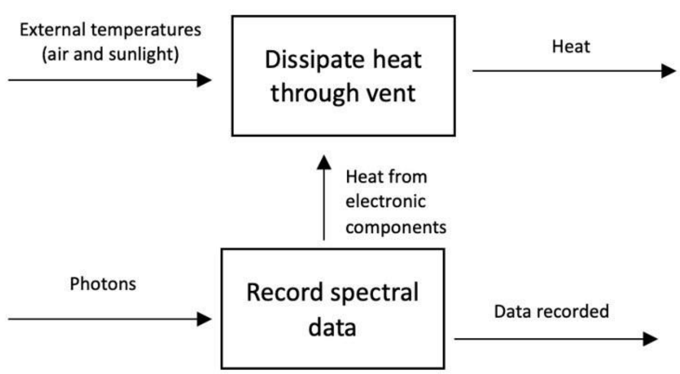

Figure 4: Functional Model

The Functional model is the same concept as the black box model and in the example of this project it is about as simple. It shows the breakdown of what is happening and where within the system it occurs in a more coherent way than. It is important that the unit can reliably and easily dissipate heat to protect the internal electronics. It must do this within the constraints of size and weight to allow it to be drone mounted. The functional model for the internal electronic components would be much more interesting and robust, however the EE sub-team will be handling all that portion of the design.

4.2 Concept Generation

Sub System	1	2	3
Optics	Linear Array ✓	Fiber Optic	Camera
Shape	Rectangular Prism ✓	Cylinder	
Cosine Corrector	Silica glass ✓	PTFE Film	Microscope Slide
Pressure Equalizer	Inside / Outside ✗ Balloon	Inside / Outside ✓ Vent	Inside / Outside Hole
O-ring	Rubber	Fluorocarbon ✓	FFKM
Material	ABS	Onyx ✗	Polycarbonate ✓

Figure 5: Morph Matrix

The main subsystems that the ME team is concerned with are the optics, size of the enclosure, sealing, pressure equalization, and the material of the enclosure.

Optics is how the light will be turned into data that can be read by a computer and then analyzed by the user. The 3 options are a linear array, fiber optics, and a camera. The pros for the linear array are that it is cheaper and easy to use. The cons are that it is subject to shifting and will result in inaccurate results as it requires the use of lenses to transform the light into a rainbow because its array of pixels is set up in such a way that each one can only read the light at a certain wavelength. The pros of a fiber optic cable are that there is no need for mirrors, and it will yield consistent results. The cons are that it is expensive and difficult to mount to chips without blocking the light fiber. The camera pros are that it is cheap and easy to use. The cons are that it is bulky so it will increase the size of the enclosure and it requires modification to remove filters to it can accept more ranges of light.

Size concepts are the geometry of our enclosure and will govern how everything on the inside will integrate. The device must fit within the drone payload space and the drone must be able to fly with the device attached. The shape of the enclosure is a rectangular prism. The rectangular prism's pros are that it is easy to manufacture/ 3D print and it will integrate easily with most drones and mounting systems. The cons are that it has sharp edges but that can be avoided with filleting in CAD. The cylinder has no pros as it is just an awkward shape and is difficult to make.

The Cosine corrector will make the light entering our device spectrally flat meaning the light entering will be transmitted through the cosine corrector at a consistent percentage, preferably around 90%. There are 3 options, fused silica quarts glass, PTFE film, and a microscope slide. The fused silica quarts glass has pros of high transmissibility and ease of access. The cons are that it will have to use some fastening glue to attach it to the box and it could be easily removed if a force is applied to a side face. The PTFE film's pros are once it is fastened it will be more secure because it is flush to the surface because it is a film. The cons are that it is difficult to attach to the box as it is very thin and makes it susceptible to punctures and it has lower transmissibility. The microscope slide has pros of high transmissibility and cons of weak strength.

The pressure equalizer is what will keep the box stable in temperature and pressure by allowing either air to enter or using a clever balloon system to achieve this. The 3 options are a balloon, a purchasable vent, and a hole. The pros for the balloon are that it is a quite simple strategy to equalize the pressure and will not let any ingress or air enter the enclosure. The cons are that it will take up more space than other options because it has 4 components, and it could get pricy if we cannot find the right balloon readily available. The vent pros are it is only one piece, cheap, and will be easy to install. The cons are it could go bad and let ingress enter unless we spend a large portion of our budget on an expensive vent rated for submerging. The hole is not considered as it is open directly to the outside and anything can enter the enclosure.

The O-ring is what will seal the largest entry point of our enclosure off from the outside, so it is especially important that its selection is taken seriously. The three options are rubber, fluorocarbon, and FFKM. The rubber is not considered as being the cheapest but will not offer much resistance to corrosives and irritants. The fluorocarbon O-ring pros are that it is resistant to outdoor weather and most irritants. The cons are that it can be semi-pricy for an O-ring. FFKM's pros are that it is specifically resistant to weather exposure and sunlight and a broadband of chemicals and acids. The cons are also the price. [26]

Material selection is of the upmost importance as this will take the brunt of the weathering and sun exposure. The three options for material are ABS, Onyx, and Polycarbonate. The pros of ABS are the high glass transition temperature at 100 C which is the temperature that the 3d printed thermoplastic starts to become gooey. It is also cheap and readily available. The cons are that it has a lower melting temperature at 190 C, and it is not the best looking when completed. The pros of Onyx are the smooth final product, readily available, strong, and a high melting point at 220 C. The cons are it is semi-pricy, it must be printed on campus by students so the quality of product might vary, and the glass transition temperature is lower than ABS at 70 C. [27] Polycarbonate has pros of high strength, it has strong outdoor ratings, and it looks good. The cons are that it is expensive.

4.3 Selection Criteria

Long lifespan (ER1), Internal temperature control with vents (ER2), Easy to access data in EE side (ER3), Water and dust proof (ER4), Optics designed for full range (ER5), Drone can fly while carrying (ER6), Fits within drone payload space (ER7) , and Optics secured (ER8) are the engineering requirements that drove the concept selection as being the criteria that all of the selection decisions were based on. Each of these requirements are quantifiable as shown in Table 1 and in the engineering requirements section. A summary of those quantities is a long life of 5 years, found by looking at the lifespan of polycarbonate. Stable internal conditions are desired to be plus or minus 5 degrees Fahrenheit difference between the inside and outside. This can be tested by inserting thermal couples connected to a computer and reading the temperature data and calculating the difference after putting the device in a freezer. Tight tolerances can be tested by reading the specs on the 3D printer used and measuring the gap present on the device after printing in an area that should have been flush. Waterproof is based off the NEMA 3X rating that is rain proof so we can simulate rain and then after drying open the device and inspect it for water inside. Small is testable by measuring the dimensions after printing. Lightweight is also testable by weighing the device with a scale after assembly is complete.

4.4 Concept Selection

Each design shown in a morph matrix in **Appendix B Figure 27** was ranked based on how well it stacked up against the datum based on customer requirements. These designs were all ranked based on industry standards shown in order of viability for our application, ranging from green being the best to orange being the worst. Only the top three were drawn out as shown in **Appendix B Figures 24-26**. The updated CAD is shown in **Appendix B Figures 39 and 40**. The preliminary revised CAD is shown in **Appendix B** as well in **Figures 28-38**.

The team went through a comparison phase, in which subsystems were either supported or ruled out in designs and began working towards drawing potential concept designs shown in the Pugh chart in **Appendix A**. These concept designs were then narrowed down and ranked using a decision matrix in **Figure 21** based on the engineering requirements, in which a top design was decided on shown in **Figure 25**. Since then, a rough Bill of Materials has been made, listing all the items being considered as well as their quantities and costs. This figure can be seen below in **Appendix A**. With the materials laid out and an idea of what is being designed, the team has begun working towards creating the model for the 1st prototype demonstration along with its virtual demonstration.

5 Schedule and Budget

5.1 Schedule

For the fall semester, the team mapped out each assignment according to due date and created a Gantt chart that can be viewed in **Figure 6**. Each week's assignments have sections that are color coordinated according to which team member is designated in completing it. Torrey is primarily working on the team's website and optical layout development while Tyler worked on the prototyping and CAD modeling. For reports and presentations, the team collaborates with one another and delegate tasks accordingly. From the Gantt chart, the team can conclude that we are on task for completing each assignment within its respected due date.

Figure 6: Fall Semester Gantt Chart

For the spring semester, the team created a new Gantt chart, which can be viewed in **Figure 7**, according to the schedule provided. The assignments are color coordinated the same as the previous chart and are split up between team members. According to the spring semester Gantt chart, the first website check will be done by the end of February, testing will be done near the end of March and the final CAD/model will be assembled in the beginning of April. The results from testing as well as the final report will be completed along with the second website check mid-April and the final presentation at the end of April. The team hopes to then hand off the device for future applications in the beginning of May. If all goes according to plan, the team is sure to complete each assignment in an effective and efficient manner.

Figure 7: Spring Semester Gantt Chart

5.2 Budget

The original project budget the team split between the Mechanical Engineering (ME) team and the Electrical Engineering (EE) team was $1000, with $500 going towards both portions of the device. The total team budget was then increased to $5600, courtesy of the NASA Space Grant Consortium from Chris Edwards. The team used the increased funds to upgrade every aspect of the project, especially the optical system and this is the only reason the device will produce useful data. The team self-funded ~$100 used to purchase items from the BOM that were cheaper in person at Home Depot.

5.3 Bill of Materials (BoM)

The total cost of the BOM was $5,306.01 which yields a remaining budget of $294. **Appendix A: Figure 22.** The cost to produce 1 single unit is $1,267.69. The extra money spent within the budget was for a printer, extra filament, and extra parts in case something broke or got ruined. The manufacturing BOM is shown in **Appendix A: Figure 23**, the team manufactured 2 prototypes used for fit, drop, and destructive testing. The team also manufactured a laser test jig to help align the lenses within the device. The final device was then manufactured.

6 Design Validation and Initial Prototyping

6.1 Failure Modes and Effects Analysis (FMEA)

When assembling the model, failure to seal the housing correctly or a potential breach in one of the walls can likely cause failure within the design while operating. A full FMEA was done, which can be viewed in Table 2, to test the potential failures as well as show their causes while ranking them according to their Severity (S), Occurrence (O) and Detection (D) to get their Risk Priority Number (RPN). Since the main potential failure can be concluded to be a breach in the design, the RPNs for each part proved to be close in value. The main potential causes for mechanical failure are the environmental conditions that the model will face when isolated in different areas of a region. These can include water from rain or humidity, which can cause the mirrors to fog and dampen internal components, as well as dust or dirt getting in the box, which can cloud and change the reflectance of the mirrors. To mitigate these potential failures, the team added an extra door to the design which creates an individual compartment for the mirrors and requires a second O-Ring to allow for better sealing. This in turn will increase the overall product cost but is necessary in maintaining a secure and protected design. To test, the team would assemble the model fully without the internal components and submerge it within a tank of water to see whether it emits air from within as well install thermistors and move the box to more extreme temperatures to monitor its changes. To do this, the team would need the fully printed model (sealed), a tank of water, thermistors, a freezer, an oven, and an Arduino to record data from the thermistors.

Table 2: FMEA of Sealing in Design

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
2 Fasteners (Holds model together)	Corrosion, Breaking	Improper sealing and mounting	3	Weather conditions, improper usage	1	FEA force analysis and	3	9	Compare different materials and sizes
3 O-ring (Seals Model)	Breach in O-ring	Electronics fail	5	puncture during installation	1	Seal box and submerge while empty	2	10	Perform test(s), inspect O-rings for damage
5 O-ring (Seals Model)	Breach in O-ring	humidity and dust form on mirrors	5	pressure is not adequately equalized	1	Seal box and submerge while empty	2	10	Perform test(s), inspect O-rings for damage
6 Silicone (Sealant)	Breach in Silicone	outside conditions effecting mirrors and correction	5	Outside conditions, pressure, temperature	1	Seal box and submerge	2	10	Perform test(s), inspect for damage
8 USB-C Rubber Seal (Seals ports)	Breach in port	Failure to power and extract data	4	Weather conditions, not resealing	1	Insert seal into port and submerge	2	8	Perform test(s), inspect for damage

Since the optics in the system dictate whether the spectrometer can record the proper spectral data according to the client's requirements, the team must fully consider each part to ensure the design operates accordingly. Therefore, a full FMEA was done, which can be viewed in **Table 3**, to test the potential failures as well as show their causes while ranking them according to their Severity (S), Occurrence (O) and Detection (D) to get their Risk Priority Number (RPN). The RPNs of the Mirrors, PCB and Cosine Corrector proved to be highest within the subsystem since a failure in one of them can cause errors in the collection of data. The main potential causes for these failures are weather conditions that can cause build up in humidity, dust, heat or pressure within the design and improper mounting, which can result in a loss in light distribution or the PCB not detecting the spectral data. To test and configure the layout of the optics in the design, the team will use the Zemax software along with USB-C data collection from the model to perform light distribution test(s) as well as change the angles and focal lengths to meet the required parameters. The team will also be utilizing the Czerny-Turner method for the layout of the mirrors and be comparing results to ensure precision and accuracy within the model.

Table 3: FMEA of Optics in Design

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
2 Fasteners (Holds model together)	Corrosion, Breaking	Improper sealing and mounting	3	Weather conditions, improper usage	1	FEA force analysis and	3	9	Compare different materials and sizes
4 Cosine Corrector (Spectrally flat)	Correction failure, Spectral Data Distribution	Incorrect data being transmitted	5	Covered aperture: humidity, dust, etc.	3	Zemax software: light distribution test	3	45	Clear aperture, test model, replace if needed
6 Silicone (Sealant)	Breach in Silicone	outside conditions effecting mirrors and correction	5	Outside conditions, pressure, temperature	1	Seal box and submerge	2	10	Perform test(s), inspect for damage
7 PCB (Data collection and storage)	Mechanical Failure	Incorrect data, chip failure	7	Heat, humidity builds up, insufficient powering	2	Data collection, Zemax, physical	5	70	Test(s) for functioning, light distribution and replace if needed
11 Mirrors (Reflect Light)	Light diffraction	Incorrect wavelength range, light distribution	6	Improper angling, focal lengths, damage to box	2	Zemax software: light distribution test	4	48	Perform Zemax test, configure mirrors to fits requirements

6.2 Initial Prototyping

6.2.1 Physical Prototype

The question trying to be answered by the physical prototype is what is the air and water permeability of the 3d printed material, Onyx? We want to know this because we plan to completely seal our unit from the outside, so we want to know if air and or water are just going to slip through the layers and enter our unit and cause catastrophic failure. Luckily, nothing got through so under normal conditions there should be no air or water permeability though the layers of our 3d print. This helps us with our design because now we know that our material will survive outside with typical weather.

6.2.2 Virtual Prototype

The questions trying to be answered by the virtual prototype was where our mirrors are supposed to be aligned and positioned. We achieved this by using a simple program called Beam4 to model how light will bounce off mirrors and we were able to produce a working prototype that depicted how the light will behave inside of our system. The answer extracted from this was that the current system that we had in place was close to what Beam4 put out. So, we will use these findings to correct our model and ensure that the angles match up and the light reaches our sensor. Our results can be seen in **Appendix B Figure 32.**

6.3 Other Engineering Calculations

6.3.1 Balloon size increase - Tyler Lerew

The use of the unique pressure equalization system employs a latex balloon attached to a short section of PVC pipe that that open to the outside, the PVC pipe will be filled with an air permeable material so air can diffuse through but nothing else. So, when the outside pressure changes the balloon will either expand or contract in turn changing the volume inside the box and equalizing the pressure. Using the following equations, the volume of the balloon will consume 3.5 in^3. $V=V_0 \, (T1/T0)*exp^{((-c*y))}$ & $c=(\rho*g)/P_0$ Rho being density in Flagstaff, which is assumed to be: 0.062 $lb/(ft^3)$. Y being altitude and assumed to be a maximum of 330 ft. V_0 being the volume of the deflated balloon, found by $V_0 = 4/3 * \pi * r^3$ with r being assumed to be 0.75in. T0 will be assumed to be 68 °F and T1a to be 122 °F (50 C) and T1b to be 32 °F (0 C). Finally, gravity = 32.174 ft/s^2 & P0 = 11.3 psi (@ 7000ft). Plugging everything in, at T1a the volume of the balloon is 3.17 in^3. At T1b the volume is 0.832 in^3. Back solving to get the radius, they are 0.91 in & 0.583, respectively. We need at least 3-3.5 cubic inches of space for the balloon, the current design has 14.25 cubic inches. We will be shortening the overall height of the box to save on material since the balloon only needs a small amount of space.

6.3.2 Math Model – Torrey King

The heat transfer math modeling that I completed for presentation three consisted of a basic model of how heat will permeate through the wall of the housing unit. The wall material properties were given from the print material we are planning to use. Some other assumptions were made about the surrounding conditions. In the equation, T refers to temperatures, either in wall or in surrounding fluids, ρ is the density of the wall, Cp is the specific heat of the wall material, V is the volume of the wall, k is the thermal conductivity of the onyx material by mark forged, H is the convective heat transfer coefficients for the surrounding fluids.

Using this equation and MATLAB iterations, its calculated that going from 100°C inside and 30°C outside we will still transfer heat away from the electronics within 60 seconds as shown in the plot below.

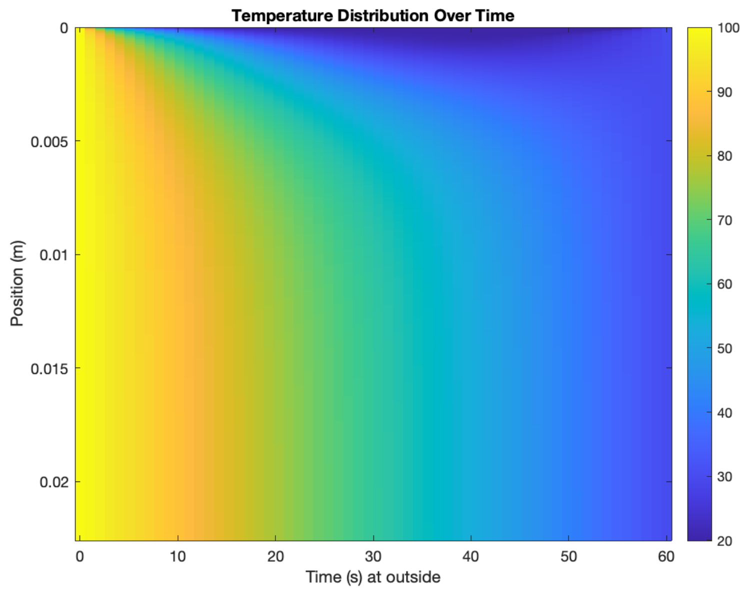

Figure 8: MATLAB Heat Results

6.3.3 Czerny-Turner Mirror Method- Derrick

The Czerny-Turner method allowed for calculations of the diffraction angles and focal lengths of the mirror layout to fit the proper spectrum requirements needed within the system. The center wavelength, λ_C, was calculated using the spectral range provided by the client of 350 to 2500nm and was calculated using $\lambda_c = \frac{(\lambda_2 - \lambda_1)}{2}$ to find a value of 675nm. A geometry angle, Φ, and grating, G, were then required which was given as 90̊ and 1200nm. These were then used in the following equation, $\alpha = \sin^{-1}\left(\frac{\lambda_c G}{2\cos\left(\frac{\Phi}{2}\right)}\right) - \frac{\Phi}{2}$ to find the angle of incidence, α, as 26.7̊. Then using the angle of incident and geometry angle, we can find the diffraction angle, β, using $\beta = \Phi - \alpha$ which comes out to be 63.3̊. After the angles are found, the focal lengths for focusing mirror, L_F, and collimating mirror, L_C, can be calculated using the length of the detector, L_D, which is given as 3in along with equations $L_F = \frac{L_D \cos(\beta)}{G(\lambda_2 - \lambda_1)}$ and $L_c = L_F \frac{\cos(\alpha)}{M\cos(\beta)}$ which both came out to approximately 2.3in. Once those focal lengths are solved for, the last calculation to be done is for the input slit width, w_{slit} , which can be found using $w_{slit} = \frac{G\Delta\lambda L_c}{\cos(\alpha)}$ and came out to be about .56in in diameter.

6.4 Future Testing Potential

For future iteration testing, a sophisticated durability/ life test on the device done by a company like MET to simulate years of use could be conducted and would yield a more accurate estimate of the lifespan of the device. Potential vibration tests can also be performed in the future to test whether vibration from a drone in operation will impact the device's functionality while being mounted. This test can determine how much vibration the enclosure can withstand as well as give insight into potential areas of concern within the design.

7 Final Hardware

7.1 Final Physical Design

7.1.1 Top Level

The following figures show the top-view of the device. The main enclosure, optics door, electronics door, hardware such as screws, lens cap, and electrical connectors are shown.

Figure 9: Final CAD

Figure 10: Final Physical Version

7.1.2 Optical System

The optical subsystem shows the 3 mounts, slit assembly, and internal 3D printed orientation that holds the mounts in place.

Figure 11: Real-Life Optical Design

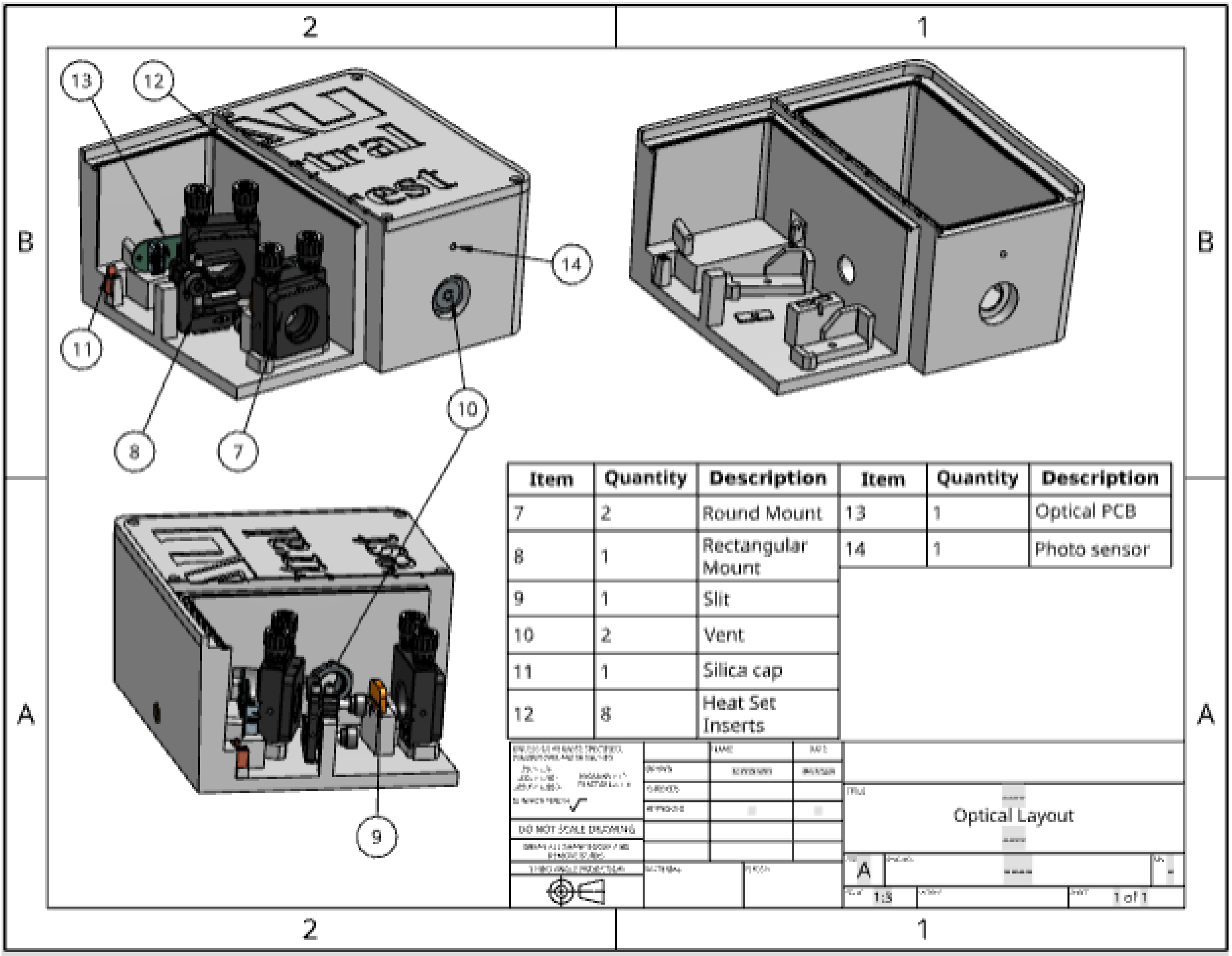

Figure 12: Optical Subsystem

7.1.3 Enclosure and Sealing

The enclosure and sealing are the most important part of this project because if water gets into wither chamber the device will not function. Proper sealing is imperative. Using a 165 Neoprene 70A durometer O-Ring with a 3/32" diameter the following values are calculated. 1.39% stretch is the amount the O-ring stretches to fit inside the groove within the 3D print (Industry standard is less than 5%), 79% of the groove is filled by the O-ring (Industry standard is 75-85%), and O-ring compression by the door is 27% (Industry standard is 20-30%). Each of these values fall within the industry standards for O-ring groove design which was confirmed by the successful ingress testing performed. The figure below shows the cross section of the designed O-ring groove.

Figure 13: O-Ring Groove Cross Section

7.1.4 Valuable Iterations

7.1.4.1 Optical Design Iterations

The iterations that occurred within the optical layout were the transition away from a cosine corrector and to a specialized entrance lens. The overall number of lenses also decreased from 5 to 4 with one still being embedded in the external wall.

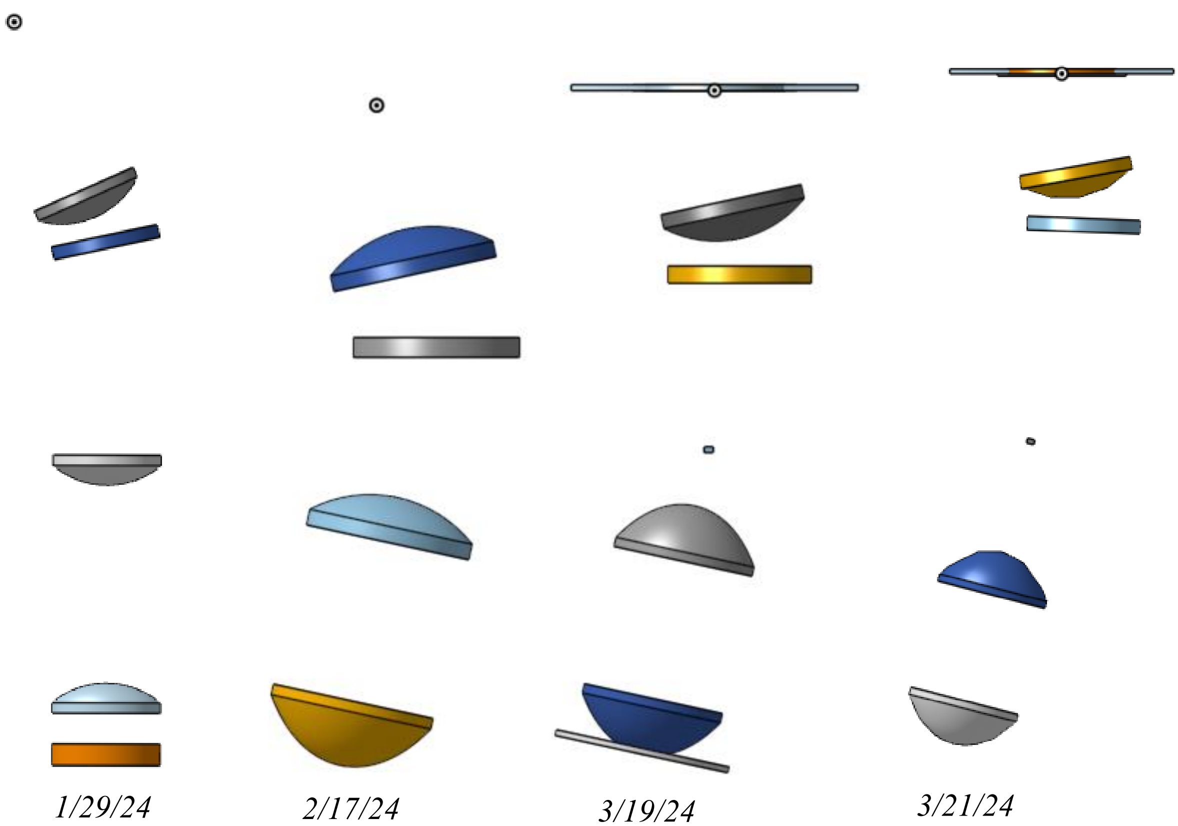

Figure 14: Optical Design Iterations

7.1.4.2 Enclosure Design Iterations

The device started by using fiber optics to get the light to the detector before the team moved to a mirror-based design in iteration 3. At the end of the 1st semester the major design change to a transmission design was made. The 5th and final iteration depict a transmission design that accurately bends and splits the light into the detector. Larger images are shown in Appendix B.

Figure 15: Enclosure Design Iterations

8 Final Testing

8.1 Top level testing summary table

This top-level testing summary table provided below shows a series of tests that were conducted during the testing phase of this project. A total of seven tests were performed, each serving a specific purpose in evaluating various aspects of the product's performance and reliability. These tests included a laser alignment test for the optics, a heat test for the enclosure, a 3D print mount connection test, a flight/drop test for the optics, a destructive test on the enclosure, a seal/vent test for outside weather conditions and a spectrum tube color adjust test that will be done by the EE team with the help of the ME team. These tests serve as critical measures to validate both customer and engineering requirements, ensuring that the product meets the highest standards of quality and performance.

Table 4: Top-Level Testing Summary

Experiment/Test	Relevant DRs
Ex 1: Laser Alignment	CR5, CR 8, CR9, ER1, ER5, ER8
Ex 2: Heat test	CR1, CR2, CR4, ER1, ER2
Ex 3: 3D print mount connection	CR3, CR6, ER8
Ex 4: Flight/drop for optics	CR1, CR4, CR6, CR7, ER 1, ER4, ER8
Ex 5: Destructive test on enclosure	CR1, CR4, CR6, CR7, ER 1, ER4, ER8
Ex 6: Seal/vent test upon submersion	CR2, CR4, ER2, ER4
Ex 7: Spectrum tube color adjust	CR2, CR5, CR9, ER5, ER8

8.2 Detailed Testing Plan

8.2.1 Laser Alignment

8.2.1.1 Summary

This experiment aims to ensure precise alignment of the optics for a reflectance optical spectrometer. The primary design requirements include using optics within the 400-1000nm range, drone-mountable operation, and resilience to temperature changes (0-50°C). The test will focus on aligning the lenses and gratings, examining stability under various conditions such as drone vibrations and temperature fluctuations. Successful alignment is critical for ensuring predictable light transmission to the spectrometer's chip. This experiment lays the foundation for reliable spectrometer performance by establishing precise optic alignment, crucial for accurate data acquisition.

8.2.1.2 Procedure

1. Select a laser based on factors like beam width, power, wavelength, and safety class.
2. Design a CAD model to center the laser onto the optic entrance and 3D print a mount using PLA.
3. Measure the off-center alignment of the laser at each lens point, both horizontally and vertically.
4. Progress through alignment steps, starting with the optic entrance and moving to internal mounts.

5. Iterate adjustments of mounts as necessary for precision alignment.
6. Record measurements and adjustments made during the alignment process.

8.2.1.3 Results

With the use of a 3D printed jig, the optic system was tested using a laser going through each mounted lens until it reached the detector. As the light is distributed through each lens, the mounts are carefully analyzed and adjusted, if necessary, for better optimization. When testing, the laser was able to reach the detector, covering around 0.5 in or 55% of the chip and signifying the lenses are lined up correctly. There were some odd reflections noticed within the enclosure, however these can be mitigated through painting the interior matte black. Shown in the below figure.

Figure 16: Laser Alignment

8.2.2 Heat Test

8.2.2.1 Summary

This experiment evaluates how the spectrometer enclosure responds to temperature changes, ensuring internal components remain within acceptable temperature ranges. The test focuses on gradual temperature changes and the enclosure's ability to maintain semi-constant internal temperatures. Maintaining stable internal temperatures is vital for preserving optic alignment, electronic functionality, and battery life. This test helps ensure the spectrometer's durability and longevity under different temperature scenarios, crucial for its overall performance and reliability.

8.2.2.2 Procedure

1. Install three thermocouples to measure temperatures in the optic chamber, electronic cavity, and ambient temperature outside the enclosure.
2. Use a standard house oven set to low temperature and a refrigerator/freezer to induce gradual temperature changes.
3. Monitor temperature changes over time and observe the response of seals, vents, and polycarbonate material.

8.2.2.3 Results

The following table summarizes the results from the heat test, the second column is the difference in linear expansion between the various components of the optics chamber found by assuming the heat transfer through the lens mount is the same heat transfer that the lenses and nylon tip of the set screw experience. This assumption resulted in much larger differences because heat transfer is function of surface area, so assuming the heat transfer is the same but though a much smaller area increases the surface temperature. This is an unrealistic assumption. The third column assumes the surface of the lens mount, lens, and nylon tip all have the same surface temperature which is more realistic to what will happen during normal operation. The difference in linear expansion is much more reasonable on the order of 10^{-5} inches. This result confirms the hypothesis that the difference in linear expansion will be so low that there is nothing to worry about when it comes to the lenses falling out of the mounts when a large temperature difference is present.

Table 5: Linear Expansion Results

Location	**With same q as mount (in)**	**With assumed surface temperature (in)**
Diff of nylon to entrance	0.0342	0.0000959
Diff of nylon to focus	0.0338	0.0000466
Diff of nylon to grating	0.0339	0.0000232

8.2.3 3D Printed Fits

8.2.3.1 Summary

This experiment verifies the fit and alignment of components within the spectrometer enclosure, addressing design requirements related to ease of access, weight, and securing optics during flight. Testing component fits is essential for refining the enclosure design and ensuring all parts integrate seamlessly. This experiment aids in optimizing the spectrometer's functionality, contributing to its overall reliability and effectiveness during operation.

8.2.3.2 Procedure

1. Use Bambu Lab X1 Carbon printer to print features of interest, such as vents, mounts, and hardware, based on CAD models.
2. Make necessary cuts to isolate features for testing without printing the entire model.
3. Assess how components fit and align together, ensuring flush fits, sealed enclosure, and proper alignment.
4. Record observations regarding the quality of fits and any necessary adjustments.

8.2.3.3 Results

This test is used to determine if components fit and align as intended. If the print fit, there would be no need for further development, however if they did not align, the component fit is reprinted and retested using different tolerances until satisfactory. This helps ensure that every component is secured properly and drives forward progress in optimizing the enclosure's functionality and performance.

8.2.4 Flight/Drop for Optics

8.2.4.1 Summary

This test evaluates the survivability of optics within the enclosure when subjected to drops from varying heights. It assesses the design's durability, environmental resistance, and ability to maintain optic layout during operation. This test is crucial for validating the design's robustness and longevity in real-world scenarios, informing further improvements if necessary. It ensures the optics can withstand impacts during operation, contributing to the overall reliability of the spectrometer.

8.2.4.2 Procedure

1. Prepare a sealed enclosure with optics securely positioned inside.
2. Measure and record the height of the platform from which the drop will occur.
3. Position the enclosure on the platform and release to simulate drops from specified heights.
4. Repeat the test using different heights to ensure reliability.
5. Assess the condition of optics and enclosure after each drop, noting any damage or weaknesses.
6. Anticipate a range of results using equations related to impact force, material properties, and environmental factors.

8.2.4.3 Results

When testing the optic system's resilience at varying heights, the optics were able to withstand drops from approximately 3 and 5 feet, from the top of a counter to a hard floor and drop from head height. As the height of the drop increased, one of the mounts sustained some substantial damage due to a 20 ft drop from the top of the Knoles parking structure, which can be see below in **Figure 7**.

Figure 17: Optics Damage Due to Drop

This is a result of one of the mounting screws breaking out of the enclosure during the impact and causing the mount to unsecure, clashing into the wall. With these results considered, some design changes over securing the mounts have been done.

8.2.5 Destructive Test on Enclosure

8.2.5.1 Summary

This destructive test aims to assess the durability and resilience of the designed enclosure by subjecting it to simulated drops from various heights with just the enclosure and rocks to replace the weight of the optic system. This test provides valuable insights into the enclosure's limitations and potential areas for improvement. It helps ensure the design meets customer requirements for durability, environmental protection, and component security, enhancing the spectrometer's overall reliability and performance.

8.2.5.2 Procedure

1. Simulate drops from different heights with rocks as replacements for the weight of the optics, starting with mild heights and progressing to more severe drops.
2. Assess the damage to the enclosure after each drop, documenting any weaknesses or failures.
3. Evaluate the enclosure's ability to withstand impacts and maintain structural integrity.
4. Use theoretical calculations to predict potential damage based on material properties and impact forces.

8.2.5.3 Results

When simulating drops from different heights, the enclosure did better than expected, and took extra efforts along with the drops to cause complete failure. As the height increased, going as high as 60 ft from the top of the San Francisco parking garage, the main damage sustained only occurred on the exterior of the enclosure. A view of the damage on the enclosure from these destructive tests can be viewed in the figures below.

Figure 18: Full Device Damage

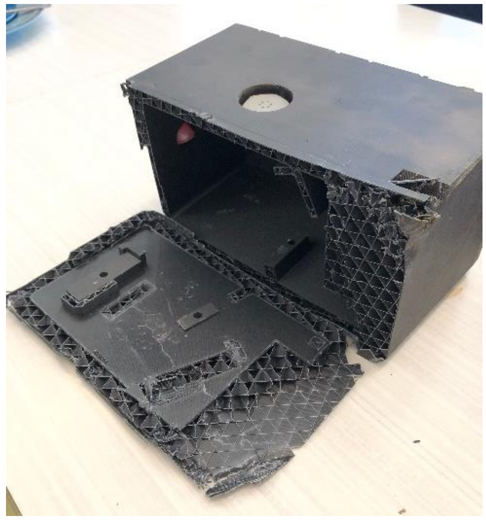

Figure 19: Optics Chamber Complete Failure

It turns out that the internal components potentially coming loose and moving around within the enclosure during the impact caused the most damage. With a rock as a replacement for the optics in this test, if the rock were to come unsecured during the drop, it would clash within the walls of the enclosure during the impact, causing damage internally as well as externally. Nonetheless, the device withstood all the drops without completely failing and to get it to break, the team had to undergo more extreme destructive tests involving some trees, rocks, and physical force.

8.2.6 Seal/Vent Test upon Submersion

8.2.6.1 Summary

This test assesses the enclosure's ability to protect internal components from environmental factors like water and dust. It aims to validate the enclosure's environmental resistance and ensure it meets or exceeds specified ratings. This comprehensive test ensures the enclosure's effectiveness in protecting internal components from environmental hazards. It verifies that the design meets or exceeds specified ratings for water and dust resistance, enhancing the spectrometer's reliability and durability in real-world applications.

8.2.6.2 Procedure

1. Submerge the sealed enclosure in water for varying durations, from short-term to longer periods.
2. Assess water ingress by placing white paper inside the enclosure and observing any wetness.
3. Test the enclosure's resistance to dust and sand by exposing it to blowing sand/dirt using a leaf blower.
4. Evaluate the ingress of dust/sand/dirt and any potential damage to internal components.

8.2.6.3 Results

During the submersion test, the fully sealed device was able to float on top of the surface of the water, allowing for no ingress in any portions of the design. As the enclosure was fully submersion, the held for approximately 10 seconds before bubbles began to appear from the seals of the main doors. Although water was able to get in the enclosure, this still proved to be very pleasing since device is only meant to survive weather conditions such as rain or snow. When testing for ingress of dust or dirt, from repeated cycles of a simulated dust storm using a leaf blower, the design held resilient to the outside conditions and allowed for no contaminants to go inside the enclosure.

8.2.7 Spectrum Tube Color Adjust (Performed by EE Team)

8.2.7.1 Summary

This experiment aims to calibrate the spectrometer chip for various wavelengths, ensuring accurate data acquisition and functionality. It focuses on confirming the spectral range of 400-1000nm and aligning optics for consistent performance. This calibration process ensures the spectrometer operates effectively within the specified spectral range and provides accurate data acquisition. Collaborating with the EE team ensures chip accuracy and functionality, contributing to the overall success of the spectrometer's operation.

8.2.7.2 Procedure

1. Use spectrum tubes to emit predictable wavelengths and calibrate the spectrometer chip accordingly.
2. Build a calibration curve for wavelength density and location on the chip.
3. Ensure optics alignment is accurate at different temperatures to maintain functionality.
4. Collaborate with the EE team to finalize chip accuracy and data retention.

9 Future work

The immediate next steps for this project would be to calibrate the CCD chip wavelength alignment via spectrum tube test. Next, would be to investigate extending the optic wavelength range by stacking another optic system with focus on different range 1000-2000nm. Finally, conducting a study on replacing the expensive adjustable mounts with 3D printed holders to reduce overall weight and cost.

10 CONCLUSIONS

This report contains the entire process from start to finish of the Spectral Forest capstone project. Starting from the project description from the client, the DRs are produced, the benchmarking against the industry standard, literature review, initial calculations, design concepts, design selections, design refining, budget, BOM, FMEA, prototyping, final calculations, final design, testing, and plans to move forward are all discussed. The overall outcome of this project was a success as the device passed on required testing procedures and with the completed EE design would collect data as intended! The purpose of the device is to analyze the spectral range of 400-1000 nm in an outdoor setting. The device must withstand typical weather events such as wind, blowing dust, and rain. It must be drone mountable, lightweight, and small to ensure it fits in the drone's payload area and does not affect the drone flight time to an exceeding degree. The final solution successfully transmits the wavelength range of 400-1000 nm to the detector inside the devi, is under the max payload capacity at 2.5lbs, fits inside the drone's payload space, does not allow ingress, and protects the internal components from the external environment.

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12 APPENDICES

12.1 Appendix A: Table of Figures

Pugh Chart						
Criteria	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Durable	-	=	=	=	D	-
Vents ensure semi-constant conditions	+	=	+	+	A	=
Unit is sealed	-	=	-	=		=
Ease of access	-	+	-	=	T	+
Reliable	-	+	-	+		=
UV resistant	-	=	+	=	U	=
Affordable	+	-	-	-	M	=
S+	2	2	2	2		1
S-	5	1	4	1		0
S=	0	4	1	4		6

Figure 20: Pugh Chart

Design #:	-	Design # 2		Design # 4		Design # 5	
Criteria	Weight	Unweighted	Weight	Unweighted	Weight	Unweighted	Weight
Durable	0.15	85	12.75	90	13.5	80	12
Vents ensure semi-constant conditions	0.15	90	13.5	100	15	90	13.5
Unit is sealed	0.2	95	19	95	19	95	19
Ease of access	0.05	100	5	50	2.5	50	2.5
Reliable	0.2	95	19	100	20	90	18
UV resistant	0.2	90	18	90	18	90	18
Affordable	0.05	0	0	100	5	90	4.5
Total	1	Sum	87.25	Sum	93	Sum	87.5
Relative Rank	N/A	3		1		2	

Figure 21: Decision Matrix

Bill of Materials: Purchased Items

Item #	Item	Item Description	Vendor & Part #	Quantity	Cost $	Cost Per unit $	Purchase or Manufacture	Weight [oz]	to buy
1	Polycarbonate CF filament	Filament that is used to print our device	Amazon	3	$136.77	$ 45.59	Purchase	N/A	yes
2	Amazon Basics TPU 3D Printer Filament, 1.75 mm, Red, 1 kg Spool (2.2 lbs)	Filament for vibration dampening	Amazon	1	$ 30.70	$ 30.70	Purchase	N/A	yes
3	M4-0.7x10mm Stainless Steel Pan Head Phillips Drive Machine Screw 2-Pieces	For grating mount	Home Depot	2 pk (2)	$ 2.50	$ 1.25	Purcahse	0.1	yes
4	M4-0.7 x 20 mm. Internal Hex Button-Head Cap Screws (12-Pack)	For lens mounts	Home Depot	1 pk (12)	$ 6.99	$ 6.99	Purchase	0.1	yes
5	18-8 Stainless Steel Button Head Torx Screws M4 x 0.70 mm Thread, 10mm Long	For door	McMaster-Carr #90991A122	1 pk (100)	$ 6.64	$ 6.64	Purchase	0.1	yes
6	Phillips Rounded Head Thread-Forming Screws for Plastic, 18-8 Stainless Steel, Number 1 Size, 1/8" Long	For PCB standoffs	McMaster-Carr #99461A605	1 pk (50)	$ 15.65	$ 15.65	Purchase	0.1	yes

7	Medium-Strength Steel Coupling Nut	Zinc-Plated, Grade 5, 1/4"-20 Thread Size	McMaster-Carr #90977A130	1	$ 5.67	$ 5.67	Purchase	0.25	no
8	Plastic Submersible Cord Grip NPT Threads, for 0.39"-0.55" Cord OD, 1/2 Knockout Size	For pressure system	McMaster-Carr #69915K57	5	$ 24.95	$ 4.99	Purchase	1	yes
9	UV-Resistant Thick-Wall PVC Pipe for Water 4 Feet Long, 1/4Pipe Size	For pressure system	McMaster-Carr #5066K38	1 (4ft long pc)	$ 13.60	$ 13.60	Purchase	1	yes
10	303 Stainless Steel Tapered Heat-Set Inserts for Plastic M4 x 0.7 mm Thread Size, 7.92 mm Installed Length	for screwing screws into	McMaster-Carr #97163A153	5 pk (10)	$ 38.90	$ 7.78	Purchase	5	yes
11	165 Neoprene O-Ring, 70A Durometer, Round, Black, 6-1/2" ID, 6-11/16" OD, 3/32" Width (Pack of 5)	To seal the door	Amazon	1 pk (5)	$ 8.42	$ 8.42	Purchase	0.1	yes
12	Cosine Corrector	25.4mm Dia., 3mm Thick, ISP Optics CaF_2 Infrared (IR) Diffuser	Thor Labs WG41050	2	$136.12	$ 68.06	Purchase	1.06	yes
13	Diffraction grating	Richardson Gratings 600 Grooves, 25 x 25mm, 400nm, Plane Ruled Reflection Grating	Thor Labs GT25-06V	2	$254.18	#######	Purchase	0.96	yes

14	Collimator	25.4mm Dia. x 25.4mm FL, VIS-NIR Coated, Plano-Convex Lens	Edmund optics #62-599	7	$346.50	$ 49.50	Purchase	3	yes
15	entrance lens	25mm Dia., 0.66 Numerical Aperture Uncoated, Aspheric Lens	Edmund optics #47-729	2	$520.00	$ 260.00	purchase	N/A	
16	Round Lens Mount	SM1-Threaded Kinematic Mount for Thin Ø1" Optics	Thorlabs KM100T	4	$741.24	$ 185.31	Purchase	19.2	yes
17	Kinematic Rectangular Optic Mounts	Kinematic Mount for 1/2" Tall Rectangular Optics, Right Handed, 8-32 Tap	Thorlabs KM05S	2	$225.14	$ 112.57	Purchase	3.36	yes
18	Silicone	Mildew-Resistant Silicone Sealant	McMaster-Carr #7545A611	1	$ 36.62	$ 36.62	Purchase	0.5	yes
19	USB-C Rubber Seal	Würth Elektronik	Digi Key #732-11387-ND	5	$ 3.15	$ 0.63	Purchase	0.1	no
20	USB-C Panel Mount Connector	Panel-Mount USB Cord	McMaster-Carr #4872N19	2	$ 26.34	$ 13.17	Purchase	4	no
21	Plasti Dip	11 oz. White General Purpose Rubber Coating Spray	Home Depot	2	$ 17.96	$ 8.98	Purchase	0.5	yes
22	Black paint	12 oz. Black Matte Interior/Exterior Spray Paint and Primer in One Aerosol	Home Depot	1	$ 6.98	$ 6.98	Purchase	0.5	yes
23	Foam	Fill PVC pipe so only air can pass through and nothing else	McMaster-Carr #1298N4	1 (3ft pc)	$ 14.69	$ 14.69	Purchase	0.1	yes
24	Latex balloon	Will be attached inside box to PVC pipe	Walmart	5	$ 5.00	$ 1.00	Purchase	0.1	yes

25	Silica pellets	Will be inside box to absorb any moisture in the air	McMaster-Carr #2189K16	2 (pk. 10)	$ 17.68	$ 8.84	Purchase	0.21	yes
26	3D printer	Used to print the final product	Bambu Lab	1	#######	########	Purchase	N/A	yes
27	0.4mm Hardened Steel Backup Nozzel	Used to print the CF filament	Bambu Lab	2	$ 29.98	$ 14.99	Purchase	N/A	yes
28	Disposable Nitrile Gloves	To handle lenses and to paint box	Home Depot	1 pk (10)	$ 2.98	$ 2.98	Purchase	N/A	yes
29	KN95 5 Layer Respirator Mask	To stop breath from landing on lenses	Home Depot	1 pk (10)	$ 2.50	$ 2.50	Purchase	N/A	yes
30	2 in. Flat Chip Brush	To paint the inside and outside of the box	Home Depot	2	$ 2.94	$ 1.47	Purchase	N/A	yes
31	Canned Air	To remove dust from lenses if any	Staples or Walmart	1	$ 7.88	$ 7.88	Purchase	N/A	yes
32	Vent	Equalize pressure	PolyCase PART#: UA-006	5	$ 19.45	$ 3.89	Purchase	0.01	yes
33	8 in. UV Resist Zip Ties	To hold balloon on pipe	Home Depot	1 pk (20)	$ 3.31	$ 3.31	Purchase	0.05	yes
34	Slit Assembly	Allows the light to enter the device	Xometry. Purchaser: Send your email to ttl58@nau.edu to gain access to the quote	3	$ 65.22	$ 21.74	Purchase	4	yes
35	14-In-1 TORX Multi-Bit Screwdriver	Used to install tamper-proof screws	Home Depot	1	$ 17.97	$ 17.97	Purchase	N/A	yes
36	Glue Stick	For bed of printer	Walmart	1	$0.97	$ 0.97	Purchase	N/A	yes
37	Heat Set Insert Tool	Used to heat set screw inserts	Amazon	1	$ 59.99	$ 59.99	Purcahse	N/A	yes
38	Prototype device #1	Will be used for testing purposes	Travis	1	$ 20.00	$ 20.00	Purchase	18.25	no
39	First Demo ME 476C	Used to prove concept and test fits	Jake Draper (Friend)	1	$ 10.00	$ 10.00	Purchased	19.2	no

Figure 22: Purchased BOM

Bill of Materials: Manufactured Items						
Item #	**Item**	**Item Description**	**Vendor & Part #**	**Quantity**	**Cost $**	**Cost Per unit $**
1	Final 3D printed device	Will house all internal components	In house	1	N/A	N/A
2	Prototype device #2	Will be used for testing purposes	In house	1	N/A	N/A
3	Prototype device #3	Will be used for testing purposes	In house	1	N/A	N/A
4	Lightweighting Mounts	To decrease weight	Machine Shop	4	N/A	N/A
5	Testing jigs	To line up light sources or mounts	In house	2 to 4	N/A	N/A

Not Started
Completed
In Progress
Removed from plan

Figure 23: Manufacturing BOM

12.2 Appendix B: Iterations

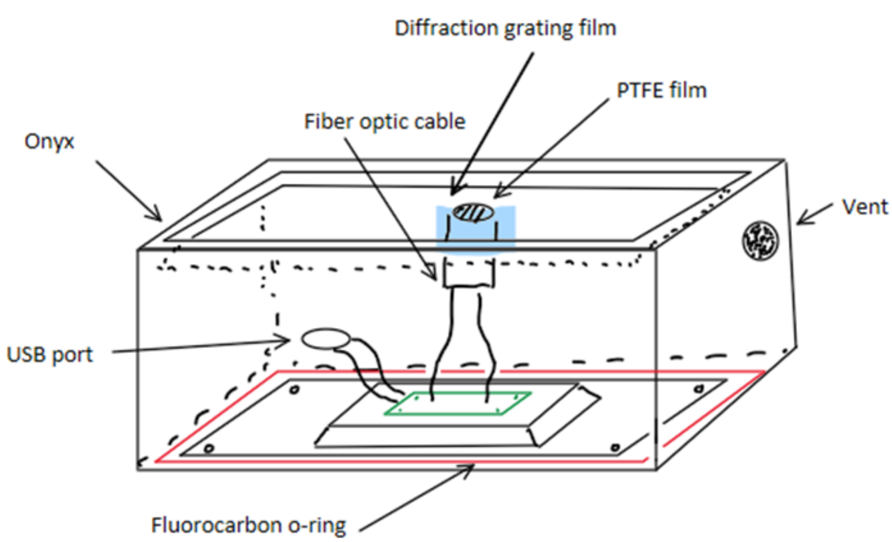

Figure 24: Initial Design 1

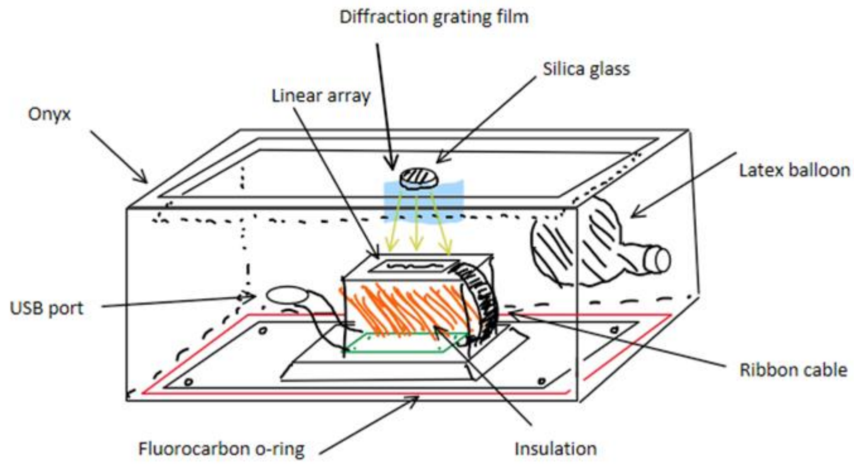

Figure 25: Initial Design 2

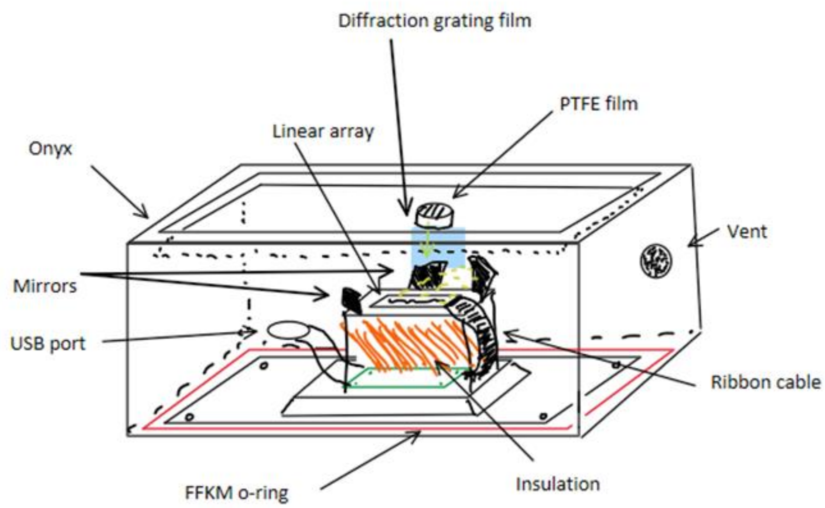

Figure 26: Initial Design 3

Morph Matrix						
Subsystem	1	2	3	4	5	6
optics	Linear array	fiber optic	camera	linear array	linear array	linear array
shape	cylinder	ectangular pris	Cone	rectangle	rectangle	rectangle
cosine corrector	ilica/quarts glas	PTFE film	licroscope slid	silica glass	PTFE film	silica glass
pressure equilizer	latex balloon	vent	hole	nverted balloo	vent	vent
o-Ring	rubber	flurocarbon	FFKM	flurocarbon	FFKM	rubber
material	ABS	Onyx	Polycarbonate	onyx	onyx	onyx
insulation	yes	no	yes	yes	yes	no
mirrors	yes	no	yes	no	yes	no

Figure 27: Morph Matrix

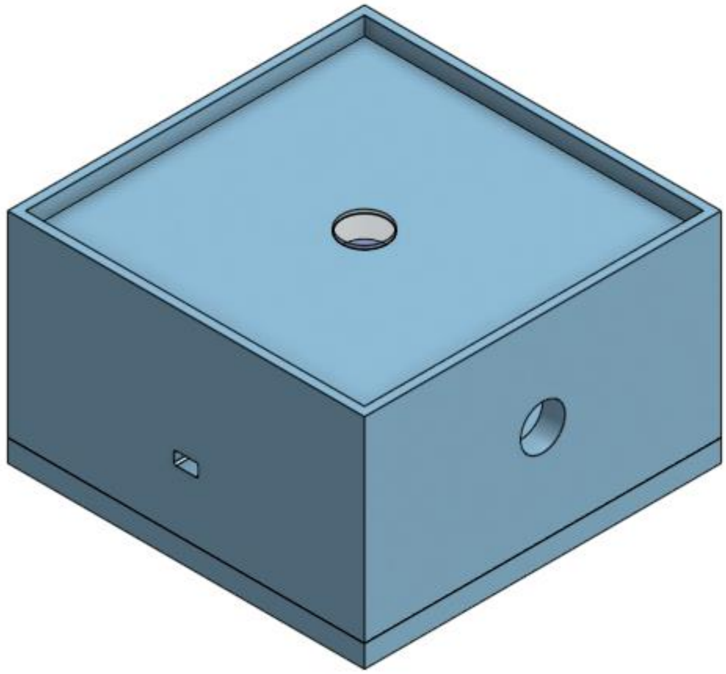

Figure 28: ISO CAD View (1st Iteration)

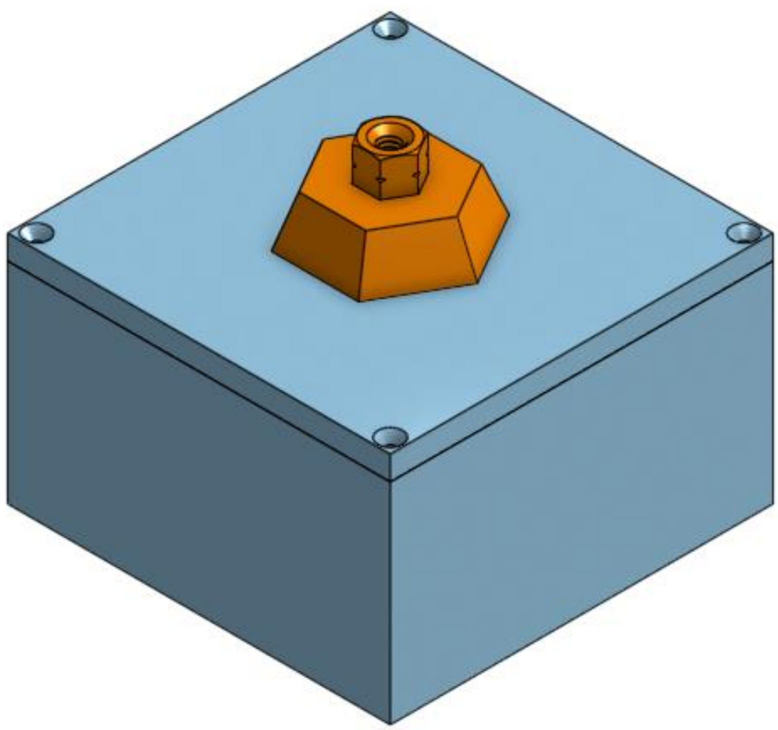

Figure 29: Bottom ISO CAD View (1st Iteration)

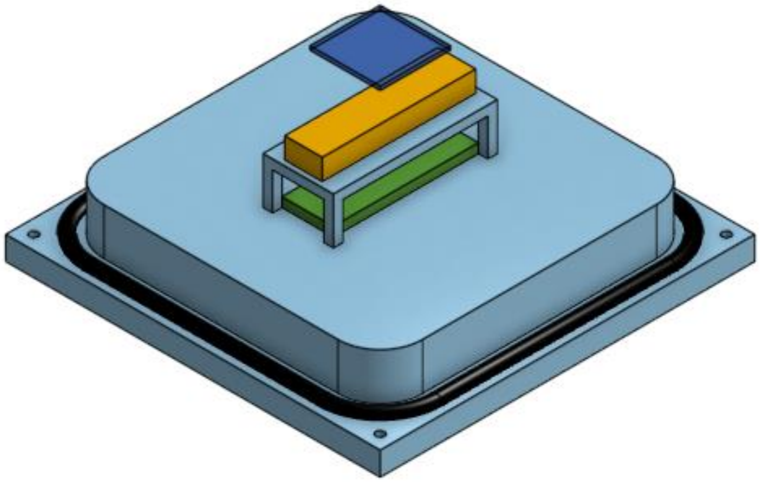

Figure 30: Internal CAD View (1st Iteration)

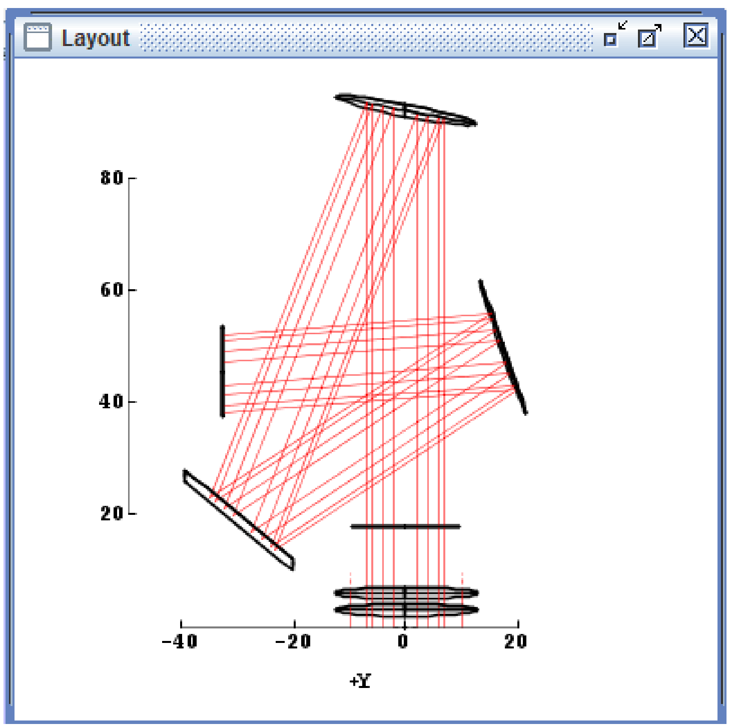

Figure 31: Beam4 Results (2nd Iteration)

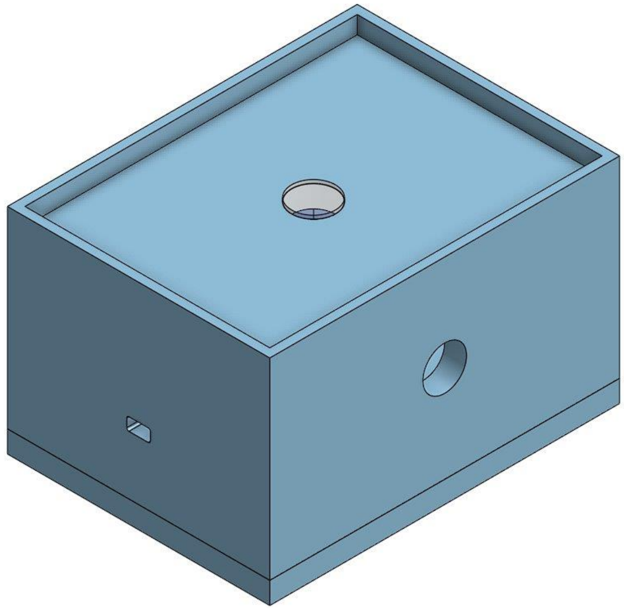

Figure 32: ISO (2nd Iteration)

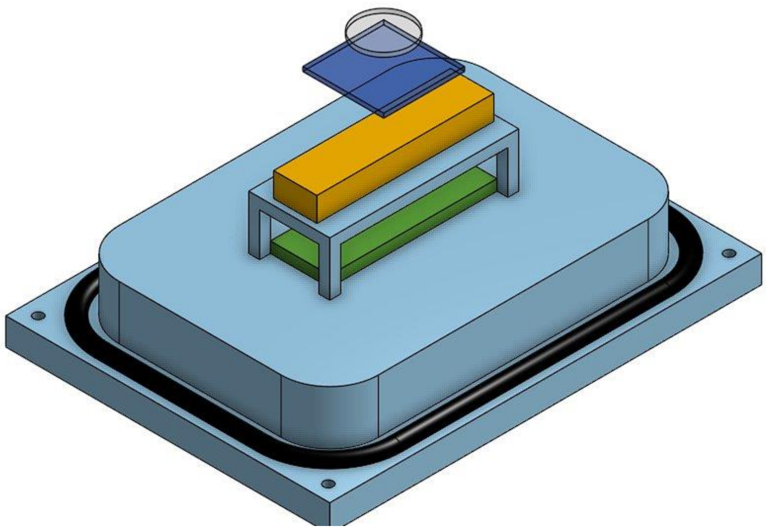

Figure 33: Internal ISO (2nd Iteration)

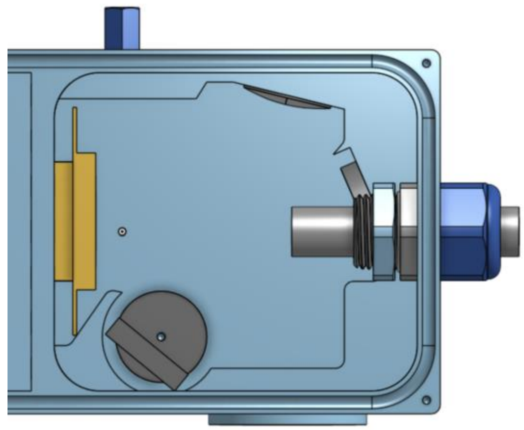

Figure 34: Top View of Mirror Layout (3rd Iteration)

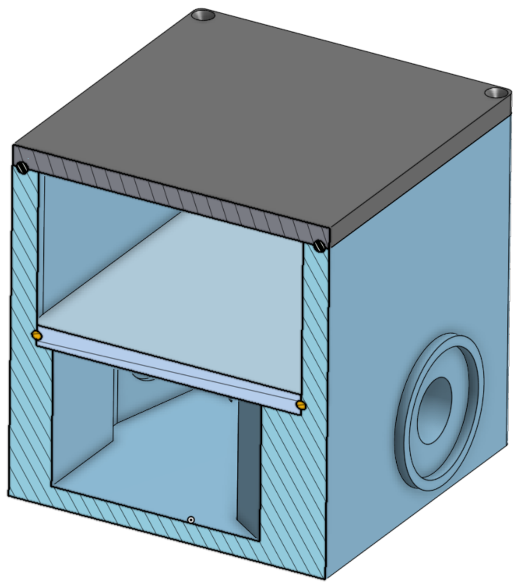

Figure 35: Section View (3rd Iteration)

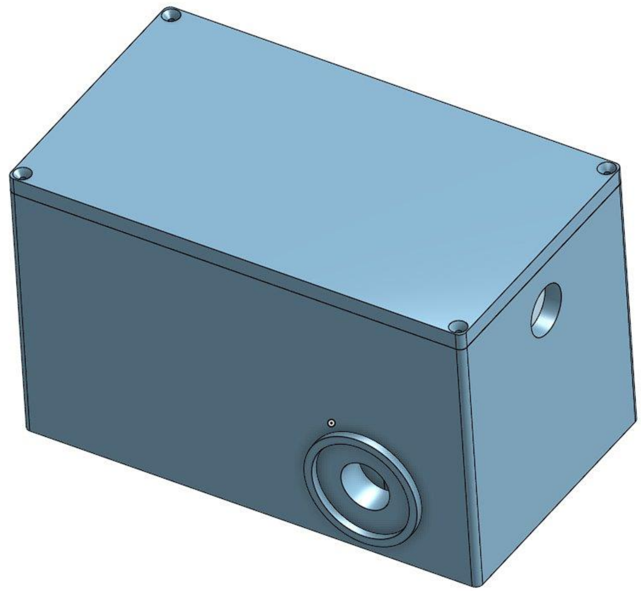

Figure 36: External ISO (3rd Iteration)

Figure 37: External ISO (4th Iteration)

Figure 38: Internal Top View (4th Iteration)

Figure 39: External ISO (5th Iteration)

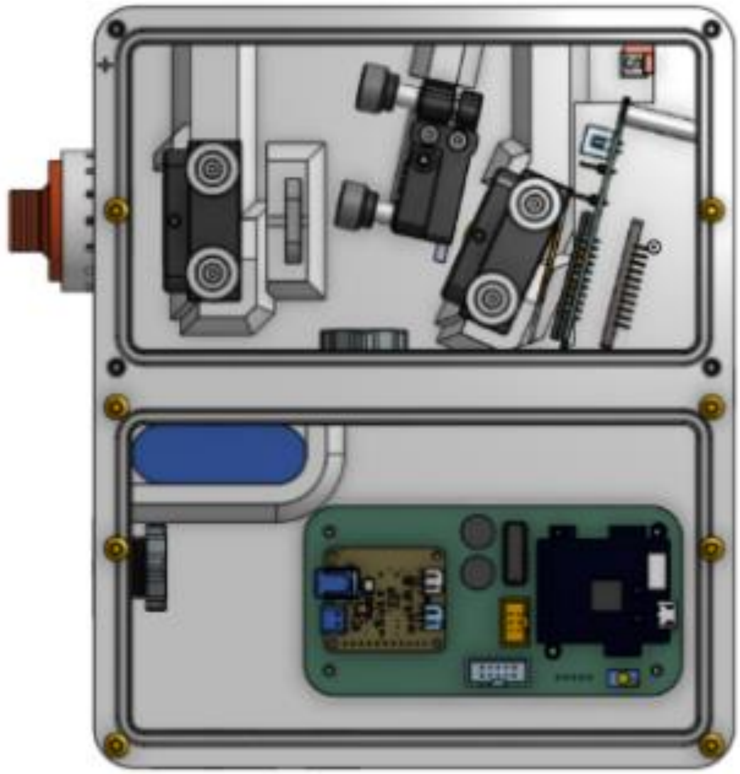

Figure 40: Internal Top View (5th Iteration)