

# **C.H.A.N. - O.S.M.**

**Climatic High-Altitude Navigator  
For Optical Smoke Measurement**

05/05/2025

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## List of Acronyms

# Chapter 1: Project Summary

For over half a century, Central Florida has been the center stage of America's space odyssey; from the Saturn rockets to the Shuttle program, to the rise of SpaceX and the fall of Boeing; Floridians have bore witness to it all. Although it is easy to get lost in the glory of multi-billion dollar space endeavors, there are few avenues for amateur space exploration. Despite this, there are plenty of people who are interested in pursuing a job or hobby in this field. This produces an environment rich in potential contributors for expanding the depth of human knowledge in this field. To this end, STEM kits are often an effective educational tool for removing barriers of entry to a field. While there exist many STEM kits in areas such as robotics, there is less competition with High Altitude Ballooning kits.

The primary objective of the Climatic High-Altitude Navigator (C.H.A.N) Balloon project is to create a Balloon Payload System (B.P.S.) that will be affixed to an off-the-shelf balloon. This balloon will record the temperature, air pressure, humidity, and wind speed during its flight up to 100,000 feet. In addition, the B.P.S. will report the balloon's latitude, longitude, altitude, speed, pitch, and bearing. The B.P.S. will also house the Optical Sub-System (O.S.S.) which consists of a spectrometer and front-end detector electronics. The purpose of the sun-spectrometer will be to detect O<sub>2</sub> and H<sub>2</sub>O absorption lines in the VIS-IR (sunlight) spectrum. Finally, the B.P.S. will record video during the flight. This will be accomplished with an action camera such as a GoPro.

Success will be determined by demonstrating each of the system's capabilities during a 150-200 foot tethered launch. If successful, the next steps will be to conduct an untethered high altitude launch in which the payload exceeds 100,000 feet. The desired outcome is to stay in communication with the B.P.S. over the duration of its flight, and recover it upon landing. This will demonstrate commercial viability of our project for educators, hobbyists, and researchers alike.

## Chapter 2: Project Description

### 2.1 Project Background and Motivation

The Central Florida area is well known for its aerospace work. NASA, SpaceX, and Blue Origin are just a few of the local companies that continue to push the boundaries of this field. On Campus, IEEE, Knights Experimental Rocketry (KXR), and the Knights Satellite Club (KSC) are dedicated to aeronautics based projects. Our project inspiration came from one student after designing an ion propulsion system. After finishing that project, he received a flash of inspiration to continue looking upward in both his next project and career. He found a surprisingly high demand for local groups willing to pay to have their own products attached to a high altitude payload. This revelation led to the foundation

of our group which eventually became the creation of an affordable, user-friendly system equipped with a wide variety of peripherals.

This payload is meant to be attached to any off-the-shelf weather balloon to be carried to a high altitude. When reaching its apex, the balloon pops and deploys a parachute allowing it to safely land for reuse. The payload will need to be cheap enough to be affordable for beginner level enthusiasts, as well as being light enough to satisfy a variety of federal regulations.

## **2.2 Current Technologies and Previous Projects**

### **2.2.1 Spectral Telescope for Star Classification**

This is a past senior design project aimed at analyzing the spectral range of stars outside the Earth's solar system. The project itself is a long-range telescope capable of figuring out the missing wavelengths in the spectral array response of the star. The spectrometer designed and created for this telescope is in the same family of classification as the one the team plans to use for this project: a Czerny Turner. However, for the Balloon Payload System, the classic Czerny design will be in an unfolded form to avoid using mirrors and reflective gratings. The telescope project utilized the traditional folded alignment, involving a reflective holographic grating and two low transmission concave mirrors [\[1\]](#).

### **2.2.2 High-Altitude Balloon Kit**

There are many off the shelf high altitude balloon kits available for purchase. They typically come with a balloon and a small payload. Our project is unique in the fact that we can custom pick our parts. This means we can go to a desired altitude with our desired payload and get specific desired data. For example Eagle Pro's High Altitude Balloon kit does not come with the ability to downlink information and cameras to capture the flight [\[2\]](#). Another aspect of our project is that we are equipping our payload with GPS, a sensor suite, and a spectrometer.

### **2.2.3 UCLan Near Space Balloon**

A student group from the University of Lancashire (UCLan) launched a payload that was able to reach 100,000 ft [\[3\]](#). This group project was more focused on capturing cosmic ray data rather than atmospheric data. It is painted black, likely to reduce noise from light from the detectors and the scintillators in them. We will do something similar as we do not want solar interference due in our Optics subsystem.

We are looking to collect atmospheric, not cosmic, data. We also want this simple enough to be operated by anyone. Their payload certainly needed to follow many extra government regulations, which may be intimidating for a first time user. Their system was launched and had no monitoring capabilities for its data, though it had a GPS system that enabled tracking it down.

## **2.2.4 UAlbany NASA Eclipse project**

This project by UAlbany students was coordinated with NASA [\[4\]](#). Eclipses are a fairly rare phenomenon and not much is known about how the atmosphere reacts during them. UAlbany collected temperature, pressure, humidity, wind speed and direction during its flight. The payload was launched in New Mexico.

This behavior is what we want to encourage for many local areas. Our goal is less about a particular height and more about affordability, and ease of use. Not having to deal with things like federal approval go a long way to encouraging more people into High Altitude Ballooning.

## **2.3 Goals and Objectives**

### **2.3.1 Overall Payload Goals**

#### **Basic Goals**

- Successful launch of a payload suspended by a weather balloon, that can measure and record:
  - Temperature
  - Air Pressure
  - Relative humidity
  - Wind speed
  - Velocity (linear & angular)
  - Latitude & longitude
  - Altitude
  - Black Smoke (Unused Fuel From Combustion)
- Transmit select data such as location & altitude from the payload to the receiver station.
- Present the data collected from the payload's onboard storage in a clear manner.

#### **Advanced ECE Goals**

- Present the live data received from the payload by the base station in a clear manner.
- Design a mobile app for Android and IOS.

#### **Stretch Goals**

- Successfully reach 100,000 feet.
- Recover balloon from an untethered launch.

### **2.3.2 Payload Objectives**

- Successfully connect and poll each sensor in a set interval indefinitely.
- Store data in a local unit.
- Transmit data using a radio frequency method to the customer with a base station in range according to the specification sheet.

### **2.3.3 Optics Subsystems Goals & Objectives**

#### **Basic Optics Goals**

- Design an optical system to detect the percent of transmission through a sample of outside air (smoke) and a sample of clean air.
- Determine the level of smoke presence in comparison with the air.
- Optoelectronically interface the optical lens system and the analog output.

#### **Advanced Optics Goals**

- Design an optical system to detect gasses produced by burned iodine at the wavelength of 520 nm.
- Determine the presence of iodine gasses and the intensity of the smoke.
- Plot the readings on a graph and measure the distance between the air measurements and smoke measurements to determine smoke severity.
- Optically design and add a narrow FOV lens to the onboard camera to limit distortion and provide a non-fisheye flight video.

#### **Stretch Optics Goals**

- Obtain a full spectrum – from UV to far IR – and determine the chemical composition of the sample based on the absorption lines.
- Quantify the harmful elements present in the wildfire smoke sample and provide first responders with a full report on the composition of the air in specific regions of the forest in question.

#### **Basic Optics Objectives**

- Using a broad spectrum LED, align a series of Collimating and Focusing lenses to control the light onto the sample cell, onto the diffraction grating, and onto the photodiodes.

- Utilize a diffraction grating to split the white light into the 520 nm and 633 nm wavelengths to be picked up by two separate photodiodes.

### **Advanced Optics Objectives**

- Have two “lanes” of lenses operating at the same time: one for smoke analysis and one for baseline clean air analysis to be used as a reference. Include a blacked-out photodiode to account for the dark current.
- Connect each photodiode to a transimpedance amplifier to produce enough electrical signal to be sent to the analog-to-digital converter (ADC) for processing and plotting of the points on a graph.

### **Stretch Optics Objectives**

- Utilize a photodiode detector array that ranges from UV to IR to collect the incident diffracted light and convert the optical power to electrical signal.
- Include a scattering measurement to determine the size of the soot particles, water molecules, and iodine byproducts.
- Have an automatic trigger system that transmits the data to the local authorities if the smoke/iodine concentration is too high.

### **2.3.4 Receiver Station Objectives**

- Design a system that allows a customer with a portable electronic device to collect data from the weather balloon.
- Utilize an available GUI able to graphically represent the data collected by the payload.

The primary goal of this project is the successful operation of a Balloon Payload system (B.P.S) during an tethered balloon flight. The project will encompass designing the electrical and optical systems in addition fabricating a container for them.. The design will be compatible with most commercially available weather balloons. The B.P.S. will consist of an onboard sensor suite and an Optical subsystem for gas detection.

The sensor suite includes peripherals for measuring temperature, air pressure, humidity, wind speed, as well as balloon location, altitude, direction, and velocity. The two major subsystems are the Telemetry and Atmospheric subsystems. The shared objective between the subsystems is for our payload to poll each sensor at constant intervals. The primary objective for the Atmospheric subsystem is to provide accurate measurements under the unique circumstances of a high altitude setting. The primary objective of the Telemetry subsystem is to provide an accurate location of the B.P.S during flight.

The optics objectives involve utilizing a white LED as the light source and keeping the entire system dark and contained. Any outside light will result in background noise, making the signal difficult to distinguish. Next, the goal is to diffract it into multiple wavelengths to isolate the absorbance wavelength of O<sub>2</sub> and a wavelength amongst green to provide a high power reference. Finally, the system will detect those two specific wavelengths with two separate photodiodes assigned to those wavelengths.

Another objective is to view the data in real time on the ground. The RF subsystem will transmit data to the base station for display on an LCD screen. The design must be portable and energy efficient enough to work with modern portable devices. A Graphical User Interface (GUI) will also be implemented to process and present the data visually.

### **2.3.6 Hardware**

#### **Atmospheric Subsystem**

The core of our project involves reading atmospheric data at different altitudes. We will employ sensors to get the four basic atmospheric conditions of temperature, air pressure, humidity (RH), and wind speed. The measured data will be stored on a local storage device then transmitted in time intervals to a ground station for a real time display of data. Additionally, we will attach a camera to the payload for a top down view of the landscape. However, to keep the design cheap and simple, the camera will not be sending its video feed. This data will be stored on a separate local storage device for view after collection.

The sensors will face a variety of environmental conditions. They will need to be able to operate within fluctuating temperatures as hot as 30°C to temperatures as cold as -40°C. Additionally, they are likely to experience a large amount of moisture and rain from the clouds and must be protected from the physical forces due to higher winds.

#### **Telemetry Subsystem**

The telemetry subsystem records the position, altitude, direction and velocity of the payload while in the air. It includes a GPS, altimeter, and IMU. While it is subjected to the same conditions as the atmospheric sensors, the telemetry subsystem is crucial for retrieval of the balloon. A failed recovery means loss of data since it will all be stored locally on the payload. Additionally, the payload consists of many metal, plastic, and semiconductor parts, which pose an environmental risk in the event of not being able to recover the payload.

#### **Payload Design**

The electronics and optics experiment will be housed inside a 3D printed and insulated box we are calling the Balloon Payload System (B.P.S.). This housing must be able to reliably house and protect all of the optical components, antennas, parachute and other systems while being lifted up through the atmosphere by the balloon. From liftoff to landing the payload will be cleverly designed to face and handle a variety of environmental concerns. Although we

are not being graded on the mechanical design, this aspect must be able to deliver otherwise it will compromise the entire project. Some of the concerns we are designing around are heavy moisture in the air, low temperatures, and shock of landing. We go more into depth on this topic in our constraints section in Chapter 4.

### Radio Frequency (RF) Subsystem

Retrieval of the B.P.S. plays a major role in our design. The RF subsystem requires an antenna and transmitter on the balloon to send information to the base station. The base station utilizes a matching RF module and antenna to receive data packets from the payload to be displayed on an LCD screen.

The communication method is chosen based on the balance of bit rate vs range. Bluetooth, a common method, can send large amounts of data, but only operates at short ranges. Our payload sends telemetry and atmospheric data, which is a small data stream. Therefore, we will choose a long-range method to maximize our retrieval chances.

### Optics

The optics subsystem consists of a spectrometer composed of two lenses, a pinhole, and a transmission grating. The light enters through the pinhole and travels along the optical path, where the light is diffracted into the individual wavelengths and focused on the detector. Since a white LED is the source of light in this project, the range of potential wavelengths that can be produced is nearly limitless. Refer to *Figure 2.1*. To take budget and general feasibility into account, the team decided to fashion a simple detector on our own. This component will be just two photodiodes: one at a peak transmission within the visible green region, and one at an absorbance valley in the NIR region.

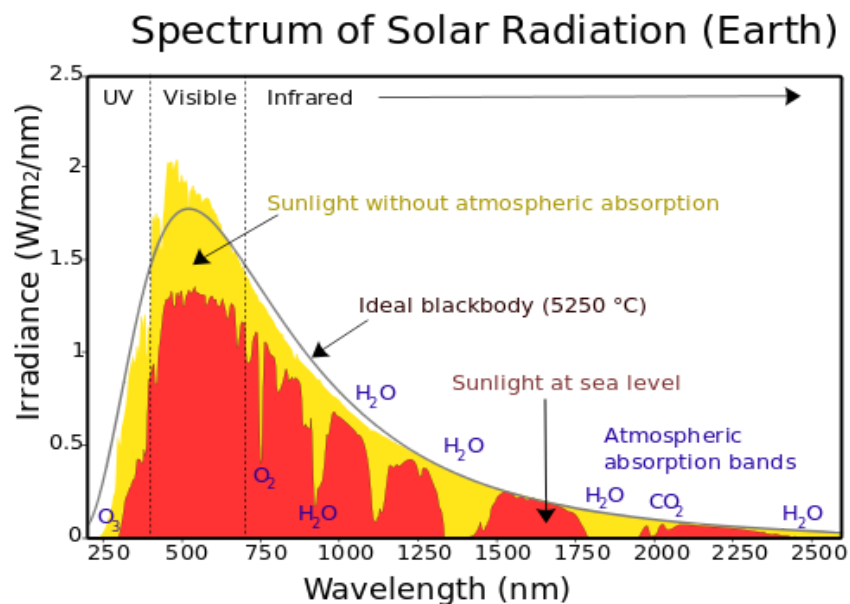


**Figure 2.1: Solar Spectrum.** Source: Nick84 [\[CC BY-SA 3.0\]](#), via Wikimedia Commons

The white LED will guarantee a consistently adequate amount of power and provides the same blackbody transmission curve as the sun, shown above in the figure. The sun spectrum produced from this setup will have drops in transmissivity, indicating the presence of common atmospheric gasses such as  $O_2$ ,  $H_2O$ , or  $CO_2$  as shown in the solar spectrum graph. Since the detector portion will be limited to only two photodiodes, this means only two distinct wavelengths will be detected. One will be the controlled reference (green) and one will be the absorbance marker for a given molecule. Since  $O_2$  has a sharp drop and is close to the visible spectrum, a silicon-based electronic component can be used. This will be the only gas detected in this project. The further into the infrared means more money invested in the photodiode.

To limit contamination of the system and reduce background signal (light) noise, the spectrometer will be fully enclosed and darkened. To detect oxygen gas, two tubes will be connected to the outside of the enclosure with a clear “cuvette” box connecting them in the middle. This box will be placed between the focusing lens and the two photodiodes. This setup will provide insight on the change in oxygen presence at the different altitudes of the balloon’s position, whether the information be used for weather data prediction or environmental changes over time. The goal and objective for this particular project is to qualitatively provide data, not quantitatively. The spectrometer and detector setup will merely detect the presence of molecules, not the concentration, density, or numerical count.

The general layout of the spectrometer is an unfolded Czerny Turner, starting with an entrance slit, followed by a collimating lens to collect the beam and pass it through a diffraction grating then a focusing lens to guide the separated wavelengths onto the two photodiodes, resulting in two signals. The detector in this system will be a green photodiode to be used as a reference signal (preventing false positives) and a NIR photodiode that operates at the absorbance wavelength of oxygen gas. The resolution will be admittedly low due to time, budget, and physical space constraints on the payload, but the mere presence of the gas – or lack thereof – should be resolvable.

### **Power**

A power system is the key to electrical system operation. It must remain active for as long as the telemetry is needed. An operational time of 3 hours is sufficient for a launch, landing, and retrieval. The power system must take an unregulated, DC battery voltage and deliver stable power to its peripherals. The battery will begin at a relatively high voltage and be stepped down via voltage regulators to a series of power buses. There will be a separate bus for each unique voltage necessary to power each peripheral.

### **Electronics Hardware Diagram**

Refer to *Figure 2.2* for the Balloon Payload System Electronics Hardware Diagram. This illustration shows which member of the team is responsible for each sub system. In addition, it shows how all the components are connected to each other, whether it be wired communication, wireless communication, or power bus.

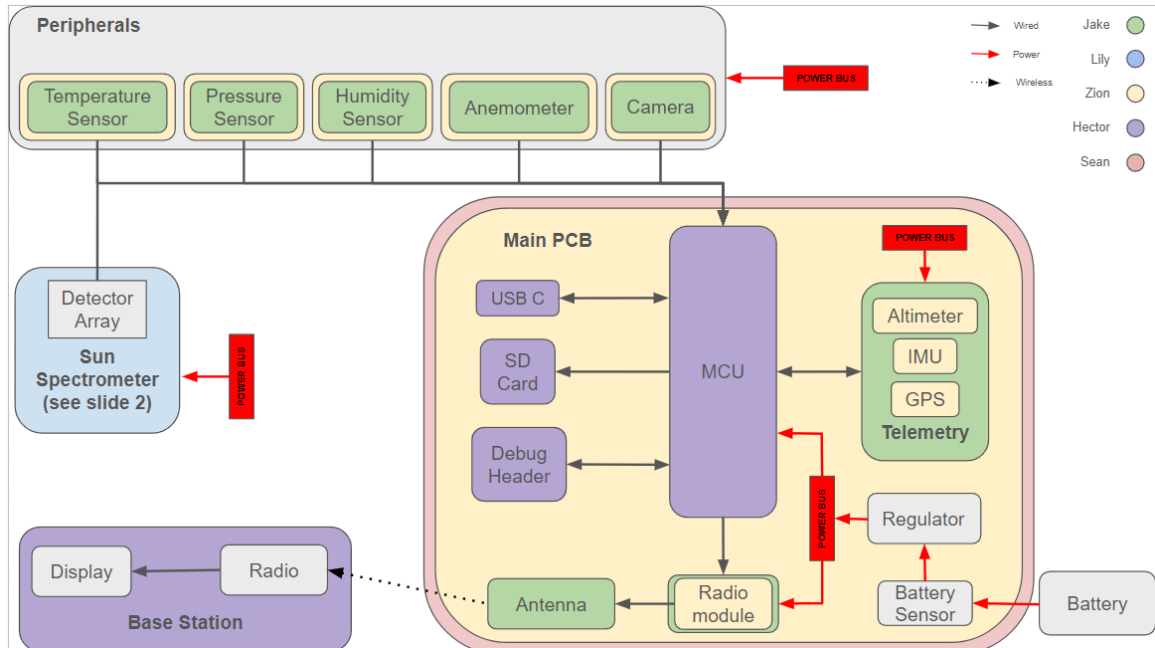


**Figure 2.2: Hardware Diagram**

### Optics Hardware Diagram

Refer to *Figure 2.3* for the Optics Hardware Diagram. It details how the light travels from the slit, through the collimating lens, the diffraction grating and the focusing lens, to the detector array. No dimensions are included in the diagram, as they will likely change multiple times during construction and calibration.

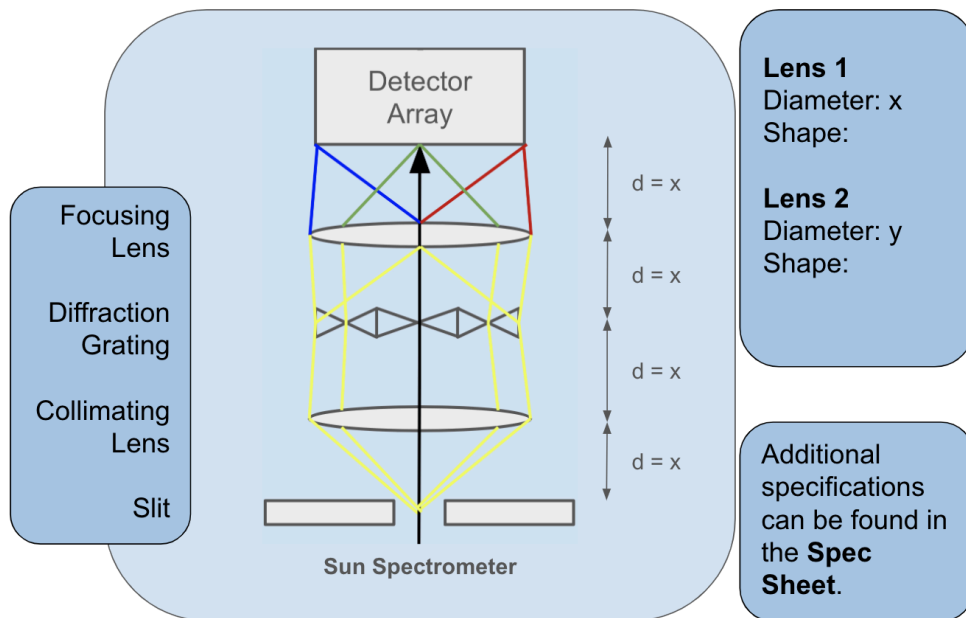


**Figure 2.3: Optics Hardware Diagram**

## **2.3.7 Software**

### **Payload Software**

The main objective of the B.P.S is to receive and collect atmospheric data to observe local weather conditions. The software should be responsible for communicating with each sensor to collect and store the data for use during and after landing. The process begins with the collection of data from a sensor. It should then be stored locally in separate CSV files for use at the base station. Next, part of the data should be transmitted to the base station via the RF subsystem to show the real conditions and location of the payload. This process must be performed for each sensor fast enough to take reading at constant intervals. 3-4 readings per minute will be adequate to give an accurate representation of the real time measured conditions.

### **Base Station Software**

The B.P.S. is designed to be located and retrieved after launch. The base station software has two functions. The first function is to receive real time updates from the balloon. The software will do this by interfacing with a ground RF module and antenna. This function ensures proper tracking and retrieval of the B.P.S.

The second function is the implementation of a Graphical User Interface (GUI). It will use the CSV files to generate a separate graph for each sensor. The CSV files may also be transferred to any personal device for external processing.

### **Software Diagram**

Refer to *Figure 2.4* for the overall Software Diagram. It includes the work distribution of each member, a general logic tree, and the general flow of data from the sensors to the storage device and base station. The software diagram provides a guideline to the team as we integrate all the subsystems into one uniform product.

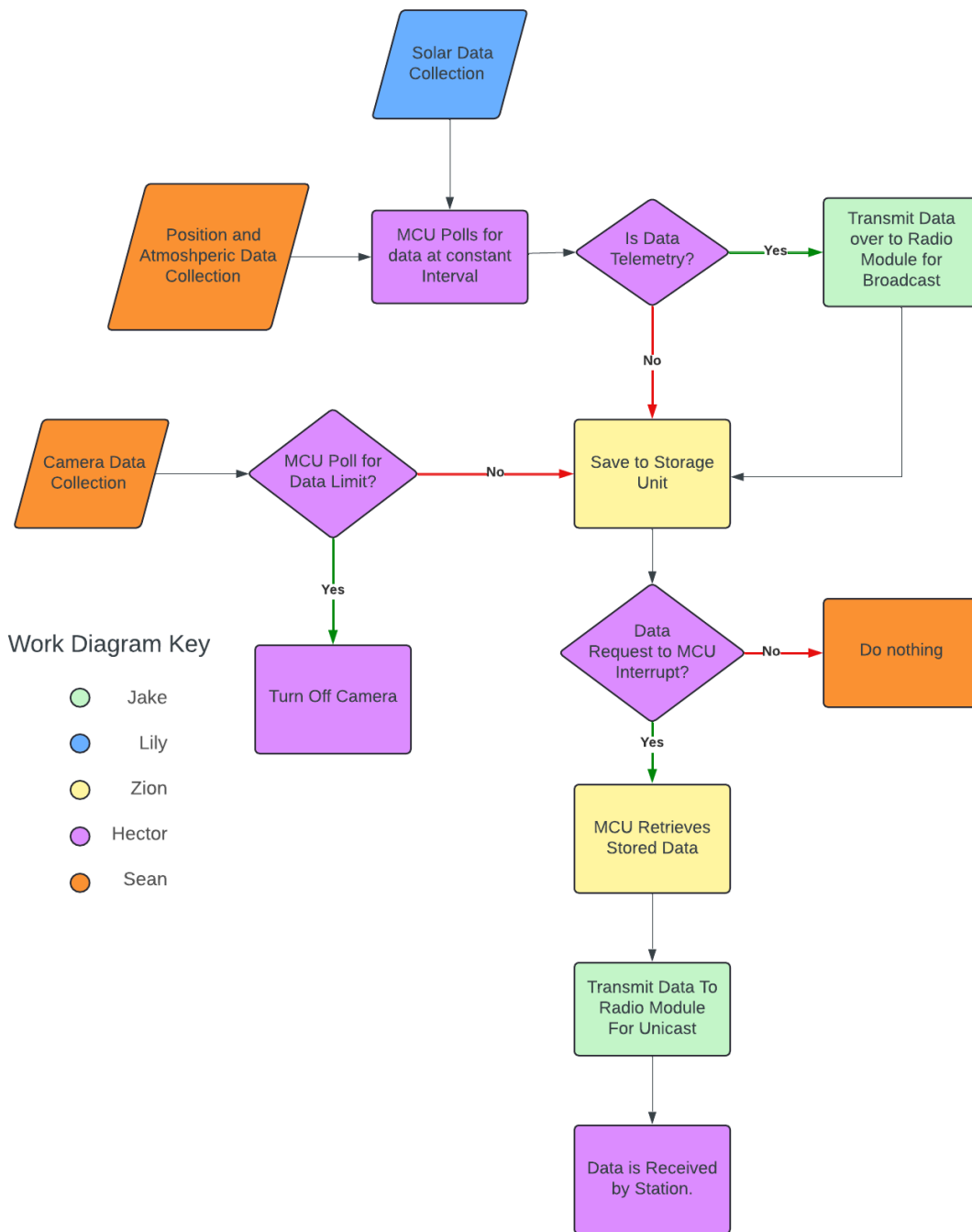


**Figure 2.4: Overall Software Diagram**

## 2.4 Specification Sheet

In order to meet our goals and objectives, we must ensure that each part we select is capable of attaining those goals. To do this, we implemented a system-wide specification sheet. Refer to *Table 2.1* for the project specifications.

**Table 2.1: Specifications**  
*By Authors*

| Total System Specs                |                          |
|-----------------------------------|--------------------------|
| Operating Altitude                | 100 - 200 ft.            |
| Battery Lifetime                  | > 3 hr.                  |
| Operating Temperature             | -50 - 30 °C              |
| Total Power Consumption           | < 10 W                   |
| Mechanical                        |                          |
| Balloon Type                      | Latex - 800g             |
| Payload Weight                    | < 4 lb                   |
| Payload Dimensions (b x w x h)    | 12 in x 12 in x 12 in    |
| Parachute Diameter                | 1.5 m                    |
| Flight Train Wire Total Length    | > 30 ft.                 |
| Rapid Deflation Device (RDD) Type | Hot Wire                 |
| Black Smoke Detector              |                          |
| Detector Specifications           |                          |
| Particulate Type                  | Uncombusted Hydrocarbons |

|                               |                           |
|-------------------------------|---------------------------|
| Particulate Size              |                           |
| Measurement Range             |                           |
| Detection Range               |                           |
| <b>Collimating Lens</b>       |                           |
| Lens Shape                    | Plano-Convex              |
| Focal Length                  | 12 mm                     |
| Diameter                      | 25 mm                     |
| <b>Focusing Lens</b>          |                           |
| Lens Shape                    | Cylindrical Plano-Concave |
| Focal Length                  | 15 mm                     |
| Diameter                      | 25 mm                     |
| <b>Diffraction Grating</b>    |                           |
| Absorption/Transmission       | Transmission grating      |
| Output Type                   | Spectrograph              |
| Groove Frequency              | 600 - 1200                |
| Grating Type                  | Ruled                     |
| Dimensions                    | 30 mm x 30 mm             |
| <b>Detector (Photodiodes)</b> |                           |

|                                        |                                              |
|----------------------------------------|----------------------------------------------|
| Incident Area Size                     | 2 mm x 2 mm                                  |
| Material                               | Silicon                                      |
| Wavelengths Detected                   | 500 nm & 750 nm                              |
| <b>Telemetry</b>                       |                                              |
| <b>Inertial Measurement Unit (IMU)</b> |                                              |
| Accelerometer Measurement Range        | +/-2 to +/-16 g                              |
| Gyroscope Measurement Range            | +/- 125 to +/- 4000 degrees per second (dps) |
| Accelerometer Sensitivity              | 0.061 - 0.488 mg/LSB (+/-2%)                 |
| Gyroscope Sensitivity                  | 4.375 - 140 mdps/LSB (+/-2%)                 |
| Bias Instability @ 25 °C               | 3 deg/hr                                     |
| Maximum Power Consumption              | 5.4 mW                                       |
| <b>Altimeter</b>                       |                                              |
| Calibrated Measurement Range           | 20 - 110 KPa                                 |
| Pressure Reading Noise                 | 1.5 - 19 Pa RMS                              |
| Accuracy @ -10 to 50 °C                | +/- 0.4 KPa                                  |
| Pressure Resolution                    | 0.25 - 1.5 Pa                                |
| Altitude Resolution                    | 0.0625 - 0.3 m                               |
| Maximum Power Consumption              | 5.04 mW                                      |

|                                               |                                |
|-----------------------------------------------|--------------------------------|
| <b>GNSS System</b>                            |                                |
| Maximum Altitude                              | 50,000 m                       |
| Maximum Velocity                              | 500 m/s                        |
| Velocity Accuracy                             | 0.05 m/s                       |
| Heading Accuracy                              | 0.3 deg                        |
| Horizontal Position Accuracy                  | 2.5 - 8.0 m                    |
| Max Navigation Update Rate                    | 10 - 18 Hz                     |
| Maximum Power Consumption                     | 241 mW                         |
| <b>Atmospheric Sensors</b>                    |                                |
| <b>Combined Temperature / Humidity Sensor</b> |                                |
| Temperature Measuring Range                   | -40 - 25 °C                    |
| Humidity Measuring Range                      | 0% - 100% Relative Humidity    |
| Temperature Accuracy @ 25 °C                  | +/- 1 °C                       |
| Humidity Accuracy @ 25 °C                     | +/- 4% Relative Humidity       |
| Temperature Resolution                        | 0.01 - 0.04 °C                 |
| Humidity Resolution                           | 0.04% - 0.7% Relative Humidity |
| Maximum Power Consumption                     | 1.8 mW                         |
| <b>Anemometer</b>                             |                                |

|                                         |                       |
|-----------------------------------------|-----------------------|
| Wind Speed Measuring Range              | 3 - 200 mph           |
| Resolution                              | 0.57 mph              |
| Power Consumption                       | User Set (~6 $\mu$ A) |
| <b>Pressure Sensor</b>                  |                       |
| Pressure Operating Range                | 10 - 1300 mbar        |
| Temperature Operating Range             | -40 - 85 °C           |
| Pressure Resolution                     | 0.012 - 0.065 mbar    |
| Temperature Resolution                  | <0.01 °C              |
| Altitude Resolution                     | 10 cm                 |
| Accuracy @ 25 °C, 750 - 1100 mbar       | +/- 1.5 mbar          |
| Accuracy @ -20 - 85 °C, 300 - 1100 mbar | +/- 2.5 mbar          |
| Temperature Accuracy                    | +/- 0.8 °C            |
| Maximum Power Consumption               | 5.04 mW               |
| <b>Radio System</b>                     |                       |
| Maximum range                           | 150 feet              |
| Communication Rate                      | 100kbps               |
| Supply Voltage                          | 5 V                   |
| Logic Voltage                           | 3.3 V                 |

|                                |                              |
|--------------------------------|------------------------------|
| Transmitter Antenna Frequency  | 915 MHz                      |
| Receiver Antenna Frequency     | 915 MHz                      |
| Transmitter Antenna Gain       | 10 dBi                       |
| Receiver Antenna Gain          | 10 dBi                       |
| <b>Camera</b>                  |                              |
| Resolution                     | Up to 5.3K                   |
| Frames Per Second              | Up to 60                     |
| Zoom (or range of auto zoom)   | Up to 2x (1080P)             |
| Video Data Storage (MB)        | Up to 1TB                    |
| Footage Capture Time (Minutes) | Up to 120                    |
| <b>MCU &amp; Related</b>       |                              |
| MCU Flash Size                 | 4 MB                         |
| MCU RAM Size                   | 520 kB                       |
| I2C Ports                      | 2                            |
| SPI Ports                      | 4                            |
| Maximum Power Consumption      | 1800 mW                      |
| SD Card Storage Format         | FAT32 (64GB<), EXFAT (64GB>) |
| Debug Methods                  | USB to UART / JTAG           |



## 2.5 House of Quality

Every design project has to balance a myriad of different desirables. Although there are many ways to represent this balance, a graphical depiction is one of the best methods to do so. We chose the House of Quality to depict the tradeoffs in our project. Refer to *Figure 2.5* for the House of Quality.

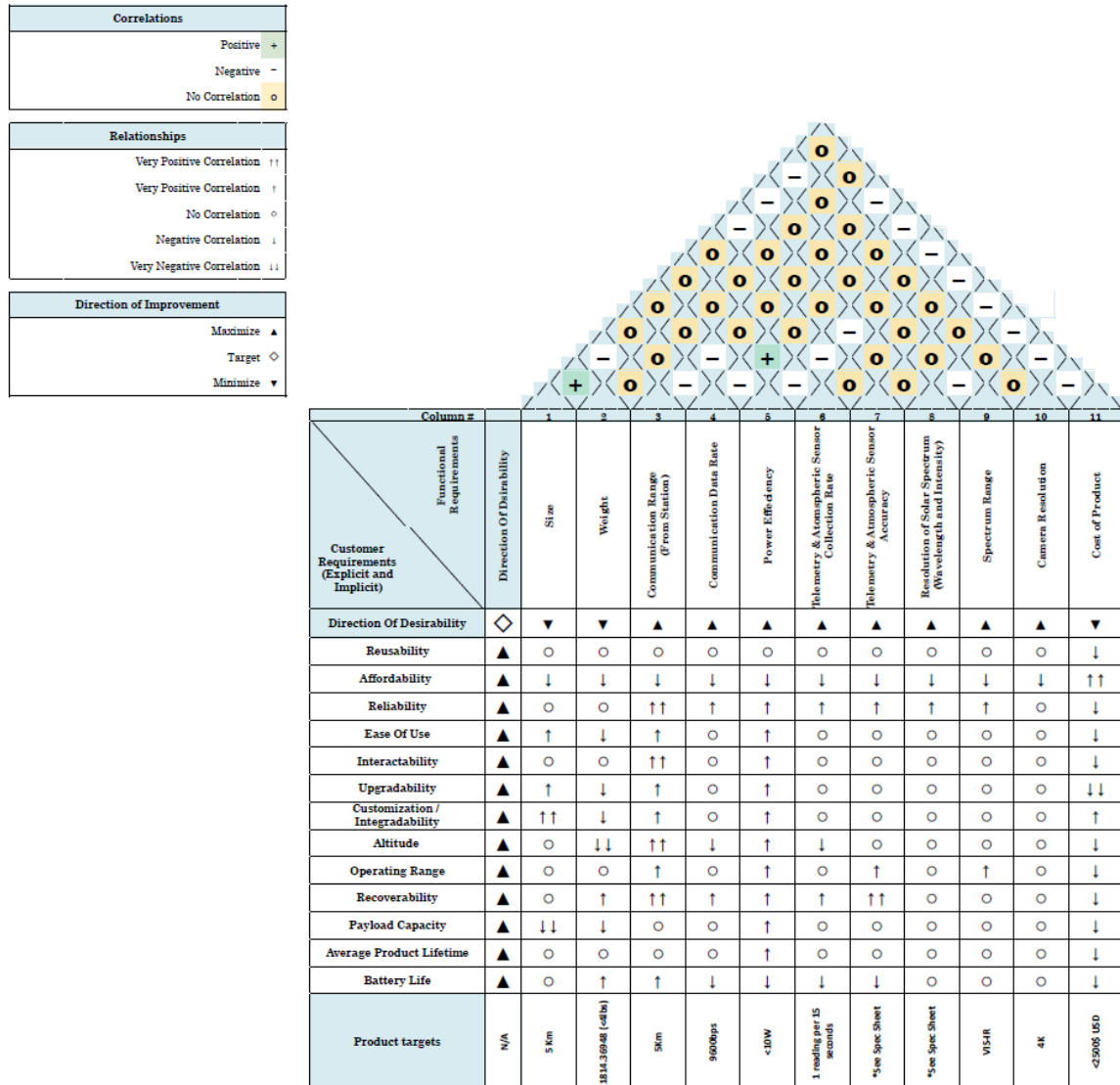


*Figure 2.5: House of Quality*

## Chapter 3: Research

### 3.1 Market Conditions

The market for a High Altitude Balloon payload focused towards entry-level hobbyists and students is promising. Recently, the US Department of Education

launched the *Raise the Bar* initiative, which is designed to increase funding towards STEM programs [7]. Simultaneously, Americans are taking great interest in space. A Pew Research study published in July of 2023 found that seven out of 10 Americans believe that the U.S. should be the world leader in space. Additionally, 55% of Americans expect space tourism to become common in the next 50 years [8]. It does not take much thought to realize that a STEM kit that allows students to “touch” the edge of space lands perfectly at the intersection of these two fronts. Given this, it is safe to believe that our product will be received extremely well by STEM educators and hobbyists alike.

## 3.2 Existing Products

Currently, there are three different types of High Altitude Balloon STEM products. These are *Baseline*, *Ready-To-Fly (RTF)*, and *Comprehensive Service*. An example of a company that offers a baseline kit is *High Altitude Sciences*. Their kit includes a latex balloon, flight train (rope), parachute, a flight computer, a mounting frame, and a balloon inflation kit [9]. The kit does not include a camera, or a tracking system. High Altitude Science recommends buying a *Spot Tracker* or equivalent, which is an all-in-one GPS tracker that communicates over the *Globalstar* Satellite network [10]. The flight computer has a GPS module, but it saves coordinates to an SD card and has no radio communication system. The kit starts out at around \$700 for a 350g balloon, but with the optional 1500g balloon, the cost increases to \$829.00. We will be able to offer a much more “put-together” system than *High Altitude Sciences*. Our payload will be protected, insulated, and trackable via long range radio. Customers will not need to purchase a separate GPS tracker, although they can option to if they want a backup.

An example of an RTF kit is made by *Strato Flights*, a German-based company that has been selling kits, parts, and even services for high altitude balloon launches since the early 2010’s. This kit includes a 1600g balloon, a GPS tracker, a datalogger, a power bank, and an action camera. The price comes to around 987,84 euros, or \$1096.93. This kit can be optioned in a cheaper configuration that does not include the action cam or the datalogger, but this does not count as an all-in-one kit [11]. *Strato Flights* takes a different approach to high altitude payload construction than us, while we are integrating almost all hardware into one system that will be contained in a custom enclosure, they provide a styrofoam box to “throw” everything into. In addition to this, because *Strato Flights* is an EU-based company, they do not have to comply with FCC regulations. Because of this, they use a cellular-based tracker that would be illegal to launch in the U.S. [12]. For these reasons, we believe we can offer a better product than *Strato Flights*.

An example of a *Comprehensive Service* is offered by *Strato Star*. *Strato Star*’s business model is focused around providing curriculum, online consulting, and FAA approval support to STEM educators. They also provide the balloon, the payload, the launch equipment, and proprietary tracking software [13]. Another

service *Strato Star* offers is R&D high altitude testing for universities, corporations, and startups. They provide 3U and 6U payload enclosures, 12 VDC and 2 A of supply power, and a realtime 2-way datalink. In addition, they include online payload development courses, payload design review, and shipping from the customer to the launch site and back again. *Strato Star* charges \$3600 per lb for their R&D services, which is quite cheap compared to satellite rideshares (~\$300,000 per lb) [\[14\]](#) [\[15\]](#). We believe we can compete with *Strato Star* by targeting more “independent” STEM educators, who may not have (or want to expend) the funds to pay for a comprehensive launch service. *Strato Star* does not set any fixed pricing for educators, instead they encourage them to “Request a Proposal.” We will offer a RTF kit with an up-front fixed price, that educators can buy and have shipped to their door within a week. Thus we are able to edge in on *Strato Star*’s customer base by providing a cheaper, clearer, option.

### 3.3 Part Selection

#### 3.3.1 Embedded Control Technology Selection

##### Microcontroller vs FPGA

The embedded controller dictates when data is collected and stored from the sensor suite, telemetry suite, and sun spectrometer. In addition, it schedules transmit signals to the APRS unit. A controller that can quickly and reliably complete all these tasks repeatedly while drawing minimal power is essential to the success of the project. There are two options for an embedded controller to suit the project’s requirements, the MCU (Micro Control Unit / Microcontroller) and FPGA (Field Programmable Gate Array).

A microcontroller contains a microprocessor / Micro Processing Unit (MPU) usually packaged with volatile and non-volatile memory and peripherals such as Digital to Analog Converters, oscillators, timers, general I/O and PWM pins, in addition to communication interfaces such as I2C, UART and SPI. These peripherals allow for direct communication between the microcontroller and other devices such as sensors, actuators, or debugging tools. Microcontrollers accomplish tasks sequentially (unless they contain more than one core), this means the microcontroller is only processing one task at any time. This can create a bottleneck if the microcontroller is responsible for multiple data streams. An advantage of the microcontroller’s sequential performance is low power consumption, as there is only one processor consuming energy. Microcontrollers are programmed with high-level languages including Python, C and C++. Because they utilize common high-level languages, microcontrollers can take advantage of libraries written for tasks such as communication protocols, control algorithms, and sensor mapping [\[16\]](#).

A FPGA is a device that consists of an array of logic blocks which can be configured in a myriad of different circuit configurations. The logic blocks within FPGAs are composed of flip-flop circuits and Look Up Tables (LUT), among other various components. Whenever a user programs an FPGA, they generate a

bitstream which triggers interconnects that piece the desired logic blocks together. This architecture allows a user to generate hardware customized for a specific task. The many individual logic blocks in FPGAs allow for extensive parallel processing, which is advantageous when dealing with multiple data streams from sensors. Because of their large number transistors, FPGAs consume significant amounts of power to process information quickly and efficiently. FPGAs are programmed via a Hardware Description Language (HDL) such as Verilog or VHDL. These languages are complex and prove a significant challenge to debug [16]. Refer to *Table 3.1* for a summary of comparison between a microcontroller and FPGA.

**Table 3.1: Microcontroller vs FPGA**

*By Authors*

|                    | Microcontroller | FPGA       |
|--------------------|-----------------|------------|
| Power Consumption  | Preferred       | Acceptable |
| Parallelization    | Acceptable      | Preferred  |
| Peripheral Support | Preferred       | Acceptable |
| Programmability    | Preferred       | Acceptable |

Comparing the two choices, one must consider the specificities of our application. The Balloon Payload System (BPS) has a numerous amount of sensors, yet a finite amount of onboard energy. The target data acquisition rate is relatively low given the BPS will be collecting data from slowly-changing variables over a long period of time. With this in mind, the microcontroller clearly shows itself as the best option. Firstly, because it is less power intensive than an FPGA, this allows for a longer runtime, which is important as it is imperative that the BPS transmit its location for well after the expected mission duration. Although the BPS hosts many sensors and subsequently the microcontroller must process many data streams, heavy parallel processing is not needed, as the data will be collected between relatively large intervals. Therefore the data can be read and saved to storage sequentially without fear of missing important variables. Secondly, ease of programming and access to libraries is critically important. Given the short timeframe of this project, having to learn a Hardware Description Language, then write code for interfacing with our sensors, telemetry, and radio transceiver from scratch, then debugging that code with little to no support is not an option. In addition, a typical microcontroller has all communication interfaces built in for seamless connection to devices, whereas additional logic may be required to interface an FPGA to outside peripherals.

Now that a microcontroller has been selected as the main embedded controller for the BPS, a specific model must be chosen.

### 3.3.2 Microcontroller Selection

#### Selection Criteria

The microcontroller serves as the backbone of the Balloon Payload System (BPS). Therefore, it is crucial that this component is chosen with great attention to several key parameters that ensure a successful mission. These parameters are: Dhrystone or CoreMark scores, Power consumption, Flash memory size, RAM size, Peripheral connections, Programmability, and Solderability.

The Dhrystone benchmark is an antiquated program widely used by embedded systems manufacturers to characterize the performance of their microcontrollers. It was developed in 1984 by Richard Wiecker, and includes a mixture of different operations to tax the capabilities of the device under test. The Dhrystone rating is given as DMIPS or Dhrystone Millions of Instructions Per Second [\[17\]](#). The CoreMark benchmark is a modern program that was designed to replace the Dhrystone benchmark although both are still in use as of the writing of this document. The Coremark rating is given as the number of iterations per second a microcontroller can reach [\[18\]](#). Both the Dhrystone and Coremark benchmarks are important to the overall performance of the BPS, as they dictate how well the MCU can process data streams from multiple sensors. The higher the benchmark score, the more confident we can be that our MCU will perform well under load.

Power Consumption is the amount of power a microcontroller consumes during run time and idle. This metric is usually given as the amount of current consumed per clock speed of the microcontroller, and the power consumed at standby / idle. Low power consumption is crucial to the success of our goals. Lower power consumption allows for a longer runtime, which increases the overhead for our mission duration, and our recovery window.

Flash size is the amount of non-volatile memory the microcontroller carries onboard. This metric is usually given in Kilobytes for embedded systems. Flash size is important to us, as we need an ample amount of space to run a Real Time Operating System (RTOS) with a comfortable amount of overhead.

RAM size is the amount of Random Access Memory the microcontroller carries onboard. This metric is usually given in Kilobytes for embedded systems. RAM size is important to the proper operation of the BPS, as we need enough RAM for our microcontroller to function optimally.

Peripheral connections are how the MCU communicates with other devices. At a minimum, the MCU must be able to support the amount of devices on the BPS. Ideally, the MCU will be able to support a fair margin more than what we need. This allows overhead in case future iterations include additional peripherals.

Programmability refers to how many steps are involved in flashing and rewriting software to an MCU. Some chips require a custom bootloader to be installed before programming, while others can be flashed right off the line. The less steps involved in flashing the chip, the less chance of issues arising.

Solderability refers to how easy it is to solder the MCU, inspect the joints, and rework if necessary. Three factors determine how solderable any specific chip is: pin location, pin number, and pin pitch. Pin location is determined by package type; some common MCU packages are LQFP, BGA, and DIP. While LQFP and DIP packages have their pins on the outside edge of the chip, BGA packages have their pins underneath the chip. This renders the solder joints on the BGA package impossible to inspect without an X-ray. Pin number is another important factor, if the MCU has an excessive amount of unused pins, they will occupy valuable space on the PCB, pose a shorting risk, and take additional time to inspect. Pin pitch is the amount of distance between pins on the chip, the greater the distance, the less likely the pins are to bridge (short) between each other during soldering. In addition to this, greater pin distance also allows easy re-working in the event of a bad solder joint or solder bridge between two pins.

### **Raspberry Pi RP2040**

Raspberry Pi has no advertised Dhrystone or CoreMark scores for the RP2040, which makes it more difficult to compare against competing microcontrollers. Nevertheless, all the other important metrics are published in the datasheet [\[19\]](#). The RP2040 microcontroller sports dual ARM Cortex-M0+ cores, a clock speed of 133 MHz, and 256 kB of RAM.

Surprisingly, the RP2040 has no on-board flash memory, but rather has support for up to 16 kB of external flash via Quad Serial Peripheral Interface (QSPI). Having to rely entirely on external flash memory is not ideal, as this introduces additional connections on the PCB that could otherwise be inside the package. These external connections are more prone to damage via manufacturing or assembly errors. Additionally, an external flash chip would take up valuable PCB area.

Although the RP2040 relies on external flash, this drawback does not eliminate it from consideration, as it is an extremely capable microcontroller. Dual cores allows the RP2040 to move large amounts of sensor, communication, and camera data in a parallel fashion, although it also introduces programming and debugging complexity. The RP2040 datasheet states that the typical power consumption is 9.4 mA/MHz, which is relatively high compared to other microcontrollers.

The RP2040 contains a host of peripherals, including two UART ports, two SPI controllers, two I2C controllers, 16 PWM (Pulse Width Modulation) channels, a USB 1.1 controller, and eight PIO state machines. The PIO (Programmable Input Output) state machine peripheral is relatively unique to the RP2040. Each state machine is connected via FIFO (First In First Out) queues to main.c. PIO also utilizes DMA (Direct Access Memory) to read the RAM without going through the

processor, and IRQ (Interrupt Request) Flags [\[20\]](#). The PIO state machines have the potential to be extremely beneficial if we decide to utilize a peripheral device with an uncommon or proprietary connection.

Once placed on a custom board, the RP2040 can be programmed via Serial Wire Debug, and USB to UART. Raspberry Pi offers a custom debugger that supports both of these interfaces. In addition, Raspberry Pi offers a comprehensive guide on how to build a usb interface to program the RP2040 [\[21\]](#).

The RP2040 comes in a QFN-56 package which has 56 connections arranged around the perimeter of the chip. There are no pins, rather there are pads that lie under the edge and wrap up the side. The pitch between these pads is 0.5 mm. While this package is not impossible to visually inspect and rework, the fact that most of the pad is located under the chip will provide a challenge. In addition, the 0.5 mm pitch is dangerously close to the minimum which can be reworked in the senior design lab.

Overall, the RP2040 sports high processing power but at the cost of increased complexity and power consumption. It also requires external Flash to operate which introduces more design complexity and room for bugs. If a battery pack is chosen to compensate for the RP2040's appetite, a reliable external-flash design is implemented, and a solid OS is written, the RP2040 could prove to be an extraordinary performer.

### **Espressif ESP32**

The ESP32 is a unicorn in that it is based neither on the ARM or AVR architecture, but rather the Xtensa LX6 microprocessor, which is a proprietary design. Nonetheless, the ESP32 competes closely with its ARM and AVR rivals. The dual core model of the ESP32 sports a CoreMark score of 994.26, at a maximum clock speed of 240 MHz, 520 kB of RAM, and up to 4 MB of Flash memory. The ESP32 Datasheet states a maximum power draw of the dual core model of 68 mA at 240 MHz, which works out to 0.28 mA/MHz [\[22\]](#).

What sets the ESP32 apart is its endless peripheral connectivity, not only does it pack 2.4 GHz Wi-Fi connectivity and Bluetooth 4.2 capability, but also four SPI interfaces, two I2C interfaces, and three UART interfaces. In addition to these, it also contains a 12-bit SAR (Successive Approximation) ADC (Analog to Digital Converter) with support up to 18 channels, two 8-bit ADCs (Analog to Digital Converters), 10 touch sensor interfaces, one combination SD/eMMC/SDIO host interface (Secure Digital/embedded MultiMedia Card/Secure Digital Input/Output), and one combination slave SDIO/SPI interface. Continuing, it includes an Ethernet MAC interface, TWAI (Two Wire Automotive Interface), RMT (Remote Control Transceiver), Motor PWM and up to 16 channels of LED PWM.

A peripheral interface that is of use to this project besides I2C, SPI, and UART is the combination host SD/eMMC/SDIO interface. This interface would utilize the SD SPI host driver to communicate with multiple SD cards, which would be

beneficial for memory integrity via redundancy [\[23\]](#). In addition, drivers to communicate with eMMC are also provided, which allows the option to use eMMC if we so choose.

The ESP32 can be programmed with a simple USB to Serial converter. The most commonly used chip for this task is the FT232RL, designed and manufactured by Future Technology Devices International (FTDI). The simplicity of flashing the ESP32 has made it of popular use with the Arduino IDE, this in turn has fostered a large maker community that offers support to anyone getting started with the ESP32.

The ESP32 differs from most other processors as it is packaged on a fiberglass PCB in contrast to a sealed plastic package. This allows the ESP32 to utilize a WIFI / Bluetooth trace antenna. The PCB package utilizes castellated and plated edges with 1.5 mm spacing between pads. This not only allows plenty of room for rework and inspection, but thick PCB pads are also much more resilient to stress from reworking than a traditional surface mount package with protruding pins.

### **Atmel ATmega328P**

The ATmega328P is possibly one of the most popular microcontrollers available, a large factor of this is due to its simple 8-bit single-core AVR architecture. Given that the ATmega328P is not the most advanced among its peers, its Dhrystone Rating sags at a pitiful 0.01271122 DMIPS [\[24\]](#). Regardless, this little microcontroller still packs a variety of features, such as a built-in two-cycle multiplier for crunching numbers quickly, 32 Kbytes of Flash memory, 2 Kbytes of RAM, and a wide operation range of 2.7 to 5.5 Volts [\[25\]](#).

The ATmega328P really shines when considering power consumption, the datasheet claims 1.5 mA at 4MHz when operated at the 3V logic level. This yields a power consumption rating of 0.375 mW/MHz. The datasheet does not rate the power draw at the maximum clock speed of 16 MHz, which is only achievable when powered with at least 4.5V.

The ATmega328P does not offer many options when it comes to peripherals. The microcontroller sports 1 USART (Universal Synchronous and Asynchronous Receiver Transmitter) port, 1 I2C port, 6 PWM pins, an SPI interface, and an 8-channel 10-bit ADC. This sparse range of interfaces may prove the ATmega328P unusable for the BPS, as it would need enough physical connections to handle multiple telemetry sensors, atmospheric sensors, transmitting packets, etc. In short, the ATmega328P is a solid microcontroller in its own right, but between low processing power and limited peripheral connections, it is far from the best choice for our application.

Much like the ESP32, the ATmega328P only needs a USB to Serial converter to be flashed with a program. In addition, an Arduino Uno R3 board can be used as a converter given its own ATmega328P is removed. The simplicity of the ATmega328P, means that programming it on a custom board will not be an issue.

All one has to do is either implement a USB to Serial converter on the main board, or use a standalone converter over a UART header.

The ATmega328P comes in multiple packages. The easiest to solder is the 28-pin DIP package, which uses through-hole 2.54mm spaced pins. This package is so large that it can be easily soldered by hand, on the downside it takes up a significant amount of board space. An alternative package is the 32-pin TQFP which places the pins around the edge of the device, and uses a 0.5 mm pitch.

### **NXP i.MX RT1062**

The NXP i.MX RT1062 is best known as the MCU that powers the Teensy 4.1 development board. The Teensy 4.1 is known as the most powerful board that can be used with the Arduino IDE and subsequent libraries. The i.MX RT1062 runs a single ARM M7 core at 600 MHz, which yields a CoreMark score of 2314 - more than twice as high as the dual core ESP32 [\[26\]](#). The i.MS RT1062 packs 1 MB of RAM, yet like the RP2040, this MCU has no onboard Flash memory. However, there are plenty of options for connecting external Flash, such as SDRAM, SLC NAND Flash, Parallel NOR Flash and Quad SPI Flash with XIP support [\[27\]](#).

Despite its brute speed, the i.MX RT1062 does not consume an excessive amount of power - at full speed (600 MHz), the screaming single core chip consumes approximately 74 mA, which works out to approximately 0.123 mA/MHz [\[28\]](#). This number is surprisingly lower than the ESP32, especially given the fact it boasts a much higher CoreMark score.

The i.MX RT1062 affords endless peripheral options: two USB 2.0 controllers, two Ultra Secure Digital Host Controller (uSDHC) interfaces, two Ethernet controllers, eight UART modules, four I2C modules, four SPI modules, and two flexCAN modules [\[27\]](#). With such a plethora of options, the i.MX RT1062 allows plenty of headroom for future revisions where additional sensors or communication modules are needed. Unfortunately, there is a downside to having so many peripheral connections. The i.MX RT1062 only comes in a 225 pin BGA package, which is not only difficult to solder, but also diagnose. The pins in a BGA package are positioned below the chip, making it impossible to visually inspect for solder bridges between pins or inadequate connections. While the i.MX RT1062 is an incredible microchip, for this reason, it is not suited for amateur design projects.

The i.MX RT1062 handles programming a bit differently than the previous MCUs. Based on one of its most common applications as the heart of the Teensy 4.1 development board, the i.MX RT1062 can be flashed straight over USB with no converters. In addition to this, PJRC (the makers of Teensy) offers an ad-on for the Arduino IDE dubbed *Teensyduino* which allows one to flash programs straight from the Arduino IDE [\[29\]](#).

The i.MX RT1062 falls woefully short of its competitors when it comes to packaging. This MCU utilizes a 225-pin BGA package, which hides an astronomical number of pins deep under the chip. Not only does this eliminate the possibility of inspecting solder joints with the naked eye, but it also makes reworking impossible. If there is a significant issue after soldering the chip, the only way to solve it with the resources in the senior design lab is to re-solder it and pray all the pads align with no solder bridges.

### **STMicroelectronics STM32F446**

The STM32F446 (like the i.MX RT1062) is another single-core heavy hitter. Based on the ARM Cortex-M4, it clocks out at 180 MHz and sports a CoreMark score of 608. Better yet, the STM32F446 packs up to 512 Kbytes of *on board* Flash and 128 Kbytes of RAM with no need for external chips. The STM32F446 is competitive when it comes to power consumption, reaching values as low as 0.2 mA/MHz during run mode. The STM32F446 packs 20 different peripheral interfaces, including up to four I2C busses, up to four USARTS, up to two UARTS, up to four SPIs, two CAN busses, an SDIO interface, and USB 2.0 [\[30\]](#).

Although the STM32F446 ranks lower than the I.MX RT1062 in terms of its CoreMark score, it comes in a variety of LQF packages which makes it much easier to solder and diagnose. All the pins lay on the outside of the chip, allowing for each solder joint to be visually inspected and probed during troubleshooting. Most importantly, STMicroelectronics offers a development board patterned after the Arduino Uno R3 (NUCLEO-F446RE) which features the STM32F446. This allows for rapid prototyping and verification that our peripherals will work with the microcontroller.

When it comes to programming, the STM32F446 is an odd bird. Instead of relying on a USB to Serial converter, ST Micro offers their own ST-Link which supports the Joint Test Action Group (JTAG) protocol and Serial Wire Debug (SWD) [\[31\]](#). The ST-Link communicates directly with ST Micro's own Cube IDE which makes programming any of their chips in that method quite easy. Unfortunately, complexity arises when one uses other IDEs besides the Cube IDE. For example, if one wishes to use the Arduino IDE, they must first pay special attention to which parameters they select for uploading to the MCU, otherwise bugs will develop [\[32\]](#). In addition, some STM32 chips (such as the F446) do support programming directly over USB, but this requires the Cube IDE to first flash the proper bootloader [\[33\]](#).

### **3.3.3 Microcontroller Decision**

Refer to *Table 3.1* for a comparison of the aforementioned MCUs. The group decided to use the ESP32 for three reasons: onboard flash, programmability, solderability, and low power consumption. This may be confusing, as the i.MX RT1062 and the STM32F446 beat the ESP32 in several other categories. While this is true, the solderability and programmability of the ESP32 weighs much heavier on the final decision than performance and peripheral numbers. The ESP32 also boasts the largest on-board Flash size by a wide margin, almost

eight-times larger than the STM32F446. On top of that, it has the second highest Coremark score, the second largest on-board RAM bank, the second lowest price, and one of the lower power consumption metrics. In summary, the ESP32 is the best choice for our brand new design, as it not only supplies sufficient computing power to handle all our sensors, but it also is straightforward to program, is easy to solder, and has a large pool of peer-to-peer support.

The specific ESP32 model chosen was the ESP32-WROOM-32UE-N4. This particular model does not have an onboard WIFI / Bluetooth antenna, as wireless functionality is not a requirement of the Balloon Payload System. This is one of the most powerful ESP32 models, it sports dual cores, 520 kB of RAM, a maximum clock speed of 240 MHz, and all the peripherals. This certain model also offers up to 16 MB of RAM, we opted for 4 MB as this was more than enough for our application.

**Table 3.1. MCU Comparison**  
*By Authors*

|                             | RP2040 | ESP32  | ATmega328P | i.MX RT1062 | STM32F446 |
|-----------------------------|--------|--------|------------|-------------|-----------|
| <b>CoreMark</b>             | NA     | 994.26 | NA         | 2314        | 608       |
| <b>Dhrystone</b>            | NA     | NA     | 0.0127     | NA          | 225       |
| <b>Flash Size (Onboard)</b> | 0 kB   | 4 MB   | 32 kB      | 0           | 512 kB    |
| <b>RAM Size</b>             | 256 kB | 520 kB | 2 kB       | 1 MB        | 128 kB    |
| <b>USB 2.0</b>              | 0      | 0      | 0          | 2           | 1         |
| <b>USB 1.1</b>              | 1      | 0      | 0          | 0           | 0         |
| <b>UART</b>                 | 2      | 3      | 0          | 8           | 2         |
| <b>USART</b>                | 0      | 0      | 1          | 0           | 4         |
| <b>SPI</b>                  | 2      | 4      | 1          | 4           | 4         |
| <b>I2C</b>                  | 2      | 2      | 1          | 4           | 4         |

|                                |        |             |             |               |              |
|--------------------------------|--------|-------------|-------------|---------------|--------------|
| <b>CAN</b>                     | 0      | 1           | 0           | 2             | 2            |
| <b>SD Card Interface</b>       | 0      | 1           | 0           | 2             | 1            |
| <b>Programmability</b>         | Medium | Easy        | Easy        | Medium        | Difficult    |
| <b>Solderability</b>           | Medium | Easy        | Easy        | Difficult     | Medium       |
| <b>Power Consumed (mA/MHz)</b> | 9.4    | 0.28        | 0.375       | 0.123         | 0.2          |
| <b>Cost Per Unit (\$)*</b>     | 0.70   | 1.00 - 6.79 | 1.52 - 3.03 | 12.56 - 18.79 | 7.23 - 11.48 |

\*Prices on Digikey as of 7/21/2024

### 3.3.4 Temperature Sensor Technology Selection

Temperature is by far the biggest concern in regards to atmospheric conditions as well as the operation of the BPS during its voyage. Temperature differentials are related to the final air pressure, humidity, wind speed. Any large change in temperature entails a change in these other conditions, not the reverse. For example, an uneven heating of the earth's atmosphere causes a temperature gradient, this causes a change in air pressure and this difference in air pressure causes a heat transfer via a change in the wind. Additionally temperature affects how much water can be held by the air, which is humidity. Additionally, many electronics are going to be affected by the temperature change from the ground to the stretch goal of 100,000 feet. Liquids will freeze, electrical components may stop working, certain batteries can rupture as well. On a hot spring or Summer's day in Florida, the temperature could range from -68C° to 30C°. The complication mainly arrives from the back end as the operating temperature range for many of these sensors will only go as low as -40C°. Thus, the biggest concern of a temperature sensor will likely be a large operating range, followed by a high accuracy. The other main concerns are resolution and durability. Most Thermometers will not add significant weight or size.

#### Thermocouples

Thermocouple technology is based on fusing two metals together and using their intrinsic potential differences in heat to determine temperature. Thus their range is highly dependent on the metals Chosen (Engineering, O, *What is a Thermocouple*). Different measurement ranges exist depending on the metals used. Fortunately, nearly all options have a measurement range that is within our

upper limit. However, we are more concerned about lower temperature values, particularly if we plan to meet our stretch goal of 100,000 ft where temperatures are likely to go as far as -60 C°. Here is a table of the Thermocouple materials and their ranges

**Table 3.2. Thermocouple Material Types**

*Authors: (Watlow, n.d.)*

| <b>Thermocouple Type</b> | <b>Useful/General Application Range</b> | <b>Notes</b>                                                                                                                    |
|--------------------------|-----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|
| <b>B</b>                 | 1370-1700°C<br>(2500-3100°F)            | Easily contaminated, require protection.                                                                                        |
| <b>C*</b>                | 1650-2315°C<br>(3000-4200°F)            | No oxidation resistance. Vacuum, hydrogen or inert atmospheres.                                                                 |
| <b>E**</b>               | 95-900°C<br>(200-1650°F)                | Highest output of base metal thermocouples. Not subject to corrosion at cryogenic temperatures.                                 |
| <b>J</b>                 | 95-760°C<br>(200-1400°F)                | Reducing the atmosphere is recommended. Iron leg subject to oxidation at elevated temperatures--use larger gauge to compensate. |
| <b>K**</b>               | 95-1260°C<br>(200-2300°F)               | Well suited for oxidizing atmospheres.                                                                                          |
| <b>N</b>                 | 650-1260°C<br>(1200-2300°F)             | For general use, better resistance to oxidation and sulfur than Type K.                                                         |
| <b>R</b>                 | 870-1450°C<br>(1600-2640°F)             | Oxidizing atmosphere recommended. Easily contaminated, require protection.                                                      |
| <b>S</b>                 | 980-1450°C<br>(1800-2640°F)             | Laboratory standard, highly reproducible. Easily contaminated, require protection.                                              |
| <b>T**</b>               | -200-350°C<br>(-330-660°F)              | Most stable at cryogenic temperatures ranges. Excellent in oxidizing and reducing atmospheres within temperature range.         |

The Type, or letter, of Thermocouple will categorize the sensor beyond just range. For our purposes, we are interested in two factors, the range and the Thermocouples resistance to oxidation. There are parts of the atmosphere with much more oxygen than others, and as Thermocouples rely on metals exposed to it, preventing oxidation is important to maintain a long lasting sensor with accurate readings. A type T is the most important for a standard or high altitude launch due to its huge temperature range as well as having the best oxidation resistance of all the types. Type E, K, J and N are possible, yet undesirable choices for a low altitude launch since they mainly focus at higher temps, but can operate out or interested ranges. The other options, B, S, R, and W-5 all are very sensitive to exposed oxygen and will likely oxidize our sensor much quicker than what can reasonably be accepted.

Thermocouples are inexpensive and robust, with a large range of temperatures available. The tradeoff is thermocouples are less accurate than other technologies. (Atmospheric Engineering, O, *Working principle*). However, accuracy is important, as long as we are within the specification of  $0.5^{\circ}\text{C}$  while within its measurement range, this is still very viable for our purposes. Since this is atmospheric data, small deviations in temperature will not hinder the insight of the collected data for a couple reasons. Firstly, The temperature data we are gathering will not be used for any other engineering control within the system. Second, this data is used for reporting the atmospheric conditions as is, and wont be used for further quantification, like how one can use something like the heat from a chemical reaction to measure reaction efficiency and will not be used in a line of mathematical analysis that is sensitive to small errors. The final consideration is the purchase of the device itself. Ideally a small surface mount device is desired. This optimizes for space, ease of operation, and how well secure the probe is. However, most thermocouples come in larger bulky components. This means the installation and operation of the probe is going to be more difficult than for example, the thermistor, and RTD.

### **Resistance Temperature Detectors & Thermistors**

Both of these technologies work on the same principle. Therefore the environmental factors affect them mostly in the same way. RTDs and thermistors differ in their material construction and objective function (Nihal K, 2022). Because RTD are usually made up of 1 material, such as platinum, they are linear over a large range of values. As noted, the operating range is the most desirable quality to have. However, the trade off here is that an RTD will be the most expensive option on the market, compared to other temperature sensors. If budgetary restrictions allow. Out of all the technologies, this is likely to be the most desirable option for high altitude launches. Since a thermistor comes from a mix of at least two metals, they are designed with high accuracy in mind. While thermistors are often designed to be much more accurate than RTD's this is at the cost of having a narrower measurement range. For our stretch goal, a higher linear operation range is preferable over an extremely high sensitivity or accuracy.

However, for our test launch or future lower altitude launches, a thermistor could be a more desirable choice. If our project were to be launched on a hot Floridian summer day, the temperature could be around 37 C°. For the demonstration purposes the temperature is unlikely to change much beyond that, but, as mentioned previously, if our product goes high enough up in the atmosphere, the temperature may decrease to -60 C°, which is almost a 100 C° change. If we were to pick a thermistor over an RTD, we would likely see a less accurate product overall due to taking readings so far outside our linear range. A more customizable model reading values at a consistent height would prefer a thermistor. However, the linear operating range of thermistors will never be linear at extreme hot or cold values, leaving the choice of a thermistor highly dependent on the season and altitude of interest.

### **IR Sensor**

IR Temperature sensors, which became popularized in the Covid 19 pandemic is perhaps the most unique technology. There are no metallic junctions, or exposed metallic leadings. They are robust and don't use fragile parts and could survive an impact from the landing of the parachute without worry. The most unique advantage, which is why they saw mainstream use in 2020, is that IR temperature sensors are non contact. There is no need for any physical connection to the object of interest. There is no need to consider oxidation resistance, or other inclement conditions which cause damage to the components.

This advantage, in this case, is the biggest weakness and other drawbacks exist as well. Firstly, We are reading ambient heat from the atmosphere, rather than the surface from a physical object. IR temperature sensors are very ineffective for this purpose (STANMECH, n.d). The only possible design is to add a reading point for the balloon. Such a point would need to be a material that could match temperature with the air, or a high thermal conductivity, without being affected by Sun's rays, or or be shaded. Additionally, all other technology has made it easier to find and purchase surface mount devices. These are bulkier and require much more manual effort in the securing and calibration. While there are many fantastic applications of IR, for our needs any possible design would yield no overall advantage for us, removing this from consideration entirely.

### **Bimetallic Strips**

Bimetallic Strips are created by connecting two different thin metal strips together. Unlike the thermocouple, which uses a thermoelectric property, Bimetallic strips utilize the metal's expansion coefficients, a thermomechanical property. (WIKA USA, n.d.) This technology is often found in heavy machinery and at home HVAC systems, mainly due to there cost and that there relatively narrow range is fo the ranges that people want a building set at

Bimetallic Strips are unique in the sense that they are purely mechanical. Thus, the operation requires no power source as opposed to the other technologies which require some method of electrical reading as an output. In this project,

there is no special need for this functionality, and the mechanical signal would be converted into an electrical one regardless. They are very cheap due to the simplicity in its design (Engineer's Academy, 2018). The biggest flaw in bimetallic strips comes from interferences in high vibrations from outside the system. The BPS in higher altitudes is likely to experience high winds, thus it is likely that this shaking could harm the efficacy of the reading.

### **Semiconductor Sensors**

Semiconductor Sensors encompass p-n junction and MOS sensor technologies. These devices operate by using the change in their IV characteristics to determine temperatures. The p-n junctions do this by using two diodes and comparing the difference in voltage between them. These sensors are very cheap, relatively inaccurate, and slow to respond compared to other technologies. However, they are very notable in that this is technology used by most manufacturers when it comes to packaging IC, rather than just the sensor. An IC will already have additional functionality such as I2C communication, or analog to digital conversion but in, leaving the interfacing of the sensor with the system significantly easier.

While a more indepth evaluation will be done when looking at manufacturer options, it is important to note here that an IC is very desirable for all sensors, not just for temperature. While each sensor has qualities, such as accuracy or range that is important, at the systems level, trading simplicity and ease of production/installation, at the cost of accuracy only as long as we remain within our specifications is the most important aspect.

### **Technology Choice**

Most choices are viable for our BPS. The IR is out due to its inability to read ambient temperatures. If this were not the case, it would certainly be higher on the accuracy value. The bimetallic strips are also removed from consideration. The main advantage is their cheap cost and tolerable low operating range. The main concern is the sensitivity to shaking. It's possible that the BPS will experience less shaking and vibration and will mostly move the wind in a smoother fashion, but the cost isn't nearly as much of a concern once the fact that every performance metric is dead last, excluding the fact that IR limitation on ambient temperature.

Between the rest of the technologies, the RTD is going to be the choice of interest. The biggest performance factor is the operating range, and the thermocouple, type T and some type K's, have this. However, RTDs have by contrast the 2<sup>nd</sup> strongest best range. Firstly, the components themselves are not going to be surface mount components. The interfacing of the sensor to the hardware should be as simple as possible and it is not difficult to find a couple of different low temperature RTD sensors going as low as -55°C or -60°C RTD's. As long as the range is within what we expect the temperature to be, then we aren't concerned beyond that. Thus the surface mounted RTD's are better. Second, the

performance of the RTD in other aspects is higher. The accuracy and resolution is much more stable, and while it may be more expensive and have a slower response time, our readings will likely be about a minute long and the response times of the different technologies are rated from microseconds to seconds at the slowest. Additionally, changes to temperature in the atmosphere is not extremely drastic so the response time won't need sudden large changes.

**Table 3.3. Temperature Technology Choice**

| Technology     | Operating Range | Acc.      | Res.      | Response Time | Cost      |
|----------------|-----------------|-----------|-----------|---------------|-----------|
| Thermocouple   | Best            | Good      | Good      | Best          | Good      |
| RTD            | Great           | Excellent | Excellent | Good          | Good      |
| Thermistor     | Not Good        | Best      | Best      | Great         | Excellent |
| IR             | Excellent       | Terrible* | Good      | Best          | Bad       |
| Bimetallic     | Limited         | OK        | Limited   | Limited       | Best      |
| Semiconductors | Good            | Good      | Good      | Good          | Good      |

*\*Ambient Temperatures only*

### 3.3.5 Temperature Sensor Part Selection

The PTS0603M1B100RP100 and PTS080501B100RP100 are both very similar RTD's made by Vishay. They are an almost identical datasheet. Their distinction is that they are a 603 and 805 model. The 603 is cheaper but has higher measuring current draw. The 805 has a couple different versions, including a 100 and 500Ohm variant. However, even the 100Ohm variant has a smaller measuring current, advantageous for power limitations, but is more expensive. While the thermal response time is slightly higher for the 805, at worst it is a 0.5 second difference, so it is negligible for the frequency of our readings

The 32208548 is a through hole component made by YAGEO. This version is the 100 Ohm, Class F0.3 (B). This variant is important as this is the -70°C version, which is why this part stands out. A surface mount is preferred in general for ease of use, however, the sensor itself in a through hole is a distance away from the board, which keeps it surrounded by the environment more. Ideally more surface area contact to the environment is better for response times, but a surface mount component would generally be able to withstand a landing better.

Accuracy is not listed, rather stated to be IEC compliant, either as a class B thermometer in the case of the PTS components, or an f 0,3 in the case of the

32208548. While not listed on the datasheet, the IEC 60751 standard is often used for these parts and the class designation is listed on the component name/designation. Resolution of the parts is dependent more on the ADC conversion, so resolution is not listed on any of the parts.

It's important to strike a balance between performance and convenience for parts. The Vishay parts are surface mounted but have a 15°C operating range difference on the low end. While the 32208548 has the most comfortable range. Between the extra cost and the through hole, we will be going with the PTS0603M1B100 RP100 Vishay model for it has the best performance per cost.

**Table 3.4. Temperature Sensor Part Selection**

| Component                      | Accuracy  | Resolution | Power Consumption | Operating Range | Cost   |
|--------------------------------|-----------|------------|-------------------|-----------------|--------|
| <b>PTS0603M1<br/>B100RP100</b> | +/- 0.3C° | N/A        | 0.1-0.5mA         | -55-175C°       | \$2.38 |
| <b>PTS080501<br/>B100RP100</b> | +/- 0.3C° | N/A        | 0.1-1.0mA         | -55-175C°       | \$2.52 |
| <b>32208548</b>                | +/- 0.3C° | N/A        | 0.3-1mA           | -70-500C°       | \$3.12 |

### 3.3.6 Air Pressure Sensor Technology Selection

Barometers come in two main designs, mechanical and electrical. The mechanical versions include the Mercury and Aneroid Barometer, while the electrical versions include Piezoresistive and Capacitive Barometers. Air pressure. As altitude increases, air pressure decreases for 2 reasons. First, the temperature is much colder at higher altitudes. This is because the earth's surface can absorb much more heat from the sun than the air can while the air is also responsible for reflecting heat and light back into space. Second, the density of air also decreases at higher altitudes, leaving much less air to cause large air pressure changes. Unlike the temperature thermometer measuring and operating ranges, The range of air pressure under atmospheric conditions will never go high enough to threaten the balloon's operational ability, nor is it likely to saturate the air pressure sensor, while a lower end reading in the worst case scenario will be below detection limits. Thus the focus of the air pressure sensor will be with respect to resolution then accuracy with an emphasis on low level readings.

#### Mercury Barometers

Mercury in thermometers are largely banned in the US due to their toxicity. Instead, the barometer's design would need to contain a different liquid to overcome this issue. Mercury was used over water due to size constraints. Water is a much lighter liquid so it is affected by very small changes, while this means the sensitivity increases, that main column size also largely increases (Lu, 2022). Thus the original design switched to mercury to avoid a column that was meters

tall. However, most “Mercury Thermometers” used in the current world are alcohol, usually isopropyl.

Mercury thermometers in a BPS application would be challenging. Mercury accuracies are on par with other types, so the main advantage is that this is a purely mechanical system based on liquids (Davies, 1986; 1). Thus no external power is required to operate. Since the BPS has no engine or other propulsion system, the extra weight won't increase power consumption anywhere else either. However, since the results need to be transmitted to a base station, an electrical output is preferred as the signal will be sent to the base station along with all the other atmospheric data. Additionally, the sensor needs a stable platform, a relatively large amount of space, and will likely weigh more than all the other options. The extra space will also make proper insulation difficult if not impossible. However, the two biggest problems are the temperature and stable platform. With unpredictable wind speeds, the payload could shake quite a bit, leading to responsibility issues and the landing may break the barometer entirely. Finally, the liquid could simply freeze at high enough altitudes where the atmosphere gets extremely cold. To the final point, an Isopropyl system won't freeze until almost  $-90\text{ }^{\circ}\text{C}$ , but most other liquids will. However, the density of mercury,  $15.6\text{g/cm}^3$  is over 15 times more dense than isopropyl alcohol,  $0.786\text{g/cm}^3$ , a large sacrifice in size will need to be made. In summary, while this barometer is a given good low altitude cost effective barometer for a static location, it would be a poor choice in this weather balloon or similar products.

### **Aneroid Barometers**

While mercury thermometers are liquid mechanical systems, aneroid barometers are non liquid mechanical systems. A metal capsule which expands in response to air pressure and the output is a dial movement. Since there are no electrical parts involved, there is no power used in the operation of the sensor. Aneroid Barometers will not have the same size constraints, nor will it falter as much to temperature. It will not be as fragile as a mercury thermometer and can operate at higher wind speeds.

The biggest flaw is that the output generated will need to be converted into an electrical signal in order to transmit it. There are no engineering controls in the system that require the monitoring of air pressure, so no mechanical signal is ever necessary for successful operation. For signal processing, it is much more convenient to use an electrical design, such as the piezoresistive or capacitive technology. Even if an aneroid barometer were to be used, the design would be to use another passive pressure sensor to read the aneroid barometer. This design would be very awkward, it would be just as easy to cut the aneroid barometer out entirely.

### **Piezoresistive/Piezoelectric Pressure Sensor**

The piezoresistive sensor turns a mechanical strain into an electrical resistance change (Avnet Abacus, Piezo, n.d.). This option is the least affected by temperature thus far, assuming the thin film that is put under pressure is

temperature resistant. The piezoresistive sensors are highly accurate with a good resolution. The two biggest flaws are the power consumption and operating temperature. Most other sensors need to be powered in order to read the signal. The piezoresistive sensors need to power a circuit in order to establish an electrically active environment, where you can calibrate the electrical resistance. Then you measure the change of that resistance meaning that this is always drawing a steady stream of power (Avnet Abacus, Capacitive Vs Piezo, n.d.). IN the case of most other sensors, the difference in the power consumption between most sensors is important as it is important to have an accurate prediction of how much power the device will have, but most sensors can be turned off between polling so the difference can be lessened majorly, but in this case. The sensor may cause a significant impact on the battery Since the BPS is expected to be fully self-sufficient in power during its flight time and retrieval, or risk not being able to find the BPS, the extra power consumption may require a higher capacity power source. If this were to be used, the best way to deal with this concern would be to use the sensor, then shut it down and no longer read after either a set time has passed, or a battery threshold has been reached. Additionally, this technology is based on the changing of resistance. However, there were multiple temperature sensors that utilized phenomena related to temperature and resistance to find temperature. These same factors will also apply to a piezoresistive system, making it less than ideal for operation at lower temperatures. While unlikely to break, the readings will be less accurate the higher the payload is while in the atmosphere. Thus, even the simple calibration would be difficult to do.

There are also piezoelectric pressure sensors. These sensors measure electric potential as opposed to resistance. Rather than a resistor, such as a wheatstone bridge, crystals, such as quartz, are used as they generate more pronounced dipoles than silicon upon pressure (Flanagan 2023). These have similar advantages and disadvantages. However, there is one big advantage that may be considered. The use of a crystal such as quartz means that it is less likely to be affected by temperatures.

### **Capacitive Pressure Sensor**

Capacitive sensors are among the cheapest and simplest designs for the electrical sensors. With a passive design, and simple mechanical configuration. Thus the sensor needs no power beside the reading of the signal, which helps with power consumption. While the flight time of the balloon is expected to be only a few hours, the unpredictability of the landing means that determining the length of time the balloon needs to be powered is tricky, unless a separate power source were to be used for the telemetry and communication which is far from a desired solution. The sensor works well under a wide range of temperatures. The first flaw in this sensor is its range of linearity is small when compared to its competitors (Avnet Abacus, Capacitive vs Piezoelectric n.d.-a). Fortunately, these high pressures are values of 70MPa or 100,000 psi. As for the lower end, they have no problems reading extremely low air pressure and can even be used in vacuum conditions.

### Technology Choice

The mercury barometers offer no benefits no matter the launch due to the major constraints associated with weather balloons, including the movement, size limitations, and possible freezing of the liquids within the system. The Aneroid Barometer lacks many of the limitations of the Mercury Barometer, but is still problematic due to the extra need of converting the mechanical signal into an electrical one. If the data wasn't going to be stored and sent via wireless transmission, but rather viewed in real time, this barometer would have been a very good choice.

While a piezoresistive/piezoelectric sensor is more accurate, the capacitive circuit has several advantages. For a low altitude launch, a piezoresistive sensor would be the better option to maximize your data quality. However, the temperature interference associated with higher altitude launches would make the capacitive sensors the better alternative. The Piezoelectric is the best, as, but the highest cost, typically more than the Piezoresistive. It is worth mentioning that the operating range column is relative to our purposes. Capacitive Sensors do not have a larger overall operating range, but since we are concerned with high altitude, low pressure readings, the capacitive sensor is the best for this environment. Ultimately, the decision will be to use a Capacitive Sensor.

**Table 3.5. Pressure Technology Choice**  
*By Authors*

| Technology  | Accuracy | Resolution | Operating Range | Cost  | Temperature Resistance |
|-------------|----------|------------|-----------------|-------|------------------------|
| Mercury     | Average  | Average    | Limited         | Great | OK                     |
| Aneroid     | Good     | Average    | Limited         | Best  | OK                     |
| Piezo (E/R) | Best     | Great      | Great           | OK    | Best                   |
| Capacitive  | Great    | Best       | Best            | Great | Great                  |

### 3.3.7 Capacitive Pressure Sensor Part Selection

Our three choices are the ICP-10101 from TDK, or two separate models, the BAO1 and BAO3. All three can operate within the same temperature Range. One almost unfortunate feature of the TDK model is that it can't run above 2.16V and, while very good accuracy, is not rated for the low pressures we need. Thus this part cannot be used Between the 01 and 03 models, the lower end is the same, around 10 mbar, while the higher end is 1200 mbar for the 03 and 2000 mbar for the 01. The air pressure on the ground is around 1050 mbar, so the lower range will be fine. That also means the higher accuracy of the 03 model can be chosen without sacrificing our range. Initially, our choice was the MS560702BA01-50.

However, every website seems to require purchases in bulk. At the cheapest, a minimum of 10 sensors on digikey which comes at a cost \$70.06.

**Table 3.6. Capacitive Pressure Sensor Part Selection**  
By Authors

| Component       | Accuracy (Pa) | Resolution (Pa) | Pressure Range (mbar) | Cost (\$) |
|-----------------|---------------|-----------------|-----------------------|-----------|
| ICP-10101       | +/-1          | 0.01            | 30-1100               | 3.67      |
| MS560702BA01-50 | +/-0.8        | 0.01            | 10-1200               | N/A Bulk  |
| MS580301BA03-00 | +/-0.8        | 0.01            | 10-1200               | N/A Bulk  |

### 3.3.8 Humidity Sensor Technology Selection

Humidity Sensors detect the amount of moisture in the air, typically in a percent of water in the air, to the total amount of water the can can hold. This present is usually bounded between 0%-100% and is called Relative Humidity. But it is possible to be higher.

The most important factor that causes humidity is geography. Locations near water tend to have higher humidity. This is because the water, lake, sea, or ocean, will absorb the sun's energy and evaporate, mixing with the air. The more of earth's surface area covered by water, the more water that evaporates and the higher the humidity. The second largest factor is temperature, the more the sun shines, the more heat is absorbed by the earth, causing more evaporation, therefore the higher the humidity, but only when there is water access.

A good example of this is Florida, which has lots of sunlight, and is a narrow peninsula that tends to be very humid. A good example of these factors is comparing Florida, Nevada, and many places in Canada. Floria is both hot and has access to plenty of rainfall. All the water and heat causes a large amount of evaporation which creates humid conditions, but it also causes a lot of rainfall. This rainfall will then carry water inland, causing high humidity to exist in Central Florida, such as Orlando, rather than just at the coastline like Melbourne and Tampa. But Nevada on the other hand is very hot. However, it is very far inland and most places, such as the Mojave Desert, has very limited access to water. Therefore even though it is very hot, it is a dry heat. Much of Canada is cold, especially in the winter. However, even in these cold conditions, the amount of water, or snow, that blankets the surface causes high humidity.

For the BPS, a rise in altitude will relate to a drop in humidity, for three reasons, the first is access to water, as water is more abundant on the Earth's surface. Second is temperature as the Earth's surface also absorbs more heat. Finally is the amount of air. The air is much thinner as altitude increases, as discussed under the air pressure sensor section, thus the evaporated water has less particles to attach to. Thus our sensor will want to have a general focus for linear low range values, much like air pressure. However, unlike air pressure, humidity

has a big interference in the form of clouds. Clouds, in terms of humidity, are supersaturated, or above 100%. With no control over the balloon's movement, it is likely to encounter multiple clouds, as well as high humidity from rain. While a low value measurement range is still very important, any sensor launched must be able to maintain functioning and recovery quickly from passing through a cloud; the focus of these sensors will be on saturation recovery, responsiveness, followed by accuracy and operating range.

### **Capacitive**

Capacitive Humidity sensors have a similar design to the capacitive pressure sensors and as such share many of its benefits and drawbacks. Capacitive humidity sensors are the most common humidity sensors. They have a wide measurement range and operating temperature ranges. They are robust and compact so they will be able to survive multiple landings in unfamiliar conditions and help keep the payload size small.

The sensor works by measuring the changing capacitance within the dielectric layer and the response time is based on how quickly moisture is absorbed and expelled for the layer, which is very fast compared to other technologies allowing for quick measurements and recovery well from highly saturated levels. This recovery ability is key as the BPS can't be controlled and avoiding clouds is impossible. The biggest drawback is that high accuracy can be difficult to come by. Since humidity tends to decrease with altitude and we are dealing with lower values, error will be less impactful, when compared to higher value readings. For instance, let's say there is a 50% error in reading at a particular time. If the readout values are low, such as 5, then the true value is within the range of 2.5-7.5. But if the readings are 80, then our range is 40-120. Thus a sacrifice of accuracy for a good responsibility is a beneficial outcome.

### **Resistive**

The resistive humidity sensor is realized using metal electrodes exposed to the environment when humidity sticks to the surface, the water that attaches causes the resistance of the material to change (Anusha, 2024b). Thus all the same problems associated with temperature are present. Resistance is affected by temperature. A calibration can be done on the ground, however, changing the temperature will throw the calibration off. Operating temperature is the condition the sensor will be able to run effectively in. The effects of temperature are captured during a run, but changing the temperature changes the based conditioning that were accounted for during the calibration. Thus the operating range doesn't mean the one calibration should be done and it will be as accurate as long as you stay within that range.

These sensors are very low cost and compact, just like the capacitive ones. The relationship between humidity and resistance is an exponential one, so these sensors are very sensitive as well. The major drawback to these sensors is that they are highly susceptible to contaminants. There is no way to clean a sensor once it's been launched. When up in the air, it is possible to go through closed,

which is essentially water attached to dust in the air(Pomelo, 2022). If the sensor is very sensitive to these interferences, it could lead to highly unreliable readings. Additionally, the operating range is limited between 5%-90%. This range is very undesirable as we expect to spend a significant amount of time either under 5%, at high altitudes, or above 90%, from clouds. Even though the accurate reading of the clouds is not of concern, less than 5% readings will be far too high an amount for an acceptable limit of detection. Thus if the cost of the sensor is not out of budget, a capacitive sensor is the preferred choice between the two.

### **Thermal Conductive**

One of the unique qualities of thermal conductive humidity sensors is that they measure absolute humidity rather than relative humidity (Kverh, 2020). Relative Humidity is how much water vapor is in the air as a percent of the total amount of water vapor that could be held by the air. So a 30% relative Humidity (RH) means that the amount of water held by the air is thirty percent of being completely saturated. Absolute humidity tests humidity in a given volume of air. It is expressed as a density such as ( $\text{g/m}^3$ ) and is used mainly in HVAC and similar systems.

The benefits of this sensor includes a superior resolution to other options, highly durable and won't be affected by very high temperature. These sensors work by using two thermistors. One of them is a reference point and is sealed in an airtight case filled with nitrogen such that the inside of the case is completely dry, while the other reads the environment. This is important, because a reference in a nitrogenous environment means we would need to test in a nitrogenous environment and they are meant to compare the humidity for completely nitrogenous environments (Anusha, 2024b).

Thermal Conductive sensors provide few advantages and many drawbacks. The resolution is superior compared to the other technologies. The durability is also nice as there will be a limit to how gentle this payload's landing can be. On the other hand, humidity in the atmosphere is usually desired in the relative form and every weather station report you see will use this metric. Absolute humidity is typically used in HVAC systems as the building has a defined volume of each room. The other problem is that the air is a complex matrix with many types of gasses. While Nitrogen is the most common gas, the air is far from what would be considered a nitrogenous environment.

### **Gravimetric**

Gravimetric sensor technology has roots in weight measurements. It uses a polymer that can absorb moisture, known as a hygroscopic material, and reads the weight change (Developer, 2024). This is a very similar idea to the capacitive, but the two couldn't be more different in function. Capacitive sensors had less resolution, high responsibility and good saturation recovery. Gravimetric sensors have a high accuracy and a desirable sensitivity when compared to the other technologies, and a low response time, which leads to two problems.

Our sensors plan to take consistent readings, as the test run is only going to be about 15 minutes. Thus if we take readings at the end of 30 seconds, it's only 30 readings. Additionally, if we consider the conditions of an actual launch, Any BPS which enters a cloud will detect a massive humidity spike. As noted previously, the large humidity spike is the reason that responsiveness is the most important factor. For the test launch and similar low altitude launches, this may be the most preferable technology. However, due to the constraints we are building for when it comes to the stretch goal, there is a major trade off between this and the capacitive sensor that need to be compared.

**Table 3.7. Humidity Technology Choice**  
By Authors

| Technology  | Accuracy | Resolution | Operating Range | Response Time | Cost  |
|-------------|----------|------------|-----------------|---------------|-------|
| Capacitive  | Great    | Best       | Best            | Best          | Great |
| Resistive   | Good     | Great      | Great           | Great         | Best  |
| Thermal     | Great    | Good       | Good            | Good          | Good  |
| Gravimetric | Best     | OK         | Good            | OK            | OK    |

Thermal Conductive sensors are immediately out of consideration, as the nitrogenous environment is not going to be viable. Gravimetric readings are very accurate, however, as mentioned, the most important factor that must be considered is the response time due to cloud interference. Gravimetric calculation can take seconds to minutes to settle. Between Capacitive and Resistive sensors, Capacitive sensors then are the most accurate, the best response time, and are very good at near vacuum conditions. Additionally, Capacitive sensors are far less affected by temperature compared to resistive sensors, so the degradation of accuracy during high altitudes will be less for them. Resistive circuits only beat it in terms of cost. Thus the choice for the humidity sensor will be the Capacitive Sensor.

### 3.3.9 Capacitive Humidity Sensor Part Selection

The three Humidity Sensors we are looking at are the Renesas HS3003, and TE's HTU21D(F) and HTU 31. As shown in Table 3.8, all have the same operating temperature and RH operating range of 0- 100%. The HS3003 offers the best in terms of accuracy, current consumption and cost. It is also slightly redundant as there is also a temperature sensor with the HS3003 as well as a humidity sensor. Overall, the response time of the HS3003, is only a few seconds while both TE models are 10 seconds. Responsivity is our most important quality, and this is a massive difference. This makes the HS3003 the desired product. However, we will be going with the HTU21D. There are 2 non performance reasons. Upon attempting to do the Hardware Design for chapter 6, it was

discovered that Renesas charges for their CAD models. This decision by the company to attempt to put an additional charge, where it seems to be industry standard not too, is the reason we will be going with the HTU21, and this decision to withhold the CAD model out of greed by Renesas will be taken into consideration for all future decisions for this project and the next. Originally, the HTU21 was chosen. However, digikey has updated the web page and states this part is obsolete and no longer sold. An unfortunate occurrence and had the part been purchased after originally writing this section, we may not have had to switch.

**Table 3.8. Humidity Part Selection**  
By Authors

| Component | Accuracy | Resolution | Response Time | Power Consumption | Cost    |
|-----------|----------|------------|---------------|-------------------|---------|
| HTU21D(F) | 5% RH    | 0.04% RH   | 5 sec         | 450uA             | \$10.95 |
| HS3003    | 1.5% RH  | 0.01%RH    | 6 sec         | 24.4uA            | \$4.58  |
| HTU31     | 2% RH    | 0.01% RH   | 3 sec         | 414uA             | \$4.76  |

### 3.3.10 Anemometer Technology Selection

Anemometers detect wind speed and in some cases direction. There are two main types. First is mechanical, which focuses on directly transferring the energy within the wind into another mechanical system and reading the output signal to calculate the wind speed. Second is electrical, which utilizes an indirect property of the wind, but using an electrical or optical quality that changes with wind speed to measure the wind speed. The change in wind speed as a function of altitude acts much like a skewed distribution. On the surface, the wind speed starts off low, then it rises as you ascend up and beyond the stratosphere, mesosphere until the exosphere, where wind speed peaks. Afterwards, the air becomes much too thin and begins acting like individual free particles rather than an amorphous atmosphere so there is no “wind” to be measured. To that end, the operating range will need to be quite large, with a preference on high values. The qualities to focus on here is oversaturation recovery as well as responsiveness, followed by accuracy.

#### Cup Anemometers

A Cup Anemometer is a simple mechanical design. It uses three to four cups angled horizontally to a motor. The wind flows into the cup causing it to spin. The number of spins over a given length of time will be the wind speed. Cup Anemometers themselves have a variety of designs. It can be a simple mechanical cup. They can be digital cups, which utilize more electronics which allows for more freedom with data transmission and logging. Features for graphical displays are also prevalent with them. Thirdly there are the ultrasonic cup anemometers. These are the most accurate cup anemometers and the

mechanical motion with the cups are completely replaced with electrical readings (*How to Use Cup Anemometer*, n.d.).

The cup anemometers are a good choice to consider for the most part. They offer a high degree of customizability, in how digital we want to be. The advantage of a mechanical design is that it can save on power. Were this design to be chosen, then an amount of stress testing would be necessary. But these anemometers are highly accurate and work well in cases where there are rapid and high changes in speed (*How to Use Cup Anemometer*, n.d.). They are also very accurate and rely on a directly proportional relationship of the number of spins to wind speed (*What Is a Cup Anemometer and How Does It Work?*, n.d.). Additionally, as it is mechanical, it requires less power than any electrical option. The drawback is that a cup anemometer is also very large and would affect the payload size and encumbrance by a large degree. Additionally, consideration is made for the reusability of the sensor. The cups will need to be able to withstand multiple landings in unpredictable territory. Unlike all the other sensors, including electrical anemometers, there is no way to be able to absorb the shock of the impact that the cups will encounter.

A unique option is available if a cup anemometer is used. The cup anemometer is always active. If we take a reading every minute, then we can spend the before and after reading time using the rotor as a generator and generate electricity as direct power or as a charging mechanism for the battery. It would make the system slightly more complicated, but it would increase the power efficiency greatly.

### **Vane Anemometer**

A Vane Anemometer is another type of mechanical Anemometer which uses thin blades or propellers that spins. These Anemometers have blades connected to a vertical shaft with which the blades can rotate around. Thus the spinning of the blades around the rotor will correspond to the wind speed. The rotation of the blades along the shaft will correspond to the wind direction (*What Is a Vane Anemometer?*, n.d.). Vane Anemometers come in many different sizes, and many handheld versions will typically not include the wind direction portion, so it is important to identify whether or not wind direction is something of interest.

For our purposes, we will not be considering wind direction. The payload will not be facing a static direction. At any given point, the BPS may be facing North, South, East, or West, and that may change in the next minute. Thus if the anemometer receives a signal on its “front face,” it would require the assistance of other equipment to determine which direction the “front face” is at any given time. While not an impossible task, the goal is more to measure the conditions of wind speed, rather than try to get directions for any sort of weather forecasting.

The Vane Anemometer is meant for meteorological and environmental applications. They can better determine subtle wind changes and have the benefit of gathering direction. This is compared to the cup anemometers, which

are better suited to operate with larger gusts of wind. For the test launch, the wind will be roughly similar to the conditions on the ground. However, as the BPS rises in Altitudes, winds become significantly more rough. The atmosphere we plan to be able to operate is up to 100,000 feet. This means we will pass well into the stratosphere, including the jet stream where wind speeds are extremely high. While both anemometers have a wide operating range, the cup anemometers are going to be significantly more accurate at higher powered gusts, with the trade off being that Vane Anemometers are better at low speeds. Another consideration is that the structure of a cup is more sturdy than a blade, meaning a cup anemometer will be more likely to withstand an impact. Lastly, Vane anemometers can be more compact, but more difficult to calibrate. While not an engineering drawback, the calibration is an important consideration of a customer's Ease of Use, meaning that for low altitudes, a Vane may be superior to a Cup.

### **Sonic**

The first of the electronic sensors, the sonic anemometer uses a pair of transducers that can measure ultrasonic sound waves. One is an ultrasonic emitter while the other is a receiver. With still air, the transit time along a fixed distance is calculated. However, upon the addition of airflow from the environment, the air density changes. This change in air density will cause a change in the speed the emitter sound waves will travel along. Wind speed can be determined by how much sound waves from one transducer to the other are either sped up or slowed down by the wind speed (Sherman et al., 2013). By mounting three of these emitter receiver pairs, the air dentistry direction, and wing direction can also be determined as well. These sensors have a very wide measurement and operating range as well.

The Sonic Anemometer, being an electrical sensor, is the first sensor that doesn't directly convert mechanical energy, thus these sensors can be much smaller than a cup or Vane. Additionally, there is much more of the sensor that can be protected and insulated from the environment. One example is that Cup and Vane anemometers may have dust and salt in the atmosphere to build up and affect the Cup and Vane anemometers, whereas the lack of moving parts in the Sonic variant is significantly less affected by this (Sherman et al., 2013). Being in Florida, particularly near the coast, salt build ups are common. Oftentimes maintenance on cars is performed more frequently on parts such as serpentine belts as the salt can eat away at some of these materials. A third advantage is the temporal resolution, or time per readings, is extremely fast. This is contrasted to the mechanical versions which need much longer times to count rotations. Though cups and blades can be made smaller, allowing for faster spins, this will always be slower than the Sonic Anemometer, and other electronic sensors.

For drawbacks however, the biggest issue is likely to be the temperature. The issue with sensors getting their result through indirect qualities, such as this case where we are using air density to get speed, is that you often have many different variables that can affect this. In this case air density can be massively affected by

temperature. Thus calibrating a Sonic Anemometer before launch, when it may be 30°C, will be much different when the air balloon is up high in the air, where it may reach as low as -60°C, whereas a Cup anemometer will not be affected by temperature nearly as much this way. While the test flight is not likely to have this issue, it will be something to keep in mind if pursuing the stretch goal. The other consideration is power. The sensor is an active sensor and requires continuous power to function and produce the soundwaves that are read. It may be possible to turn off the sensor during the times when readings will occur, which is the opposite consideration that was made to the Cup Anemometer, where its benefit was to gain power. In either case, this comes at the cost of software simplicity, and possible consumer Ease Of Use.

### **Hot-Wire**

A Hot-Wire Anemometer uses two probes on the other side of a heated wire or thermistor. As the wind comes in contact with the wire, the heat is transferred from the wire to the wind. The higher the wind speed, the higher the wind speed. From here a Hot-Wire Anemometer can either use a constant current or constant temperature method to determine wind speed. In the constant current, a constant current is held throughout the wire and the change in temperature determines the wind speed. With a constant temperature, the wire will feed more or less current into the wire to keep a constant temperature. The sensor will use the change in current to determine the wind speed (*What Is a Hot Wire Anemometer?*, n.d.).

Hot Wire Anemometers are meant for low wind speeds, typically indoor applications such as HVAC, rather than meteorological and weather forecasting applications (*What Is a Hot Wire Anemometer?*, n.d.). Because of its direct reliance on temperature, that means it is highly susceptible to humidity and temperature. As the altitude increases, wind speed will increase, while temperature and humidity will decrease. While they can work at low temperatures, and humidity, the problem lies in the calibration conditions. If it is going to work at -20°C and 40%RH, then it needs to be calibrated around -20°C and 40% RH. When Temperature goes down, the wind speed reading will be overestimated, as more heat is lost due to the environment's temperature rather than heat transfer to the wind. As RH goes down, less water in the air means less heat will be transferred to the wind than calibrated for, so the wind speed will be underestimated. The mechanical anemometers aren't dependent, nor are affected by temperature, so these factors matter less during calibration. Additionally, this is another sensor that requires the active input of electricity to be able to set an environment in order to read. Unlike the Sonic Anemometer though, the change in temperature is not as quick so the ability to turn off the sensor when not actively reading will not be feasible. Lastly, the wire is thin and fragile. There is a good chance of it breaking upon a rough landing.

### **LiDAR**

LiDAR (Light Detection and Ranging) Anemometers are the newest and most advanced anemometers. LiDAR is an optical wind speed detection technology

which shoots a beam of light out into the atmosphere and uses the doppler effect in addition to the reflection of air and dust particles to read the reflected signal.

LiDAR is the most promising of the technologies, as it relies on directly observing the wind molecules movement as opposed to using another property change such as wave propagation or temperature. It is not affected by humidity, air density, or temperature. However, LiDAR is very sensitive to movement, as it uses Doppler Shifts to get the wind speed. While all the anemometers will be affected by the lack of an unmoving and stable platform, LiDAR technology is more sensitive to the movements of the balloon and the shifting of the payload by the largest extent of all the other technologies. While it may be possible to account for or ignore the rising altitude, during high winds, the payload will need to be secured well enough to be able to stay stable in high winds throughout the launch.

### **Technology Choice**

Vane Anemometers will not be considered, however cup anemometers will be. The reason is market Vane anemometers are overwhelmingly packaged as a standalone product as opposed to something to be connected to a PCB, and conversion is unnecessary. There are many Cup anemometers that can be easily attached to a PCB. The Cup anemometers can range from \$40-\$200. The two major flaws are the limited operating range and the size and weight. The Cup anemometers are large and bulky. Implementation required sturdier mounting and ensuring that the payload is balanced in the air. Ideally, an underneath mounting is desired, however the goal of the camera is to get a birds eye view which may cause a huge conflict.

For the Sonic and LiDAR technologies, the LiDAR is the least affected by temperature. In general LiDAR is the best for our purposes due to its lessened sensitivity to all of the extreme conditions in the high altitude environment. It isn't affected by high wind speeds such as how the frictional forces of cup anemometers are. It isn't affected by temperature, nor would it be affected by a change in the humidity like a sonic would be. So even though Sonic anemometers are more accurate, due to the environment, the LiDAR is the best electrical sensor.

However, the cost difference in the technologies is so massive, the choice between a Cup anemometer, which can be purchased for \$50 cheaply, and a LiDAR, which typically sits around \$1000, will ultimately be to choose the Cup Anemometer.

**Table 3.9. Anemometer Technology Choice**

*By Authors*

| <b>Technology</b> | <b>Accuracy</b> | <b>Resolution</b> | <b>Response Time</b> | <b>Cost</b> |
|-------------------|-----------------|-------------------|----------------------|-------------|
| <b>Cup/Vane</b>   | Good            | OK                | Good                 | Best        |
| <b>Hot/Wire</b>   | Good            | Good              | Best                 | OK          |

|              |       |       |       |     |
|--------------|-------|-------|-------|-----|
| <b>Sonic</b> | Best  | Great | Great | Bad |
| <b>LiDAR</b> | Great | Best  | Great | Bad |

### 3.3.11 Cup Anemometer Part Selection

The NPN Pulse is the most cost efficient anemometer. It boasts fantastic accuracy and is less than \$20, before tax and shipping. Additionally, it is the most accurate, rated (+/-) 0.3 m/s. Its operating range is up to 70m/s, which should cover most of the atmosphere up to 100,000 ft. The downside for this is the size. While the dimensions are not physically listed, a visual of the NPN Pulse looks to be the largest, thus needs the largest, flattest surface to be attached to. On the other hand, the 1733, looks to be shorter, but has about the same size. While the size is an improvement, the size decrease is not good enough to justify the poorer performance. The Inspeed on the other hand has a significantly thinner profile. Rather than a large base, the anemometer is on a thin metal plate with holes. Using the Inspeed means there will be no constraint to the payloads size to accommodate the anemometer. The plate will just need a small slit in the casing, or be securely fastened to the outside of the box. With this in mind, the product chosen is the Inspeed. The thinness of the anemometer is the easiest to implement.

Specifically we will be using a pulse output Inspeed A pulse output means that when the anemometer reaches a certain position, typically after a full rotation, then an electrical signal is pulsed. The wind speed is simply the number of pulses within a time frame, such a 1 second, and this is how all three anemometers are chosen to work. Some, such as the Inspeed, have an option to choose one with a continuous electrical output. This could allow the anemometer to be used to generate electricity when not reading. However, the implementation is not necessary due the flight time and battery chosen. The pulse is controlled by a Reed Switch. This is two disconnected wires which are pushed together via a normal magnetic force. This force comes from a magnet that rotates along with the cups. When the magnet is normal to the wires, the field creates a link between them effectively opening the switch to create a pulse.

**Table 3.10. Anemometer Part Selection**  
*By Authors*

| <b>Part</b>      | <b>Accuracy</b> | <b>Size (in)</b> | <b>Operating Range (mph)</b> | <b>Cost</b> |
|------------------|-----------------|------------------|------------------------------|-------------|
| <b>1733</b>      | +/- 0.3 mph     | 4.1x4            | Up to 150                    | \$44.95     |
| <b>Inspeed</b>   | Not Listed      | 9x6x6            | 5 -150                       | \$69.00     |
| <b>NPN Pulse</b> | +/- 0.2 mph     | N/A              | Up to 150                    | \$19.80     |

### 3.3.12 Camera Technology Selection

The main camera technologies, listed in Table 3.11, are DSLR, action cameras, 360° cameras, and low light cameras. The DSLR camera boasts the highest image quality out of all the other options. Their larger sensors can handle higher resolution, detail, and color accuracy, with a large array of camera lenses for any situation, which makes them the best choice for portraits and landscapes. They also tend to be quite large and expensive as well.

Low light cameras are geared towards low light conditions, boasting a large aperture lens with high light sensitivity. A weather balloon launch, even up to 100,000 feet, will be less than 6 hours, so it will be easy to launch away from low light conditions. A 360° camera has the best field of view at the cost of image quality. For a low altitude launch, this could be a worthwhile tradeoff. However, for a high altitude launch, even a narrow field of view will capture an immense landscape, meaning an enhanced image quality is desired significantly more in this case.

Finally, the action camera. An action camera is designed for situations similar to ours. It has a good field of view, is small, compact and durable, but contains an image quality significantly better than the 360° and low light camera. It's also designed to limit manual control. While the DSLR camera provides the best image quality, the most important factor that we are considering, the combination of its cost and weight, ultimately hinder the payload too much to use.

Thus, the base cost of DSLR cameras are in the low to mid \$3,000 USD of dollars, and that is without considering different lenses or other accessories. In contrast, action cameras can go from \$300-\$900 USD. Thus we could mount multiple cameras and get many angles in addition to having redundant parts for the cost of trading AAA image quality, for what is still very high quality. A similar thing can be done with the field of view for a 360° camera, as they go for \$800-\$1100 USD on the cheaper end.

#### Camera Technologies

**Table 3.11** *Camera Technologies*

| Technology | Resolution | Ease of Use | Lens Options | Cost    |
|------------|------------|-------------|--------------|---------|
| DSLR       | Best       | Bad         | Best         | Worst   |
| Action     | High       | Great       | Average      | Average |
| 360        | Average    | Average     | Low          | High    |
| Low Light  | Average    | Great       | Average      | Average |

### 3.3.13 Action Camera Selection

#### GoPro Hero Black 10/11

The GoPro Hero Black 10 and 11, released in September of 2021 and 2022, are the main line GoPro action cameras available. They have very good image quality when compared to other action cameras, they boost a significant number of auto features, even for an action camera, and are proven to work at very low temperatures. Many bugs and freeze have been reported on these cameras over the years, however between firmware updates, many of these have been corrected. One of the biggest current concerns is the overheating issue. The GoPro Hero 11 has had many reports of overheating by its users, and many tests have been done over sites such as YouTube demonstrating this deficiency. In order to overcome this issue a few things must be kept in mind.

In order for the camera to overheat, 2 things must be true. First the camera must be running at 60FPS and second, the camera must lack airflow. The payload will likely not be hermetically sealed, and even if it were, the running of FPS is not a huge concern as the launching of a BPS is a relatively slow process when comparing to the intended application of getting fast paced point of view sports footage, such as biking and snowboarding so even being limited to 30FPS will be acceptable.

The final concern is distortion. For a camera, the focal length determines how far the object a camera can focus on. The focus is responsible for a sharp definition of image sharpness, important for capturing depth of field. A focal length is inversely proportional to the field of view. For high altitude, a large focal length and wide field of view is preferred and vice versa for low altitude launches. The Hero uses a wide angle lens with a large field of view, while we would prefer a high focal length. This could be remedied with a separate lens, which is roughly the cost of a second camera.

#### DJI Osmo Action 4

The DJI Osmo 4 action camera comes at the same cost as the GoPro Hero Black. It comes with better low light settings and waterproofing. It has better cooling performance. Overall, DJI comes with slightly worse image quality compared to the Hero, but boasts better audio quality. The DJI doesn't have the same reported software issues and bugs as the Hero, so there is much less of a concern of the camera crashing or freezing during the launch. The biggest drawback though is the camera requires more than average manual control, which is not viable for mid flight use.

**Table 3.12.** Action Camera Selection

*By Authors*

| Camera      | Image Quality | Ease of Use | Low Light | Cost* |
|-------------|---------------|-------------|-----------|-------|
| Go Pro Hero | 5.3K 60FPS    | Good        | Good      | \$250 |

|          |        |      |      |       |
|----------|--------|------|------|-------|
| DJI Osmo | 4K FPS | Best | Best | \$300 |
|----------|--------|------|------|-------|

\*Prices based on Manufacturers website, there are many cheaper ways to obtain and in the case of the Hero, the manufacturer is out of stock at the current moment, so must be obtained from a third party.

The choice here comes down to a better image quality vs an easier time managing the camera. Since the camera will be a set it and forget it implementation, we will go with the GoPro Hero 11 Black, as Image Quality is the number 1 desire for us. Though the DJI Osmo has a notable advantage of a better low light and easier functionality, the Hero is still beginner friendly, as attested by almost every source, including detractors of the camera. In addition the low light is less important since launches will be taking place during the day. Were this project to be moved past the prototype stage, then night vision may be more important, but for the current purposes, it is not worth the big sacrifice of quality.

### 3.3.14 Spectrometer Parameters Selection

#### Pinhole

The optimal pinhole diameter for absorbance spectroscopic measurements depends on the purpose. In aiming for an accurate absorption spectrum, a small diameter is necessary to avoid deviations from the Beer-Lambert Law caused by polychromatic light.

$$A = \epsilon cl$$

**Figure 3.1:** Beer-Lambert equation where  $A$  is absorbance,  $\epsilon$  is molar absorption coefficient,  $c$  is molar concentration, and  $L$  is optical path length.

It is crucial to recognize that the "deviations" from the Beer-Lambert Law discussed here are not actual failures of the law itself. Instead, they are apparent deviations caused by the measuring instrument's inability to meet the conditions the law establishes. The principle requirement for the Beer-Lambert Law is that each photon of light hitting the detector must have an equal opportunity to absorb. This means that every photon must have the same absorption coefficient ( $\epsilon$ ), must travel through and along the same optical path length ( $L$ ), and must meet the same absorber concentration ( $c$ ). Any disruption to these conditions will result in the aforementioned deviation from the law. [#]

Another condition to consider for accurate absorption spectroscopy is the spectral bandpass. The spectral bandpass, known as the range over which the sample's transmission is measured, must be small relative to the absorber's spectral width. In dispersive instruments, the spectral bandpass is determined by the slit width and the reciprocal linear dispersion (RLD). For background on RLD, angular dispersion is the angle between two colors/wavelengths after being diffracted from white light into many colors. From this, linear dispersion can be found as the result of the product of the angular dispersion and the system's effective focal length. It can also be expressed as the spatial distance of two

wavelengths from each other in the focal plane, therefore, reciprocal linear dispersion is the inverse of linear dispersion. Here, linear dispersion is shown in Figure 3.2 normally as mm/nm and RLD is shown in Figure 3.3 commonly as nm/mm. [#]

$$D_L = dx/d\lambda$$

**Figure 3.2:** *The linear dispersion ratio*

$$R_D = D_L^{-1}$$

**Figure 3.3:** *The reciprocal linear dispersion ratio*

While RLD is fixed, the slit width or pinhole diameter is often adjustable. A smaller width/diameter minimizes spectral bandpass and polychromaticity error but also decreases the signal-to-noise ratio (SNR), which may not always be practical. In general, a higher signal-to-noise ratio is desired to obtain accurate and clear information. In the case of this project, we desire mere qualitative information, so the need for an incredibly high SNR is much less. If the spectral bandpass is one-tenth of the narrowest band's width, the polychromaticity error is about 0.8% for a Lorentzian band and 0.5% for a Gaussian band, an acceptable error margin for many applications including our own. Using an even smaller pinhole size is not beneficial if the random noise error exceeds the non-linearity error. Figure 3.4 shows the inversely proportional relationship between the diameter of the pinhole or slit width and the dispersion of the light.

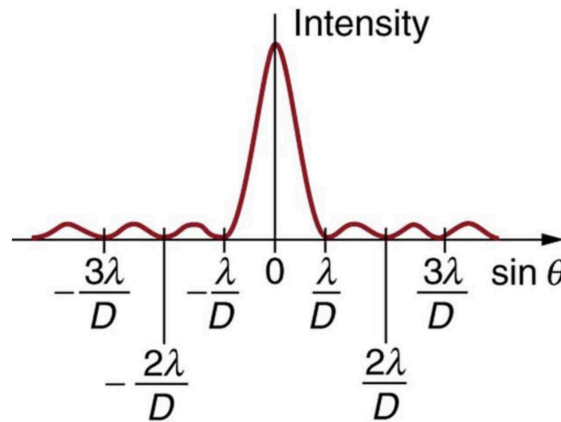


**Figure 3.4:** *Interference pattern of a single slit or pinhole and the wavelength/hole diameter relationship*

Source: Adapted from [#]

Conversely, for quantitative analysis of component concentrations, a good signal-to-noise ratio is critical, especially in trace analysis near the instrument's

detection limit. Here, the focus is on the absorbance accuracy and not the linearity of the analytical curve (absorbance vs. concentration). Quantitative analysis often relies on calibration with standard samples, resultingly making absolute accuracy less critical, as aforementioned for our specific needs. Therefore, the pinhole diameter requirements are less stringent for quantitative analysis, balancing between minimizing polychromaticity errors and maintaining a practical signal-to-noise ratio. For qualitative analysis however, the goal then becomes to generally minimize the errors present. In this project specifically, we are pushing to have as much accuracy as possible in the absorbance data, however the group can acknowledge the setbacks of time and funding for precise outcomes. With only two photodiodes being used to detect the presence of oxygen gas, a great deal of precision will not be necessary, however accuracy is still at the forefront. The exact pinhole diameter will be determined in the prototype/testing section as it is the last optical element whose measurements need to be determined. Because of this, an iris or similarly made device will be used in testing to find the best diameter size for the entrance pupil.

### **Light Source**

The light source of the project is likely going to be a white light of some sorts. In order to get a broad wavelength spectrum, the light will need to have a solar blackbody kind of emission spectrum. In addition to the wavelength needs, the light also needs to be able to produce enough power to provide enough output at the photodetector. If the power is above the minimum requirement, the data will be more reliable and more precise.

To achieve this design constraint, we are considering various types of white light sources. The best general light source for fully concentrated power would be a laser, but due to the property of stimulated emission in lasers, the light would be narrowed to one wavelength. [#] Traditional lasers can also be large, heavy, and require a significant power source that would greatly impede on our payload weight restrictions. On top of all this, off-the-shelf lasers can cost upwards of \$1000. [#] This takes lasers out of the question.

Another consideration is to use a laser diode. Laser diodes are a smaller and lighter version of traditional lasers and can be bought at cheaper prices. The downside of laser diodes is the narrow bandwidth factor, similar to that of the traditional laser. The light can be produced via a small and relatively inexpensive semiconductor, but the wavelength would be too specific for the needs of the project. This removes laser diodes from the candidate pool.

To solve the narrow bandwidth problem, a viable option is to use light emitting diodes (LEDs). The unique characteristic of LEDs is the broad spectrum they cover and ability to peak at a specified wavelength. The broadness of the emission is due to spontaneous emission. This differs from lasers' stimulated emission because there is not a directed point the energy is going to, such as a specified wavelength. In the case of these diodes, the light is able to spread across a range of up to 200 nm and still peak to emit a distinct color. LEDs are inexpensive electronic components that can be easily integrated into a schematic

design and they don't require more than roughly 5 V of input voltage. The negative side of LEDs is the power output after passing through a system such as ours, and the actual spectrum of a white LED that we would need to meet the project needs. Below in Figure 3.5, a graph containing the wavelength versus spectral power is shown.

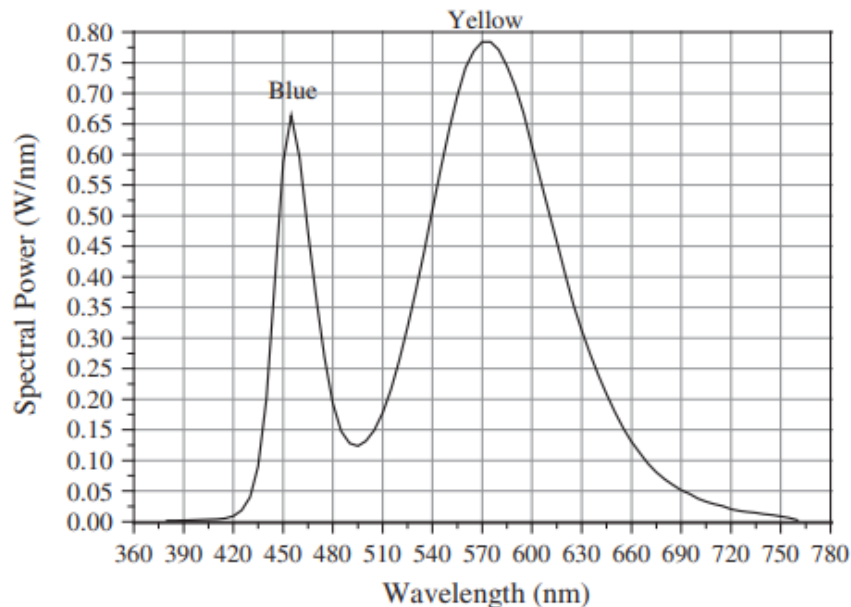


**Figure 3.5:** *Power distribution for a standard white LED*

Source: Adapted from [#]

Although this is labeled as a white LED, the primary colors are yellow and blue. While the yellow band is broad and spans from 510 nm to 680 nm, the power drops between green and blue around 500 nm. The blue in this case is not quite as precise as a laser or laser diode emission spectrum, but still does not cover the entirety of the short wavelength end of the visible spectrum. In the case of this project, a full solar blackbody would be best, which a white LED can not provide.

The last candidate under consideration is a standard lightbulb.

### **Lenses**

Due to the sizing constraints, this project calls for a compact optical setup. With this, lenses designed for shorter focal lengths and minimized diameters will be used. However, for a general overview, two types of lenses will be needed in this project: collimating and focusing.

A collimated beam of light consists of rays that are parallel to each other. Achieving perfect collimation requires either placing a minuscule light source precisely one focal length away from an optical system with a positive focal length, or observing the source from an infinite distance. Practically, both scenarios are impossible, and even in theory, diffraction causes some divergence

along the optical path despite any and all efforts. Minimizing this divergence involves balancing the focal length of the optical system and the size of the light source. To improve collimation, either the light source must be minimized or the focal length increased, but increasing the focal length requires the system to be farther from the source, reducing the captured light and the beam's power. Divergence is inevitable, as seen in a general context where larger sources produce beams with more divergence. [#] This occurs because larger sources can be seen as multiple point sources, each generating a parallel ray bundle. However, the collective effect of these bundles results in a beam with some divergence due to the varying angles relative to the optical axis as the source size increases.

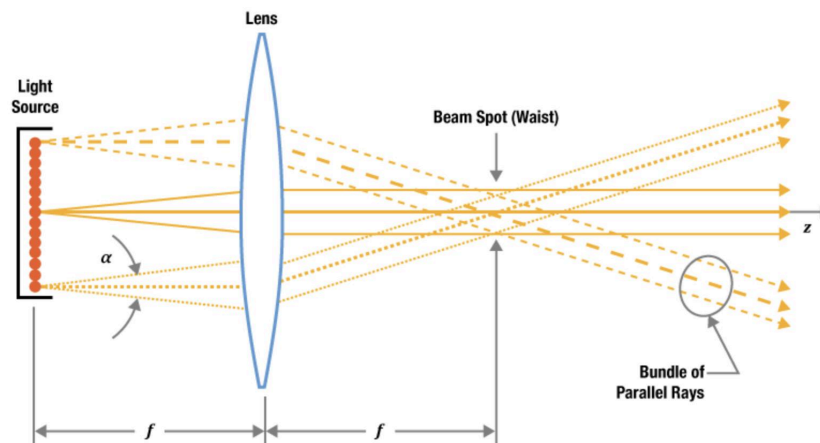


**Figure 3.6:** Collimating lens ray diagram proving imperfection and ray bundles

Source: Adapted from [#]

Focusing lenses are optical components that refract light through their curved surfaces, causing the light to converge or diverge. The optical properties of these lenses are essential for a wide variety of applications, from eyeglasses to sophisticated laser systems used in industrial manufacturing. The performance of an optical system depends on the material and shape of the focusing lens. For the visible spectrum, different optical materials can be used, while materials like fused silica (fiber optics), calcium fluoride, and sapphire are suitable for near-infrared to short-wave infrared applications. There are six different types of focusing lenses but only a few under consideration for the project will be discussed. [#]

The first of those is a convex lens, as shown in Figure 3.6. A convex lens, also known as a converging or positive lens, is thicker in the center and thins out towards the edges. These lenses are widely used in optics due to their capability to converge light rays. When parallel rays of light pass through a convex lens, they refract and converge at a focal point, which is the point where the rays meet after being refracted.

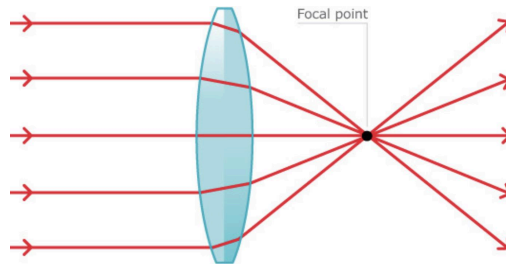


**Figure 3.7: Convex lens ray diagram**

*Source: Adapted from [#]*

Second are concave lenses. A concave lens, also known as a diverging or negative lens, causes a straight light beam from a source to spread out into a smaller, upright, virtual image. A real image is formed by the actual intersection of light rays, while a virtual image is formed by the apparent intersection of light rays. Concave lenses can produce both real and virtual images. As shown in Figure 3.7, these lenses are thinner in the center and thicker at the edges, curving inward. Concave lenses cause parallel light rays passing through them to diverge, refracting away from a common point on the opposite side of the lens. The focal point of a concave lens is the point from which these divergent rays appear to originate when traced backward. Concave lenses are used to correct visual impairments like nearsightedness, where the image focuses in front of the retina. They are also used in optical systems designed to spread out or diverge incoming light, such as beam expanders.

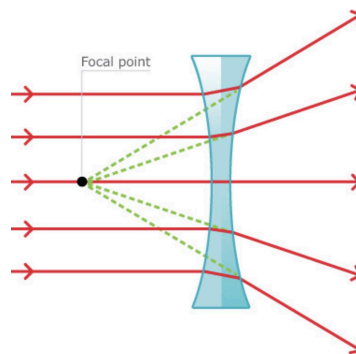


**Figure 3.8: Concave lens ray diagram**

*Source: Adapted from [#]*

The third type is a plano-convex lens, as shown on the left in Figure 3.9. A plano-convex lens features one flat surface and one outwardly curved surface, similar to a magnifying glass, as shown in the figure above. The flat side is known as the "plano" side, while the outwardly curved side is convex. This lens design focuses parallel rays of light passing through it to a focal point on the opposite side. Plano-convex lenses are commonly used in imaging systems, projectors, and magnifying glasses, where the converging properties of the convex surface are essential. The type of lens on the right is a plano-concave

lens. Similar to the concave lens previously mentioned, this lens has a face that caves in, however the other side is flat (plano). They are primarily used to diverge light rays which makes them useful in various applications like beam expanders, laser systems, and optical instruments. When parallel light passes through a plano-concave lens, it spreads out as if originating from a virtual focal point located behind the lens.

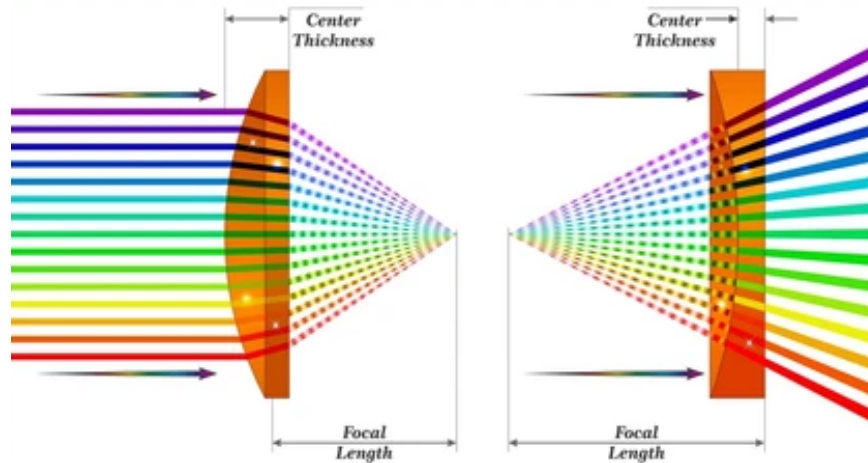


**Figure 3.9:** *Plano-convex versus plano-concave lens ray diagram, respectively*

Source: Adapted from [#]

These lenses can help control light direction, manipulate beam profiles, and enhance image quality in optical setups. They can aid in a variety of applications depending on the behavior of light needed.

### Lens Choice

It is already known that both a collimating and focusing lens are needed for the setup, but each of the basic lens variations above can fulfill those criteria. The types of lenses will be compared below in Table 3.13.

**Table 3.13.** *Lens Design Choice*  
By Authors

| Lens Type     | Average Cost | Wavelength Range (nm) | Applicability |
|---------------|--------------|-----------------------|---------------|
| Convex        | \$39         | 350 - 2200            | high          |
| Concave       | \$30         | 350 - 2200            | low           |
| Plano-Convex  | \$50         | 350 - 2200            | moderate      |
| Plano-Concave | \$38         | 400 - 2200            | low           |

Source: Edmund Optics products [#], [#], [#], [#]

As shown in the comparison, the average cost of each lens shape does not differ greatly. Considering only two lenses total will be bought in the end, the cost is bound to be between \$60 and \$100. The applicability, however, is important to note. In an effort to simulate the usability of the two most applicable lens shapes – double convex and plano-convex – Figure 3.9 displays both of the lenses used in the spectrometer design and their impact on the light waves.

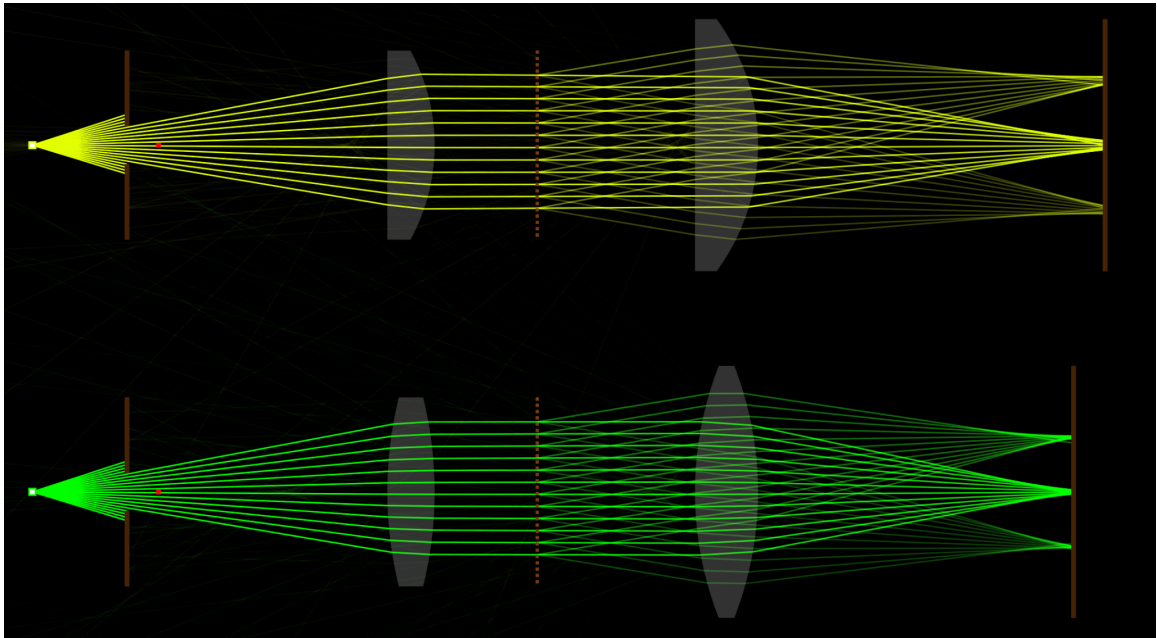


**Figure 3.10:** *Double convex versus plano-convex lenses simulated in the spectrometer setup*

*Source: Authors*

The difference between the two can be difficult to distinguish, but the focusing points by the detectors on the right of the image reveal precision, or lack thereof. When initially collimating the light with the first lens in the plano-convex example, the rays exit at differing angles, whereas with the double convex lens diagram beneath it, the rays exit in parallel with no deviation from each other. Following after that, when passing through the diffraction grating and focusing lens and interfacing with the detector, the plano-convex example does not come to exact focusing points. Not only do the rays exit at different angles after the first lens, but they also exit differently after the second lens. This results in the failure to converge to precise points on the detectors.

As seen in the double convex example, the light is able to converge to distinct points. Since the light rays exit parallel to one another after the collimating lens and converge proportionally after exiting the focusing lens, the precision of the individual wavelength focal points is greater. This, in turn, increases the power incident onto the detector, and increases the accuracy of the resulting voltage output.

Since the double convex lenses will be used for the project, the table is not needed for comparison. Instead, calculations for the diameter and focal lengths of the two lenses will be done instead.

## CALCULATIONS

### **Diffraction Grating**

In spectroscopy, after light passes through a slit or pinhole it is collimated by a lens or mirror and directed to a diffraction grating. This grating, which contains a periodic variation in its optical properties, separates the light into its component wavelengths, each directed at a specific angle. The variation in output angle with respect to wavelength, known as angular dispersion, is crucial for determining the spectrometer's wavelength resolution. The period of the grating's variation and its geometry are key factors influencing angular dispersion and efficiency. [#]

There are two primary types of diffraction gratings: ruled and holographic. Ruled gratings feature a large number of parallel grooves etched into a material. Creating an original or master grating involves using a suitable substrate, typically glass or copper, polishing it to one tenth of a wave ( $\lambda/10$ ), and applying a thin aluminum or gold layer via vacuum deposition. Parallel, equally spaced grooves are then ruled into a specific profile. The ruling engine must precisely retrace the path of the diamond forming tool on each stroke and advance the substrate by a predetermined amount after each cut. Numerous test gratings are produced and measured. Following testing, a new original grating is created on a larger substrate. Due to the high cost of original gratings, ruled gratings were rarely used until the replication process was developed. [#]

Holographic gratings, produced by the interference of two laser beams within a responsive material, create a periodic refractive index variation. For a holographic grating, a photosensitive (photoresist) material coats the substrate instead of a reflective coating. The photoresist is exposed to intersecting laser beams, creating a sinusoidal intensity pattern of interference fringes. This pattern forms a surface pattern after solvent immersion. The substrate is then coated with a reflective material and can be replicated similarly to ruled gratings. Holographic gratings, produced optically, have extremely uniform groove spacing, reducing stray light and preventing ghosting effects compared to ruled gratings. Holographic gratings can achieve higher angular dispersion due to their ability to create very fine variations and tend to perform better in the ultraviolet spectrum. With this, they can also be written on curved surfaces, enabling focusing capabilities, however, are generally less efficient and more costly than ruled gratings and face absorption issues in the infrared spectrum, making ruled gratings more suitable for infrared applications. [#]

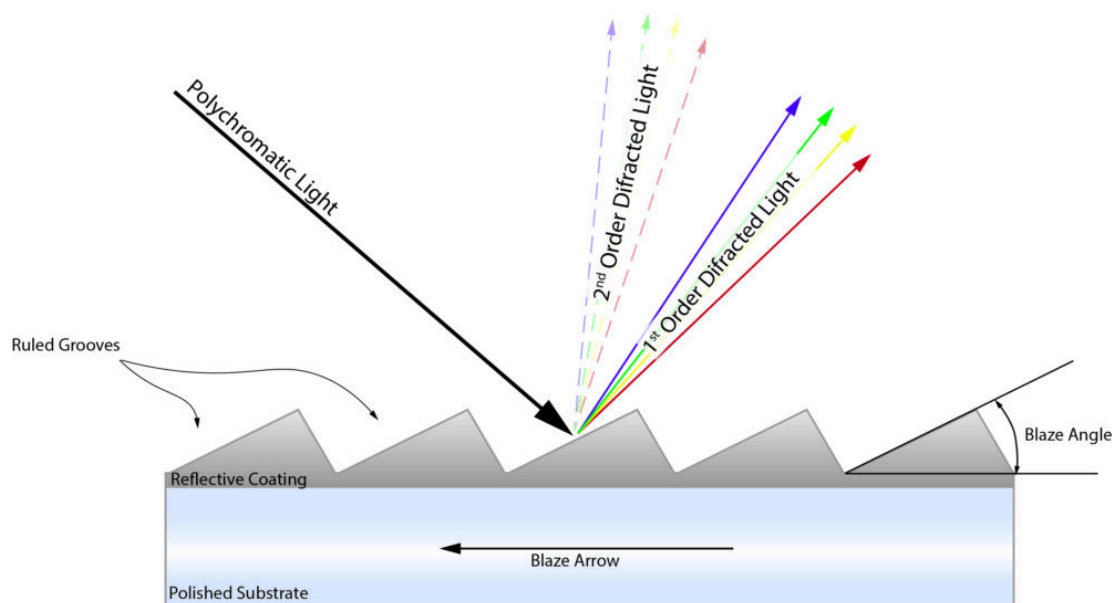


**Figure 3.11** Basic diagram of a ruled diffraction grating.

Source: Adapted from [#]

Both grating types operate on the same diffraction principles and are governed by the same equations, affecting their angular dispersion, resolution, and efficiency. Holographic gratings are often preferred for applications requiring high angular dispersion and performance in the ultraviolet spectrum, while ruled gratings are favored for infrared applications due to their higher efficiency. [#]

## Grating Choice

**Table 3.14. Grating Choice**  
By Authors

| Grating            | Spectral Range      | Cost   | Groove Density           |
|--------------------|---------------------|--------|--------------------------|
| <b>Ruled</b>       | best in infrared    | ~\$150 | best below 600 lines/mm  |
| <b>Holographic</b> | best in ultraviolet | ~\$150 | Best above 1200 lines/mm |

Source: Edmund Optics products [#], [#]

In the case of the project at hand, the ruled grating is the best approach. Due to the molecule the team would like to detect, the grating needs to be able to operate efficiently in the infrared range with minimal light loss. Another bonus with ruled gratings is that due to their modern mass-manufacturing capabilities and streamlined processes, the gratings can be relatively inexpensive without sacrificing accuracy of wavelength dispersion. The cost estimates above are the average of a range, so a smaller and more common grating could be less

expensive than projected here. Another factor to consider when choosing the specific ruled diffraction grating is the groove density. Due to the compactness of this project, less than 500 lines/mm or so would be appropriate for the application.

The setup of the spectrometer in this project is linear in nature and requires a transmissive grating making reflective gratings out of the question, therefore narrowing down the potential hardware options. Since a ruled grating has been decided, the calculations for the angular dispersion based on grooves per centimeter are shown below.

$$\lambda = 550 \text{ nm} \quad D = \frac{m}{a \cos \theta_m}$$

$$DG = 300 \text{ grooves/cm}$$

$$a = \frac{1}{300 \text{ cm}^{-1}} = 0.00333 \text{ cm}$$

$$\sin \theta_1 = \frac{(1)\lambda}{a} \Rightarrow \frac{(1)(550 \times 10^{-7})}{0.00333} = 0.0165 \rightarrow \theta_1 = 0.9454$$

$$\cos(\theta_1) = 0.999864$$

$$D = \frac{m}{a \cos \theta_m} \Rightarrow \frac{1}{(0.00333)(0.999864)} = 300.041 \text{ rad/cm}$$

$$D = 0.300041 \times 10^{-4} \frac{\text{rad}}{\text{nm}} \cdot \frac{180^\circ}{\pi \text{ rad}} = 0.00172^\circ/\text{nm}$$

$$\lambda = 550 \text{ nm} \quad D = \frac{m}{a \cos \theta_m}$$

$$DG = 500 \text{ grooves/cm} \quad \leftarrow \text{due to market availability}$$

$$a = \frac{1}{500 \text{ cm}^{-1}} = 0.002 \text{ cm}$$

$$\sin \theta_1 = \frac{(1)\lambda}{a} \Rightarrow \frac{(1)(550 \times 10^{-7})}{(0.002)} = 0.0275 \rightarrow \theta_1 = 1.5758$$

$$\cos(\theta_1) = 0.99962$$

$$D = \frac{m}{a \cos \theta_m} \Rightarrow \frac{1}{(0.002)(0.99962)} = 500.189 \text{ rad/cm}$$

$$D = 0.500189 \times 10^{-4} \frac{\text{rad}}{\text{nm}} \cdot \frac{180^\circ}{\pi \text{ rad}} = 0.00287^\circ/\text{nm}$$

## Photodetector

The effectiveness of a VIS to NIR spectrometer heavily depends on its photodetector, which converts incoming NIR light into an electrical signal. Various photodetector options are available, each with distinct advantages and limitations. There are a few options when it comes to the official approach so all will be compared to find the most appropriate for the project.

The first of them is Indium Gallium Arsenide (InGaAs) photodiodes. InGaAs photodiodes are among the most popular detectors for NIR spectroscopy, particularly in the range of 900 to 1700 nm. Their high quantum efficiency and low noise characteristics make them suitable for applications requiring high sensitivity. InGaAs detectors are especially effective for detecting weak signals due to their effective response across the NIR spectrum and relatively high dynamic range. According to Wang [#], InGaAs photodiodes can achieve quantum efficiencies exceeding 80% in the NIR range, making them ideal for low-concentration sample analysis – a benefit for the oxygen gas detection goal.

Second in consideration are photomultiplier tubes (PMTs). While traditionally associated with UV and visible spectroscopy, these tubes can be adapted for NIR applications using specialized materials. PMTs offer exceptional sensitivity and are capable of detecting single photons, which makes them suitable for applications requiring low-light detection. However, their use in NIR spectroscopy is limited due to low efficiency in the NIR range. As explained by Passos [#], PMTs are most effective up to about 900 nm, and their performance declines significantly beyond this range. The range needed will only be up to about 800nm so this is an acceptable downside.

Third on the list are avalanche photodiodes (APDs). These provide a middle ground between InGaAs photodiodes and PMTs. They operate by multiplying the photocurrent through a process known as avalanche gain, which enhances sensitivity and allows for the detection of weak NIR signals. APDs can cover a range from 800 to 1700 nm and typically offer good noise performance and faster response times compared to PMTs. The trade-off is that they require a higher operating voltage and can exhibit more noise under certain conditions, as noted in the study by Li [#].

Choosing the appropriate photodetector for NIR absorption spectroscopy is crucial for achieving the optimal performance and cost balance. InGaAs photodiodes are often the preferred choice due to their high sensitivity and efficiency in the NIR range, however applications requiring extremely low-light detection might benefit from PMTs or APDs. For this balloon's spectrometer in particular, the goal is to detect the mere presence of O<sub>2</sub>, which might not require the most sensitive detector on the market. Table 3.15 below compares the three types of detectors mentioned above to deduce the one that would best fit the project needs.

**Table 3.15. Photodetector Choice**  
*By Authors*

| Detector                  | Wavelength Range (nm) | Peak Wavelength (nm) | Cost   | Radiant Sensitive Area (mm <sup>2</sup> ) |
|---------------------------|-----------------------|----------------------|--------|-------------------------------------------|
| Si Pin Photodiode         | 430 - 1100            | 800                  | \$1.38 | 7.5                                       |
| IR Photodiode (C10439-03) | 190 - 1100            | 960                  | \$907  | 100                                       |
| InGaAs Photodiode         | 900 - 1700            | 1550                 | \$100  | 6.45                                      |

Source: Amazon [#], Hamamatsu [#], Edmund Optics [#]

As aforementioned, our project requires a wide spectral range that will enable us to increase the potential of photons being absorbed or reflected from the smoke and gas. With that being said, the Si Pin Photodiode and IR Photodiode would be the best options due to their spectral range. Another consideration for our team is the cost of materials. To account for the optics budget, the Si Pin Photodiode would be the best course of action. At this price, we can purchase multiple of these components and test them without fear under various conditions.

Since the active area of the photodiode is only 7.5 mm<sup>2</sup>, the lenses will have to account for this extremely small focusing area to avoid light and power loss from source to detector.

### 3.3.15 Antenna Technology Selection

#### Antennas

When selecting an antenna for this project there are a multitude of factors that play into what type of antenna works best. This project will require a transmission antenna as well as a receiver antenna. In this selection we will just be talking about the transmission antenna which will be attached to the payload and sent to the edge of space. Our goal is to have an antenna that will be efficient in transmitting our live data. To accomplish this goal the design parameters are as follows: frequency of transmission, gain and direction of transmission, as well as polarization. Our data will need to be transmitted at a specific frequency, this frequency will be calculated based on our peak altitude and data rate. The gain and direction of the antenna will also be a design parameter to make sure our signal is strong enough and transmitting toward our receiver. Polarization will be a factor because the polarization will aid in transmission distance and strength, this polarization will have to match between the transmitter and receiver.

#### Dipole Antenna

A dipole antenna consists of 2 wires, one positively charged and one negatively charged. These 2 wires or metal rods radiate perpendicularly to the antenna. These antennas are typically low gain but have a donut shaped radiation pattern

as seen below. The polarization will be in whichever way the antenna is perpendicular to. The benefits to using this type of antenna are its wider radiation pattern. This omnidirectional signal will allow the base station to find the signal easier. We can also use a dipole antenna as the receiving antenna. This omnidirectional radiation pattern is a must for the payload antenna. When the high altitude balloon is released for flight it will be taken by the winds. We will have no way of knowing which way it is going, especially when it gets to higher altitudes. If a directional antenna was used on the payload we would have to design a mechanism to find the location of the base station and gimbal the antenna toward the tracked location. However, the donut shaped radiation pattern will be sent all around the payload allowing an antenna on the base station to pick up the signal.

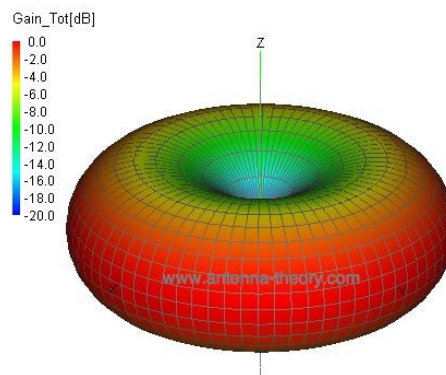


**Figure 3.12. Dipole Antenna Radiation Pattern**

Source: P. Bevelacqua, "The Dipole Antenna."  
<https://www.antenna-theory.com/antennas/dipole.php>

### J-Pole

A J-pole antenna consists of 2 parallel arms. One of these arms are typically at a quarter wavelength high with the longer arm being at a 3 quarters wavelength height. This antenna is an omnidirectional antenna which is perfect for our application. Typically a J pole antenna has about 2.5 - 3 Db of gain. This antenna is beneficial to our project because of its omnidirectional radiation pattern and gain. This is a very viable option for transmission or receiving.

qq

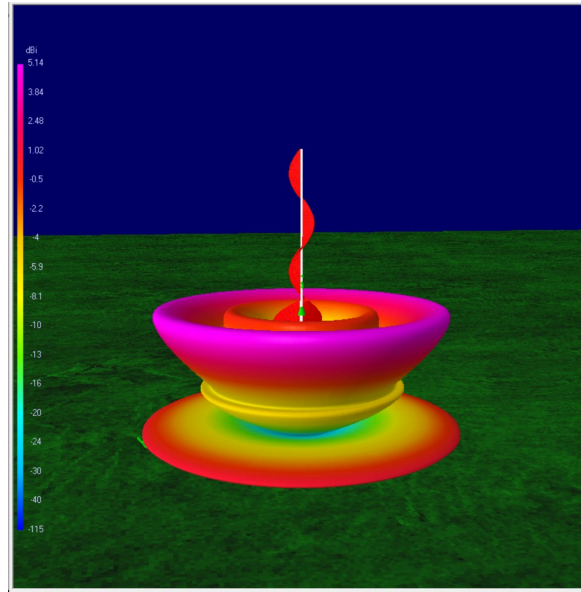


**Figure 3.11.** *J-Pole Antenna Radiation Pattern*

Source: G. Rondeau, "Modeling the J-Pole," *Squash Practice*, Oct. 27, 2020.  
<https://squashpractice.com/2020/10/27/modeling-the-j-pole/>

### YAGI Antenna

Yagi antennas are a high gain directional antenna. These are made up of a single transmission line with multiple directors and a reflector at the back. [40] This makes YAGI antennas really great for long distance communication. This will benefit our project by using its directional high gain antenna. To utilize this however we would have to implement some type of tracking and gimbal mechanism to maintain high gain communication. We can do this by using an antenna rotator. This option gives us the lowest loss however it's risky as it is a very directional signal.

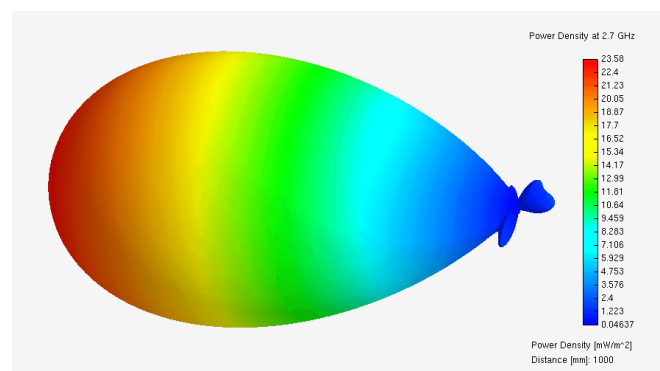


**Figure 3.12.** *YAGI Antenna Radiation Pattern*

Source: Dipl.-Ing. C. Wolff, "Yagi antenna - Radartutorial."  
<https://www.radartutorial.eu/06.antennas/Yagi%20Antenna.en.html>

### Skew Planar Antenna

A skew planar antenna is a type of loop antenna which has 4 segments called “leaves”. The leaves maintain the same phase to ensure a circularly polarized omnidirectional radiation pattern. Typically these antennas have a pretty low gain and are utilized as receiver antennas. The low gain makes these antennas a poor transmitter. As a receiver the circular polarization would be beneficial if the payload happens to be moving and changing orientation from wind. This would allow signal transmission regardless of orientation of the payload.

### Iridium Satellite Communication

The Iridium satellite constellation is a Low Earth Orbit (LEO) constellation of optically connected satellites. Using this satellite communication protocol has many advantages such as global coverage. With global coverage we don’t have to worry about range and direction of antennas on the ground. This way we can launch on a windy day and not have to worry about being out of range of the antennas. All of the Iridium modules are very small and lightweight. No matter which transceiver meets our specifications best it will not be a problem to implement onto the HAB. With this implementation we would still need an antenna to communicate with the satellites, we would use some type of patch antenna or other Iridium approved antenna.

### Antenna Decision

To decide what kind of antenna we want to use we need to look at the parameters of the launch. For transmitting data, we need to look at 2 factors, loss of signal and frequency. Our data transmission rate will likely be around 1kbps. We also need to see what our Free Space Path Loss (FSPL) will be, this is also called our link budget. This allows us to see if our losses in signal will be too much for the receiver to process. For example, if our distance is 90 miles transmitting at 915 MHz, our transmission antenna has a gain of 3 dB, and our receiving antenna has a gain of 7 dB our path loss is 119.4 dB. We can play around with our receiving antenna choices, a more directional antenna like the yagi antenna used in the example will result in a lower path loss. Whereas if we switched this to another dipole for example we will have a higher path loss. We will also need to polarize both antennas the same. Another aspect in deciding our antenna is the frequency we are going to be operating at. Although the frequency doesn’t affect the technology decided for the antenna it does affect which antenna we order. We do not want to order an antenna that does not match the frequency of our transmitter and other RF components. We will dive more into frequency in the RF Module section and talk about why we decided the frequency we did.

**Table 3.15. Antenna Technology Choice**  
*By Authors*

| Antenna | Gain | Radiation Pattern | Ease of Implementation |
|---------|------|-------------------|------------------------|
|---------|------|-------------------|------------------------|

|                          |       |       |       |
|--------------------------|-------|-------|-------|
| <b>Dipole</b>            | Okay  | Best  | Best  |
| <b>J pole</b>            | Great | Great | Great |
| <b>Yagi</b>              | Best  | Worst | Okay  |
| <b>Skew Planar</b>       | Worst | Good  | Good  |
| <b>Iridium Satellite</b> | Good  | Okay  | Worst |

**Table 3.16. Receiver Technology Choice**

*By Authors*

| <b>Antenna</b>           | <b>Gain</b> | <b>Radiation Pattern</b> | <b>Ease of Implementation</b> |
|--------------------------|-------------|--------------------------|-------------------------------|
| <b>Dipole</b>            | Okay        | Good                     | Best                          |
| <b>J pole</b>            | Great       | Great                    | Great                         |
| <b>Yagi</b>              | Best        | Best                     | Okay                          |
| <b>Skew Planar</b>       | Worst       | Worst                    | Good                          |
| <b>Iridium Satellite</b> | Good        | Okay                     | Worst                         |

For this project it makes the most sense to use a dipole antenna as the on board transmission antenna. This will ensure a nice omnidirectional radiation pattern with a decent transmission range with enough input power. On the receiving end the base station will be equipped with another dipole antenna. This will be sufficient for the demonstration tethered launch of 150 feet. However, on our stretch launch we will be switching this to a directional high gain yagi antenna which will be either on an antenna rotator or pointed manually toward the direction of the balloon.

### **Dipole & Yagi Antenna Part Selection**

**Table 3.17. Dipole Antenna Part Selection**

*By Authors*

| <b>Antenna</b>  | <b>Gain</b> | <b>Cost</b> |
|-----------------|-------------|-------------|
| <b>Sparkfun</b> | 2 dB        | 10          |

|                   |         |    |
|-------------------|---------|----|
| <b>RangeVideo</b> | 2.15 dB | 16 |
| <b>Meshtastic</b> | 10 dB   | 18 |
| <b>Pyrodrone</b>  | 2 dB    | 7  |

**Table 3.18. Yagi Antenna Part Selection**  
*By Authors*

| <b>Antenna</b>            | <b>Gain</b> | <b>Cost</b> |
|---------------------------|-------------|-------------|
| <b>Mobile Mark Y3347</b>  | 10.4 dB     | 182         |
| <b>Mobile Mark Y6646D</b> | 11.5 dB     | 382         |
| <b>Tupavco</b>            | 9 dB        | 25          |
| <b>Embedded Works</b>     | 13 dB       | 80          |
| <b>Twardio</b>            | 9 dB        | 50          |

### 3.3.17 Battery Technology Selection

The battery will serve as the main power source for the payload. Without power we will have no functional sensors, MCU, camera, or anything for that matter. It is essential we choose a battery that is capable of meeting our power demands as well as is able to hold up through the rigorous flight. There are many different types of batteries with differences from the method of holding charge, ports and connections. With the decreasing temperature expected to reach lower than -60°F as we increase in altitude we must consider what will happen to the voltage and current with this drastic drop in temperature. When choosing a battery we can expect the voltage and overall battery capacity to drop as altitude increases and temperature decreases. Once we create and calculate our electrical load table we will be able to choose a battery for certain.

#### **Lithium Ion**

Lithium ion batteries are very common in the world of electronics due to their high energy density. They work by having a transfer of lithium ions from the anode to the cathode. This flow of ions results in the movement of electrons from one side to the other resulting in an electric current flowing in the opposite direction of the electrons. This is very appealing as we would be both lighter and much more efficient with power. However, some drawbacks with lithium ion are its performance with temperature drops. As the temperature drops lithium ion batteries chemical reaction slows down significantly. If we were to utilize a lithium ion battery to power our payload we would need to design and test an insulation and heating system for the battery.

### **Lithium Polymer**

Lithium polymers are very similar to lithium ions in a sense where temperature greatly affects performance. We would need to design and test a thermal system, whether insulation or heating elements to keep the battery warm. Lithium polymer does have its pros against lithium ion however. With a smaller and lighter frame lithium polymer will be great for weight management and integration with the ability to flex the battery. Lithium polymer does not have as great of an energy density as lithium ion however the voltage output does tend to be higher. The lithium polymer will also be safer for the payload as it uses a solid or gel-like electrolyte unlike the liquid that the lithium ion uses. This solid or gel provides a less likely chance for swelling or leaking.

### **Lithium Iron Phosphate**

Lithium Iron Phosphate or  $\text{LiFePO}_4$  is typically known for its durability and resilience. These batteries also have an amazing energy density usually right around the same amount as a lithium ion battery. These batteries due to their robust design would be harder to implement due to a more robust design. However, with Lithium Iron Phosphate batteries the voltage output is much lower, this results in a longer lifespan of the battery. For our application, this battery would be a safe option and wouldn't require a whole lot of thermal management.

### **Alkaline**

Alkaline batteries are a very common battery used in everyday devices. Alkaline batteries work by having a cathode made out of manganese dioxide and an anode made out of zinc. Alkaline batteries are used for their high energy densities. They are also commonly known for their low discharge and long shelf life. Alkaline batteries also have a unique quality of a voltage drop as they discharge, with this, it is important to have a voltage regulator connected to your battery to offset these effects. These qualities make it an amazing choice for everyday devices. For high altitude balloons, however, the temperature greatly affects the alkaline batteries at high altitudes. In high altitude ballooning, the temperature greatly decreases with the rise in altitude and this greatly affects the chemical reaction in the alkaline battery. The low temperature affects the diffusion reaction which results in particles to move more slowly. This makes the output voltage drop significantly. If we were to implement alkaline batteries into our system we would have to have significant thermal controls to keep the batteries warm as well as voltage regulation to keep the dropoff and output stable. Due to all these constraints, this is likely not our first choice due to the complicated implementation to keep it regulated at temperature and support this battery's needs.

### **Lithium Sulfur Dioxide**

$\text{LiSO}_2$  batteries are made of lithium sulfur dioxide. They work by having a lithium metal cathode and a sulfur anode. The lithium ions move from the cathode to the anode causing polysulfides to be converted to Lithium Sulfide. This reaction causes electrons to move and a current discharge. Lithium sulfur batteries are beneficial to our project mainly for their temperature control abilities. These

batteries perform the best at cold temperatures compared to the other batteries considered on this list. This means that the implementation of these batteries will be the simplest as well. We will carry less thermal risk and less insulation implementation. We will still carry out the proper testing to ensure functionality and successful operation. These batteries however, cost more but carry with them a lighter weight and high energy density.

**Table 3.19. Battery Technology Choice**  
By Authors

| Battery                | Energy Density | Temperature Effect | Cost |
|------------------------|----------------|--------------------|------|
| Lithium Ion            | 2              | 2                  | 2    |
| Lithium Polymer        | 3              | 3                  | 4    |
| Lithium Iron Phosphate | 4              | 4                  | 3    |
| Alkaline               | 5              | 5                  | 1    |
| Lithium Sulfur Dioxide | 1              | 1                  | 5    |

**Table 3.20. Battery Part Selection**  
By Authors

| Battery             | Energy Density | Temperature Effect | Cost |
|---------------------|----------------|--------------------|------|
| Varta Ultra Lithium | 2900mAh        | -40°F to 122 °F    | \$9  |
| Lithium Polymer     | 1200mAh        | -4°F to 140°F      | \$10 |
| LiFePO4 26650       | 2500mAh        | -22°F to 140°F     | \$13 |
| Energizer           | 2500mAh        | 0°F to 131°F       | \$8  |
| Saft                | 7500mAh        | -76°F to 158°F     | \$20 |
| Venom LiPo          | 5000mAh        | 14°F to 113°F      | \$25 |

When comparing these technologies we are looking at three main categories, capacity, temperature range, and cost. All of these batteries are good contenders and if our hands were tied we would be able to successfully implement any of these options. But they are not, so we are going to decide based on which of these batteries fits our needs the best. It's clear to see that the Lithium Sulfur Dioxide battery comes on top in terms of performance. Not only does it have the highest energy density but its operating temperature fits our scope perfectly. Even with capacity aside, if we were to go with one of the other options we can always include more than one battery to meet our capacity needs. The other batteries run the risk of expanding, and in some cases even exploding at low temperatures and pressures. With a high priority single fault failure point such as the batteries we want to go with the more reliable option, even if it will cost a little bit more.

This is why we have decided to go with a 2 cell Lithium Polymer battery, even though some of these batteries have more storage capability at a 1 cell level and have better temperature ranges the lithium polymer is a well studied and reliable battery source. Another aspect of batteries is their rechargeability, we are going to want to test and retest at a sub-system level as well as vehicle level. This means we are going to be running many tests that require taking in power from the battery. After these tests we want to be able to recharge our battery and not throw it away entirely every time, this will get very expensive very quickly if we were not to recharge. Regarding the temperature ranges we are confident in our payload insulation. This insulation will keep the payload at a nominal temperature throughout the entirety of the flight. We can see in the chart below the stratosphere gets down to -60 degrees celsius. We are going to test our electronic system at this temperature.

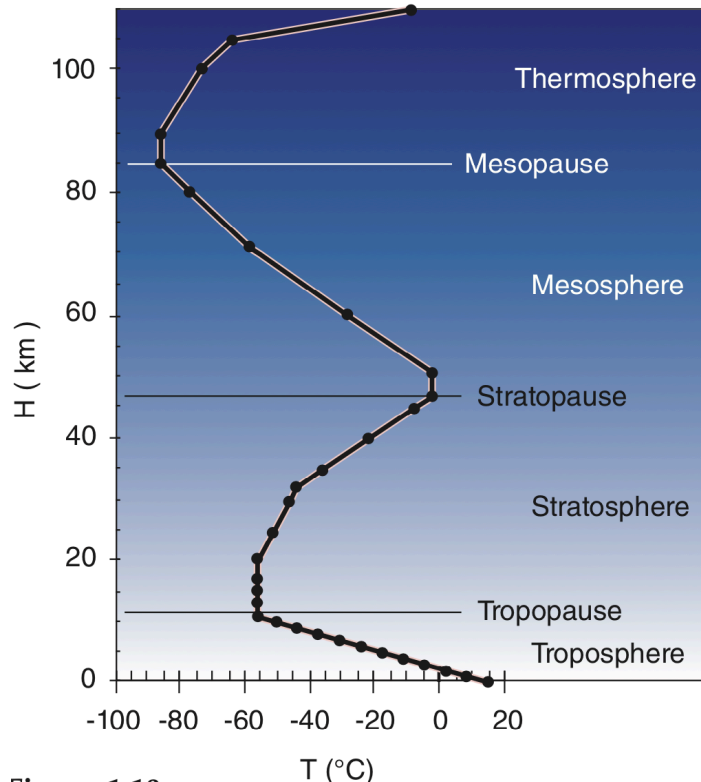


**Figure 3.13.** *Temperature vs Altitude*

Source: "UBC ATSC 113 - Layers in the standard atmosphere."

[https://www.eoas.ubc.ca/courses/atsc113/flying/met\\_concepts/03-met\\_concepts/03a-std\\_atmos/index.html](https://www.eoas.ubc.ca/courses/atsc113/flying/met_concepts/03-met_concepts/03a-std_atmos/index.html)

### 3.3.18 Altimeter

There are three sensors which compose our telemetry subsystem. The altimeter is the first of our first 3 of our Telemetry sensors. There are plenty of different methods to get this information, from pressure sensors measuring the air pressure to radar and optical based altimeters.[41] The altimeter needs to be accurate for a few reasons. First, the information itself is useful to have. It can provide a good real time update as to how close our balloon is to its target altitude and how much longer it will be in the air. Second, we can cross reference this information with our other sensors to reinforce our data, for instance, since wind speed gets higher, we can use our current altitude to justify the read wind speeds as accurate or not.

We want to design our system to either float at or pop at a certain altitude. We do this by calculating our payload weight and balloon size to fit the altitudes criteria. We can use the altimeter to transmit our elevation as key telemetry, gaining valuable information on how fast our balloon rose, what altitude it was stagnant at, and what altitude it popped at. Another use case of an altimeter could be a controlled release. For example, if we tracked our balloon's path and we wanted

to send a command to release the parachute either for an emergency ejection or for a controlled max altitude release we could do that with the data gathered from the altimeter.

### **Barometric**

A barometric altimeter works by measuring the air pressure around the device. As the air pressure decreases with a rise in altitude the barometer relates this to a rise in altitude and displays or transmits that data. The way this works is that the inside of the barometer is set at a sea level air pressure for where you are in the world. When the device rises or decreases in altitude the wafers inside the device compress (increased pressure) or expand if increasing in altitude (decreased pressure) this movement is then translated to a dial or data point for further use. [42] These altimeters are very reliable and simple to implement making them a decent option to go with. However, the wafers are affected by temperature and require calibration so we need to consider this.

### **GPS**

A GPS based altimeter utilizes the GPS satellite constellation network to triangulate signals from various satellites. It times the signals from at least four or more satellites to figure out its exact location. [43] Subsequently once we know this exact location we are able to use this to determine altitude basing it off of where around the earth the GPS receiver is located. We are already having a GPS system on board our payload so this would be fairly easy to implement as this is a built in feature on GPS. Unfortunately with GPS there is a limit on the altitude for commercial GPS which is 18,000 meters (approximately 59,000 feet). To be able to find a GPS that goes above this is rare and more expensive but necessary for our project as we aim to reach around 100K feet. With this in mind, GPS is a reasonable option if we can find a GPS that is regulated to our target altitude.

### **Radar**

Radio Frequency applications serve a variety of use cases especially in the communication and aerospace industry. One of these applications is radar, by transmitting out pulses of radio frequency waves we can see and measure the reflections from various objects. These reflections are picked up by a receiving antenna and the disturbance pattern of the reflections is analyzed. [44] One of the applications of radar we are going to be looking at for our project is the ability to transmit these signals toward the ground and measure the time they take to reflect off the ground and return to the payload. This time measurement can be accurately translated to an altitude off of the ground. A drawback of this system we have to consider is the maximum reported altitude. Commercial off the shelf radar altimeters only have a range of about 7,500 feet with military altimeters having a range of 50,000 feet. [45] Even if we were to get our hands on a military grade radar altimeter it would still be less than our target altitude of 100K feet.

## Laser

A laser altimeter is typically used to map surfaces. This technique using infrared light is also referred to as Light Detection and Ranging (LIDAR). It uses a laser beam transmitted toward the ground. These laser reflections are picked up by an optical receiving device which then categorizes the light into a voltage and measures the time the light took from transmission to receive. The time the light took to travel is then used to calculate the distance traveled. Laser altimeters on the market are fairly expensive and have a fairly low range compared to what we need for our High Altitude Balloon experiment. Another drawback of light based systems is the reliability of clear weather for accurately tracking measurements. With weather, LIDAR and other light based systems can decrease in accuracy and range proving the system to be ineffective.

**Table 3.21. Altimeter Technology Selection**  
*By Authors*

| Altimeter  | Range | Accuracy | Ease of Implementation | Cost  |
|------------|-------|----------|------------------------|-------|
| Barometric | Best  | Okay     | Best                   | Best  |
| GPS        | Great | Good     | Great                  | Great |
| Radar      | Okay  | Great    | Okay                   | Good  |
| Laser      | Good  | Best     | Good                   | Okay  |

**Table 3.22. Altimeter Part Selection**  
*By Authors*

| Altimeter      | Range                            | Operating Temp  | Accuracy                           | Cost |
|----------------|----------------------------------|-----------------|------------------------------------|------|
| MS5611-01B A03 | 30kPa up to 110kPa               | -40 °F to 185°F | ±0.5Pa/°C.                         | \$12 |
| LPS28DFW       | 260 - 4060 hPa                   | -40 °F to 185°F | ±1hPa                              | \$16 |
| MPL311A2       | 50-110 kPa (up to 10Km altitude) | -40 °F to 185°F | 1.5 Pa / 0.3 m altitude resolution | \$10 |
| MPL115A1       | 50kPa and 115kPa                 | -40 °F to 221°F | 1 kPa Accuracy                     | \$8  |

## Altimeter Selection

With all these great choices for measuring altitude we have to look at what our priorities are for this project. This is the main reason we decided to go with the barometric altimeter. Similar to a pressure sensor, these sensors are very easily implemented into our project. They are also accurate up to a high range as they don't interfere with any government regulations or are interfered by weather. We will be carrying a GPS system for tracking purposes which can implement altitude calculations. This will be our main source of altitude measurements, however if GPS is unavailable or unable to operate past a certain altitude this barometric altimeter will be implemented for cheap redundancy.

### **3.3.19 SD Card Selection**

SD Cards are a common type of memory allocation known for their use in portable electronics such as cameras. There are some different variations in SD cards, they come in regular SD, Mini SD, and Micro SD. [46] We will be using a micro SD for our camera. To get the highest data transfer speed possible we don't want to be limited by our storage device. We will look at some various parameters to get the best performance possible while also staying within a reasonable price range. The parameters that matter to us the most that we will be rating different SD cards on is write speed, read speed, capacity, and price. The SD Card will be our main storage and data collection device. All of our video, data, and flight software will be loaded onto this. As a single point of failure we need to ensure this component is reliable, fast, and can withstand the harsh environments of the stratosphere. Below we will be looking at the different classes of SD cards, the different classes are broken up based on capacity.

#### **Micro SD**

This "standard" class of SD cards are rated for 2GB and under of storage. This device uses a FAT 12 or FAT 16 file system. [47] FAT stands for "File Allocation Table". It's a method of organizing files in a way that is readable by the operating system. FAT 12 was common in floppy disks with FAT 16 still being common today. It has a maximum partition size of 32MB. [48] Given that for example, using a standard GoPro Hero 11 at 60 FPS for one hour of footage is around 27 GB this class of SD card will not be enough to handle our footage and data.

#### **Micro SD High Capacity**

A high capacity rated SD card will be denoted by the "SDHC" found in the product name. These SD cards are rated from 2 GB to 32 GB of storage. [49] This class of SD card uses the FAT 32 file system which has a max partition size of 32 GB. These SD cards are typically used in cameras, smartphones and other low storage size electronics. This would be perfect for our application if we were only focused on capturing footage, however we are going to be pulling and storing data and telemetry from a variety of sensors and systems so we ideally want something that will be more than capable of storing a vast amount of information. The last thing we want is to run out of storage to store information.

### Micro SD Extended Capacity

An extended capacity SD card is denoted by the “SDXC” in the product name. These SD cards are rated from 32 GB up to 2 TB of storage. This file system uses 64 bits to describe files. This allows a max size of 256 TB. This file system is more than enough to support our operations. In terms of storage capacity this is also plenty to support our video, pictures, telemetry and other mission data. We are going to go with an extended capacity SD card. Now we have to compare the different speed classes available on the market.

There are three different types of speed classification the SD card industry uses. These classifications are Speed Class, Ultra High Speed Class, and Video Speed Class. Let's first look at the Speed class, this classification is not as common recently as SD cards are getting faster and faster. In the speed class we have Class 2, Class 4, Class 6, and Class 10. Class 2 is rated up to 2MB/s write speed, Class 4 is 4MB/s write speed, Class 6 is 6MB/s write speed, Class 10 is 10MB/s write speed. Now let's look at the Ultra High Speed class, this is what we will be using along with video speed. The Ultra Speed Class is broken up into two categories UHS class 1 has a minimum write speed of 10MB/s and UHS class 3 has a minimum write speed of 30MB/s. Cards that use the UHS class also have two bus interfaces, UHS-I with a max transfer speed of 104MB/s and UHS-II with 312MB/s. Next we have the video class cards which are meant to capture high quality video utilizing the UHS-II interface. Will will likely utilize these cards for our camera capture storage. The V6 class is capable of a minimum write speed of 6MB/s, V10 is a minimum write speed of 10MB/s, V30 is a minimum write speed of 30MB/s, V60 is a minimum write speed of 60MB/s, V90 is a minimum write speed of 90MB/s. One application is that the video class cards are capable of 360 degree and 8K video capture.

### Micro SD Ultra Capacity

An ultra capacity SD card is denoted by the “SDUC” in the product name. These SD cards are capable of 2TB to 128TB of storage. This is the highest capacity of SD card possible in the current market. If these are available at a speed that meets our application and for a decent price this would be ideal. Typically however, these are used in super high quality video capture devices and fast computing applications.

**Table 3.23. SD Card Technology Selection**  
*By Authors*

| SD Card        | Capacity | Speed | Cost  |
|----------------|----------|-------|-------|
| Standard       | Okay     | Okay  | Best  |
| High Capacity  | Good     | Good  | Great |
| Extended Cap   | Great    | Best  | Good  |
| Ultra Capacity | Best     | Great | Okay  |

**Table 3.24. SD Card Product Selection**  
*By Authors*

| SD Card                    | Capacity | Speed | Cost |
|----------------------------|----------|-------|------|
| <b>SanDisk Extreme Pro</b> | 256 GB   | UH-I  | \$25 |
| <b>Samsung Pro Plus</b>    | 512 GB   | UH-I  | \$59 |
| <b>Lexar Gold</b>          | 128 GB   | UH-II | \$40 |
| <b>ProGrade</b>            | 256 GB   | UH-II | \$90 |

### 3.3.20 Voltage Regulation

Voltage regulation and sensing is used as a method to maintain or change voltage from our power source. In our High Altitude Balloon payload we are going to have a variety of devices that require different voltages. For example, our sensors will require 3.3 volts whereas our RF system will require 5 volts. We need to effectively take the output from our power source and scale it up or down and distribute this to different power buses for use. We want to do this efficiently with the least amount of power lost. We also want to limit the power draw so we don't burn out any pins or the bus. In this section we will be talking about different types of regulators, specifically switching and linear. We will use a combination of the two to send power to the multiple power buses that are required for our payload applications. Next we will dive into the different control modes for these regulators.

#### Linear Regulators

Linear regulators are a form of step down converters. They are very simplistic in nature, the integrated circuit is controlled by an op amp which compares the input voltage to the desired output voltage that then steps down the input voltage to match the desired voltage. Our project uses lithium sulfur dioxide batteries, which output a voltage of 3 volts. Depending on the destination of this power, we will either need to step up or step down this voltage using these voltage regulators. Linear voltage regulators are very good at keeping a low noise floor and outputting a consistent power. These regulators are great when the input - output voltage differential is small.

There are two types of linear regulators, Shunt and Series. A series regulator is, as its name suggests, placed in series with the circuit. A shunt regulator is placed in parallel with the circuit. A type of series linear regulator is a Low- Dropout (LDO) regulator. These LDO regulators are going to be used on our PCB for voltage stabilization. LDO's are applicable when there is a small input to output

differential, we will use this at the input to power buses as well as the input to components. This ensures a stable voltage enters components for efficient usage.

### **Switching Regulators**

Switching regulators are another form of voltage regulator. They are more complicated in design than a linear regulator but offer much higher usage. To convert one voltage to another they have a switching mechanism that turns on and off, for example if we had 5 volts and want 2.5 volts we can turn the switch on and off in a common pattern to only let 50% of the voltage through. Unlike the linear regulator the switching regulator can both step up and down a voltage. These regulators offer a bigger conversion factor, allowing for the input voltage to be stretched further. With this comes some disadvantages such as a higher voltage ripple and noise floor.

There are two types of switching regulators, isolated and non-isolated. Isolated switching regulators use a transformer or some other kind of isolated conversion method to isolate the input and output as well as convert the voltage. Non-isolated switching regulators offer a higher efficiency and lower cost, we will be using non-isolated regulators to convert our voltage throughout the design.

### **Buck Converters**

A buck converter is a type of voltage regulation. It uses a variety of storage components and energy components that help reduce ripple in the voltage as well as filter the waveform. Typically a buck converter will consist of a switch that changes on and off at a certain frequency, controlled by a Pulse Width Modulation Circuit. This voltage will then flow to an energy storage device such as an inductor to smooth the current and provide continuous current to the rest of the circuit. The capacitor will then smooth the waveform and provide the final voltage to the load. This is the methodology of the most basic type of buck converter, there are lots of different types of methodologies and ideas that are used for various applications and uses. We are going to look at the different types of topologies and their use cases.

### **Boost Converters**

A boost converter is a type of circuit design that increases a voltage to a certain amount. This can be used to regulate a varying voltage as well as boost a voltage for a certain power bus. A basic boost converter works by loading up an inductor with any excess current going straight to ground. When this max current is reached the switch opens and the current flows to a stabilization capacitor and is output to the load. There are many different kinds of boost converter methods of operation and topologies.

### **Voltage Mode**

In voltage mode the output voltage is set to a fixed value by utilizing the basics of Ohm's law. Voltage mode entails holding the voltage at a certain value and changing the current to meet the demands of this voltage. One of the most

common methods of voltage mode conversion is by using a voltage divider network. This uses the common voltage divider formula commonly learned in Linear Circuits 1. You can use your target voltage and input voltage to calculate what resistors you need to use to get your target voltage. The benefits of this method is that it's very cheap and simple to implement. However it's often inaccurate and has its limitations. This method is often used in small currents applications.

### **Current Mode**

In current mode the current of the inductor is controlled to produce a fixed voltage. The switch which is typically a MOSFET is controlled by a fixed clock signal. This method of current mode application has its advantages and disadvantages, with a fixed signal many converters can be linked to the same oscillator. However this fixed signal also limits how fast the current can be changed to get to the target voltage. This topology has a large noise floor and current mode circuits must be used with noise regulation circuits.

### **Hysteric**

Hysteric converters compare a target voltage with the current voltage and then turn on until the voltage is met. These converters effectively do not need a clock as they adapt to the current state of the battery and adjust accordingly. This technique is amazing at regulating the voltage but is very unpredictable as they change the switching frequency. We can create this "virtual clock" by varying the hysteresis band. This converter is a relatively simple design and highly efficient. However it has an unpredictable Electromagnetic Interference due to the switching frequency.

### **Constant On Time**

In constant on time conversion the output voltage is sensed via a network of resistors. The lowest value of the output ripple voltage is compared to a target voltage which drives the MOSFET switch. Based on this value the MOSFET is off for a varied amount of time, however when on it is on for a constant amount of time. This allows for more stable operations and voltage. Below is a graph comparing Current Mode to Constant On Time, as we can see the Constant On Time is quicker to reach the target value.

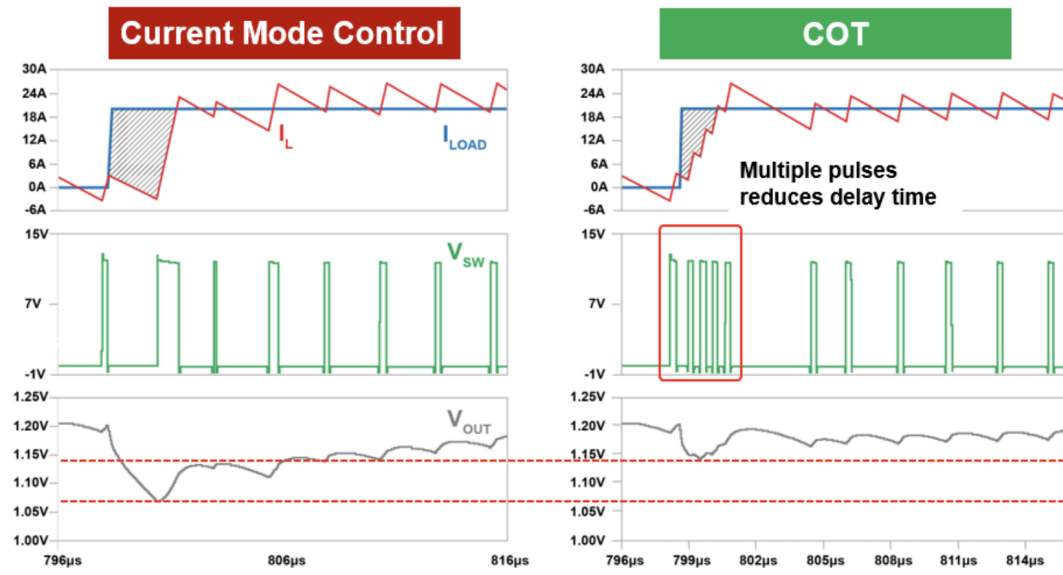


**Figure 3.14. CMC vs COT**

**Table 3.25. Technology Selection**  
By Authors

| Operation Mode   | Accuracy | Simplicity | Speed |
|------------------|----------|------------|-------|
| Voltage Mode     | 3        | 1          | 4     |
| Current Mode     | 4        | 2          | 3     |
| Hysteric         | 2        | 3          | 2     |
| Constant On Time | 1        | 4          | 1     |

### 3.3.21 Battery Sensor

The power system of the payload is a complex and fragile system. With multiple single points of failure this sub-system must be carefully designed and monitored during flight. One of the components of monitoring this is a battery sensor, placed between the battery and the rest of the power sub-system this will monitor and transmit battery information such as current voltage and charge percentage. This will enable us to see and collect this information while on the ground.

#### Adafruit LC709203F

This battery sensor is produced by large electronics company Adafruit. Looking at this sensor, it uses I2C to communicate and poll data. This data will eventually

be transmitted via the RF sub-system. This sensor is designed for a single cell battery which operates between the 3.7 - 4.2 volts range. To connect to this device it uses two JST 2 PH connectors, one for input and one for output.

### **MAX17044**

The MAX17044 is a chip made by analog devices, the MAX17043 is a similar chip made for single cell batteries while the MAX17044 is made for double cell batteries which is what we are going to be using in our case. We chose this chip because it is easy to get data with the I2C pins. The MAX17044 is also easily integrable due to being able to put our own connector.

### **SparkFun LiPo Fuel Gauge**

Sparkfun is an electronics company located in Boulder, Colorado. Looking at their LiPo fuel gauge it also uses I2C to communicate the battery percentage level as well as a “sophisticated algorithm” to detect and measure battery voltage. When looking at the datasheet however, this uses the MAX17043 chip.

**Table 3.26. Battery Sensor Part Comparison**

*By Authors*

| <b>Part</b>                     | <b># Of Cells</b> | <b>Integration Score (1-5)*</b> | <b>Cost</b> |
|---------------------------------|-------------------|---------------------------------|-------------|
| <b>Adafruit LC709203F</b>       | 1                 | 2                               | \$6.95      |
| <b>MAX17044</b>                 | 2                 | 1                               | \$10        |
| <b>SparkFun LiPo Fuel Gauge</b> | 1                 | 3                               | \$12.50     |

*\*1 is the easiest to integrate, 5 is the hardest.*

Looking at the battery sensors we are deciding to go with a MAX17044, not only is this the only one that can support our battery but it also allows us to be able to put our own connector. The MAX17044 will be very easy to integrate as we can design it right onto our power PCB. After the power goes through this sensing circuit, the result will be polled from the MCU and the power will be transmitted to the voltage regulating circuits for further use.

### **3.3.22 Radio Module**

The Radio Module is an essential part of being able to communicate, control, transmit and receive data. The radio module essentially allows two points of contact to be “speaking the same language”. This means they are running the same modulation, and configuration to allow for accurate reading of signals and

packets. Our radio module on the payload will be transmit only. Meanwhile our radio module on the ground will be received only. This is because the payload will serve as the active system, collecting and storing data. This data, telemetry, and information will then be transmitted and received by the ground station which will be utilizing the same radio module as the payload.

### **APRS**

Automatic Packet Reporting System (APRS) is a method and standard of communicating packets across the air. In the United States everyone operates at a frequency of 144.39. This way information can be picked up by other APRS users and displayed on a public database. We are going to be using APRS due to the ease of implementation and amount of users transmitting on APRS. The user count is the biggest benefit and serves as redundancy in case we lose contact with the balloon. These users will pick up our signal and upload our position.

### **LoRa**

LoRa is a similar methodology to APRS as its an open user transmission module. LoRa is known for its long range and highly accurate bi-directional capabilities. As with APRS, users can pick up LoRa signals and upload them to an open database for the public to see. LoRa is popular in Europe and does not have a lot of users in the United States. Operating at 433 MHz or 915 MHz LoRa transmitters are very accessible for purchase. This will make procurement and implementation on the easier side.

### **UHF / VHF**

Ultra High Frequency and Very High Frequency transmitters are more difficult to implement and very costly. However they are able to transmit more as they have a higher frequency. For our mission, this type of transmitter will not be necessary as we are only transmitting telemetry and data.

### **Iridium**

The iridium constellation is a network of satellites in Low Earth Orbit used for communication purposes. A module from iridium would remove the concern of losing communication with the payload, it would also be easy to implement and allow for bigger data to be transmitted. However, this system is very pricey and out of our budget.

**Table 3.27. Radio Technology Comparison**  
*By Authors*

| <b>Module</b> | <b>Data Access</b> | <b>Ease of Implementation</b> | <b>Cost (1-5)*</b> |
|---------------|--------------------|-------------------------------|--------------------|
| <b>APRS</b>   | 1                  | 2                             | 1                  |
| <b>LoRa</b>   | 2                  | 1                             | 2                  |

|                |   |   |   |
|----------------|---|---|---|
| <b>Iridium</b> | 3 | 3 | 3 |
|----------------|---|---|---|

*\*1 is the lowest cost, 5 is the highest.*

**Table 3.28. Radio Part Selection**  
By Authors

| <b>Module</b>                    | <b>Frequency</b> | <b>Data Rate</b> | <b>Cost (USD)</b> |
|----------------------------------|------------------|------------------|-------------------|
| <b>RadioMetrix HX1-144.390-3</b> | 144.39           | <10kbps          | \$65              |
| <b>RFM95CW</b>                   | 137              | 0.018~37.5 kbps  | \$10              |
| <b>Iridium 9602</b>              | 1616 MHz         | 1408kbps         | \$261             |
| <b>SX1276</b>                    | 915 MHz          | 300kbps          | \$90              |

Our project will transmit live data down to the base station. Choosing the correct transmitter is a very important aspect for the entire RF subsystem. All of the other RF components will be chosen for the ability to collaborate and work efficiently with this device. We are going to be incorporating the SX1276 as our radio module, this chip uses the LoRa network at 915 MHz. We chose this specific chip and settings based on the availability of hardware as well as the ease of implementation.

### 3.3.23 Navigational Options

#### Technology Comparison: GNSS vs Cellular Networks

There are two mainstream technologies that can be used to track the Balloon Payload System: Global Navigation Satellite System (GNSS), and Cellular Networks. GNSS relies on satellite constellations to locate a receiver, while Cellular Networks locate a receiver with cell towers. There are three different criteria to consider when comparing these two technologies: Accuracy, Service area, and Legality.

#### Accuracy

GNSS includes six different satellite constellations, all operated by different countries. The most common for those in the west is the United States' Global Positioning System (GPS). Others are China's BeiDou (BDS), the EU's Galileo, Russia's GLONASS, India's Navigation India Constellation (NavIC), and Japan's Quasi-Zenith Satellite System (QZSS) ([GPS.Gov: Other Global Navigation Satellite Systems \(GNSS\). n.d.](#)). In terms of accuracy, Galileo claims the top spot. A recent press release by the European Commission states that Galileo High Accuracy Service (HAS) can perform better than 20 cm horizontally and 40 cm vertically ([World's Most Accurate Positioning Service, Galileo's HAS, Goes Live.](#)

[2023](#)). In contrast, the US claims an average accuracy of 4.9 m with GPS ([GPS.gov: GPS Accuracy, n.d.](#)). Cellular Networks are generally much less accurate than GNSS, on the scale of 500 m to 1500 m ([How GPS, Cell Tower and Wi-Fi Triangulation Help in Tracking Location?, 2024](#)).

### Service Area

Given their orbital nature, satellites are almost always available to a receiver. In contrast, if there are not at least three cell towers in range, cellular triangulation is impossible. There is also the issue of altitude; certain GPS receivers can work as high as 80,000 m ([Eagle Flight Computer, n.d.](#)), whereas cell service practically drops off around 3000 m ([Testing Cell Signal at Altitude, 2023](#)). This is a significant shortcoming compared to GNSS, as the payload will be spending the majority of its time during flight well above 3000 m. This would only allow us to track the balloon during the early stages of ascension and the last stages of descent.

### Legality

The most important aspect of this project is that it does not violate any US law or FAA regulations. Doing so could result in a fine and soil our reputation with regulatory authorities, which could result in approval challenges for future flights. GNSS is allowed to function on a flying payload above 60,000 feet only if it is traveling at less than 1000 knots ([High-Altitude Smartphone GPS Experiment — Night Crew Labs, n.d.](#)). Given our payload is suspended by a balloon, and therefore will not be traveling at anywhere close to 1000 knots, our system is legal. However, the FAA forbids any device operating on a cell network from leaving the ground in any type of aircraft - including balloons ([Federal Communications Commission 22.925 – High Altitude Science, n.d.](#)). Because of this, operating a device with cellular network connectivity during flight would be a violation of FAA regulations. The only way to operate legally, would be to only enable cellular connectivity when the payload lands, giving us only one datapoint to track. Given that GNSS far outperforms using a cellular network, our group has chosen it as our navigational system. Refer to *Table 3.29*.

**Table 3.29** *GNSS vs Cellular Network*  
by Authors

|              | GNSS | Cellular Network |
|--------------|------|------------------|
| Accuracy     | Best | Not Best         |
| Service Area | Best | Not Best         |
| Legality     | Best | Not Best         |

### GNSS Technology Selection

The GNSS technology we select will be one of the most important pieces of the Balloon Payload System, as none of the data we store onboard or camera

footage we record will be of any use to us if we cannot accurately track and recover it. The ideal GNSS product will function at the highest altitude possible, be easy to interface with, and have multiband support.

Not all GNSS technologies operate at the same height, some can lock out as low as 60,000 feet, while others are unlocked and can operate beyond this threshold. It is critical that we choose a technology that can operate above this altitude, as it will not only allow us to better track our payload, but also provide consistent data points to correlate with other readings after recovery. Our team would be able to leave a larger impression if we were able to graph the lateral and longitudinal location of our flight along with altitude on three axis.

GNSS technologies can be assembled from discrete parts or purchased in complete packages that interface over standard communication protocols. Assembling a GNSS receiver system from scratch allows us additional design experience, but also introduces opportunities for a plethora of errors to creep in due to the team's limited design experience. Ultimately this would result in significant amounts of time spent diagnosing and repairing bugs, which would impede progress on other more-important aspects of the project. To avoid a stagnational situation, our team has opted to choose a pre-packaged GNSS technology that triangulates location then sends the coordinates over a standard communication protocol (I2C, SPI, UART, etc.) to the MCU.

For decades, GPS only allowed civilians to access one band - L1, while the military could access a more accurate encrypted band - L2. Recently, the US opened up a new band to civilians - L5, which increases both the accuracy and reliability of the receiver. Galileo also has a similar band which provides additional accuracy over a single band connection. Being able to receive and compare multiple bands allows the GNSS unit to determine which signals are reflected and which are not. A multiband enabled receiver will allow the payload to be accurately located if it lands in an area where the signal is reflected off of structures such as trees in a forest, mountains in a valley, or buildings in a metropolitan area ([Why Multi-band? Q&a With Garmin Engineer Jared Bancroft | Garmin, 2021](#)).

### **Ublox MAX-M10S**

The Ublox MAX-M10S is a small, relatively inexpensive module that delivers decent performance. One of the most impressive features of this chip is its availability to operate up to 80,000 meters, or approximately 240,000 feet. This allows a huge ceiling for future missions if we choose to raise our target altitude. The MAX-M10S also operates at velocities of up to 500 meters per second or over 1100 miles an hour, this allows the payload to maintain a GPS lock during the initial descent stage where velocity peaks. In addition, this unit has a velocity accuracy of 0.05 meters per second and a dynamic heading accuracy of 0.3 degrees. The MAX-M10S also provides both UART and I2C communication protocols, making it easy to integrate into the Balloon Payload System.

The MAX-M10S claims a position accuracy of 1.5 meters, which is not the best, but considering the size of the payload in relation to the vertical, latitudinal and longitudinal distance it will travel - 1.5 meters is acceptable. Where the MAX-M10S disappoints is the fact that it is not a multi-band system, which is understandable given the price point. Where the MAX-M10S somewhat atones for this deficiency is its ability to communicate on four different GNSS networks: GPS, GLONASS, BDS and Galileo ([MAX-M10S, 2024](#)). Overall, the MAX-M10S provides solid features at an affordable price.

### **Ublox NEO-F10N**

The Ublox NEO-F10N is quite similar to its cousin the MAX-M10S. It operates up to an altitude of 80,000 meters and can stay locked to satellites at speeds up to 500 meters per second. It also maintains a velocity accuracy of 0.05 meters per second, and a dynamic heading accuracy of 0.3 degrees. The NEO-F10N supports four different GNSS constellations: GPS, Galileo, BeiDou, and NavIC. The main feature that sets this unit apart from the MAX-M10S is its ability to communicate on the L5 band, giving it multi-band support. This not only allows positional accuracy of up to 1 meter, but also much more consistent accuracy in obstructed areas. Where this chip falls short compared to the MAX-M10S is its low number of communication protocols, the NEO-F10N only supports UART ([NEO-F10N, 2023](#)). This limits the options we have for communicating with the Balloon Payload System. Unlike I2C which is a bus that can support multiple peripherals, each UART port on the MCU can only support one. This means that if we choose too many peripherals that support only UART, we risk running out of quickly UART ports on the MCU. Overall, the NEO-F10 proves to be a close competitor to the MAX-M10S.

### **Ublox ZED-F9P**

The Ublox ZED-F9P is an absolute juggernaut of a GNSS module. It supports GPS, GLONASS, Galileo, and BeiDou constellations on both L1 and L5 bands. The ZED-F9P also supports Real Time Kinematics (RTK), which is a technology used in surveying for centimeter-level accuracy. Real Time Kinematics utilizes a reference receiver as the base station, and another receiver known as the rover. The base station is set up on a pre-surveyed area whose coordinates are known, the base station then locks on to a group of satellites. The base station sends out a signal with a correction factor that the rover uses to calculate its location with extreme accuracy ([What Is Real Time Kinematics? - Everything RF, n.d.](#)). The ZED-F9P is accurate down to 10 millimeters when RTK is enabled.

Unfortunately, we cannot utilize RTK in our application, as we do not have the budget to afford a base station or a surveying service to verify its position. That being said, we do not need the levels of accuracy RTK provides, 10 millimeters vs 1.5 meters does not make a difference when one is tracking an object roughly the size of a soccer ball over tens of miles. Regardless, RTK is an interesting technology that at the very least is worth exploring.

The ZED-F9P operates up to 80,000 meters, can keep a lock on satellites at up to 500 meters per second, and has a velocity accuracy of 0.05 meters per

second and a heading accuracy of 0.3 degrees ([ZED-F9P-04B, 2024](#)). These specifications are identical to the previous two modules discussed. This is likely because they all come from the same manufacturer - Ublox, the reason no other vendors were included is because none of them readily supplied datasheets. The ZED-F9P offers the most communication options by far: it utilizes UART, SPI, I2C, and USB 2.0. This allows us maximum flexibility for integration into the Balloon Payload System. Overall, the ZED-F9P offers many of the same features as the MAX-M10S and NEO-F10N, the main advantage it holds over these other modules is its connectivity options, as RTK capability is not feasible or needed in our case.

### GNSS Selection

Comparing the three options, they all share these common specifications: maximum operating height of 80,000 meters, maximum velocity of 500 meters per second, velocity accuracy of 0.5 meters per second, and a heading accuracy of 0.3 meters per second. They all vary in maximum accuracy, but this is based on which satellite constellation is available. Nominally, all three modules are accurate to 1.5 meters. Where they differ is multiband support and connectivity options. The MAX-M10S is the only module that does not offer multiband support, whereas the NEO-F10N only offers one connectivity option. The ZED-F9P offers multiband support and multiple connectivity options but at the sacrifice of a high price tag and a difficult-to-solder LGA package. The ZED-F9P is overkill for our application, that leaves the MAX-M10S and NEO-F10N. Ultimately, the decision comes down to which is more important: connectivity options or multiband support. The MAX-M10S was chosen for its I2C support, as this was ruled more important than multiband capability. Given that the Balloon Payload System will be launched and recovered in a rural area with little to no large structures that could reflect GNSS signals, multiband support is not critical for mission success. Refer to *Table 3.30* for a comparison of the three GNSS modules.

**Table 3.30** *GNSS Comparison*  
by Authors

|                                | MAX-M10S | NEO-F10N | ZED-F9P |
|--------------------------------|----------|----------|---------|
| <b>Altitude Ceiling (m)</b>    | 80,000   | 80,000   | 80,000  |
| <b>Max Velocity (m/s)</b>      | 500      | 500      | 500     |
| <b>Positional Accuracy (m)</b> | 1.5      | 1        | 0.01    |
| <b>Velocity Accuracy (m/s)</b> | 0.5      | 0.5      | 0.5     |

|                             |       |       |                 |
|-----------------------------|-------|-------|-----------------|
| <b>Heading Accuracy (°)</b> | 0.3   | 0.3   | 0.3             |
| <b>UART</b>                 | Yes   | Yes   | Yes             |
| <b>SPI</b>                  | No    | No    | Yes             |
| <b>I2C</b>                  | Yes   | No    | Yes             |
| <b>USB</b>                  | No    | No    | Yes             |
| <b>GPS</b>                  | Yes   | Yes   | Yes             |
| <b>Galileo</b>              | Yes   | Yes   | Yes             |
| <b>GLONASS</b>              | Yes   | No    | Yes             |
| <b>BeiDou (BDS)</b>         | Yes   | Yes   | Yes             |
| <b>NavIC</b>                | No    | Yes   | No              |
| <b>Multiband</b>            | No    | Yes   | Yes             |
| <b>Cost Per Unit (\$)*</b>  | 21.00 | 49.00 | 129.00 - 138.00 |

\*Prices on Digikey as of 7/21/2024

### 3.3.24 IMU Options

#### Technology Comparison: MEMS IMU vs FOG IMU

The Balloon Payload System relies on an Inertial Measurement Unit (IMU) to record acceleration, heading, and velocity data. This data can be used to supplement the GNSS module to provide navigational information when a satellite lock cannot be maintained. A decent IMU should perform with minimal bias instability, be compact in size, and be affordable.

The two dominant technologies when it comes to IMUs are Micro Electro-Mechanical Systems (MEMS), and Fiber Optic Gyroscopes (FOG). MEMS are microfabricated moving mechanical structures that are usually packaged like any other electronic device. They convert mechanical energy from rotation, acceleration, etc. to electrical signals that can be deciphered into readings such as heading, velocity, location, etc. Fiber Optic Gyroscopes rely on the Sagnac effect in order to convert the phase of light to a directional heading.

Fiber Optic Gyroscopes are extremely accurate, they are found in military, aerospace, and aquatic navigation applications. FOGs are known for having little to no drift and very low bias instability over time. Some FOGs are also able to measure the angular rate of the earth's rotation while still in motion, and determine the location of true north. FOGs are quite resistant to vibration due to

their lack of any moving parts, they are however temperature sensitive, but not to the degree of a MEMS gyroscope.

MEMS gyroscopes are much more popular among consumers and industry than FOGs. This is not because they are more accurate than FOGs, in fact quite the opposite is true, but because of their size and cost advantage. High-end MEMS gyroscopes are generally ten times less expensive than FOGs. MEMS gyroscopes also weigh much less and take up much less space than FOGs, this has allowed for their mass adoption in drones, cars, camera positioning, etc ([Hayward & Navigation, 2024](#)).

FOGs and MEMS are both powerful solutions, each tailored to meet a specific set of needs. FOGs are the best choice where there is little to no GNSS service and navigation is critical (such as in a military application). MEMS are the best choice where cost, weight, and size are primary concerns versus factors like attitude accuracy and bias instability. Given that the Balloon Payload System needs to be as light-weight as possible, as affordable as possible, and that it will be operating in clear view of most GNSS systems for the duration of its flight, a MEMS gyroscope is obviously the best answer. Refer to *Table 3.31* for a comparison of FOGs vs MEMS.

**Table 3.31 FOG vs MEMS Gyroscope**  
*by Authors*

|                               | FOG               | MEMS           |
|-------------------------------|-------------------|----------------|
| <b>Bias Instability</b>       | Up to 0.0001°/hr. | Up to 0.1°/hr. |
| <b>True North Positioning</b> | Yes               | No             |
| <b>Footprint</b>              | Large             | Small          |
| <b>Weight</b>                 | Heavy             | Light          |
| <b>Cost (Vs competitor)</b>   | 10X More          | 10X Less       |

### **MEMS Technology Selection**

Choosing the correct MEMS gyroscope is critical to collecting and relaying accurate telemetry information such as heading, pitch angle, roll angle, yaw (rotational) angle and velocity. A MEMS IMU should have at least six degrees of freedom, low bias instability, high update rate, a temperature compensation circuit, and a wide sensing range.

### **TDK InvenSense ICM20948**

The TDK InvenSense ICM20948 is (what TDK claims) the “World’s lowest power 9-axis MEMS motion tracking device.” The ICM20948 operates on a 1.8V architecture which allows it to consume 2.5 milliwatts during operation. The ICM20948 contains a 3-axis gyroscope unit, a 3-axis accelerometer unit, and a 3-axis magnetometer unit. This unit processes that data via multiple 16-bit ADCs and programmable filters. The gyroscope unit can be programmed to have a range of up to +/-2000 degrees per second. The accelerometer unit can also support up to +/-16 g, and the magnetometer supports a range of +/- 4900mT.

The gyroscope has an update rate of up to 9 KHz, the accelerometer has an update rate of up to 4.5 KHz, and the magnetometer has an update rate of 100 Hz. The ICM20948 also contains a digital output temperature sensor which can aid in sensor calibration. The gyroscope unit has a bias instability (or Zero Rate Output) of +/-5 degrees per second, the bias instability over temperature is +/-0.05 degrees per second per celsius. The accelerometer unit has a component-level zero g output of +/- 25 mili-g, and a zero g output vs temperature of 0.8 mili-g per celsius. The ICM20948 has communication support for both I2C and SPI ([ICM-20948, 2017](#)). Overall, the ICM20948 is a very well-rounded unit that offers 3 different kinds of measurements in one package, while consuming low power and not breaking the bank.

### **CEVA BNO086**

The BNO086 is a 9-axis gyroscope / accelerometer/ magnetometer that also packs an ARM M0+ processor which performs sensor fusing to produce rotation vector headings which includes drift correction. The BNO08X series was originally designed for VR applications that would interface with Android-based smartphones, hence the onboard processor that spares the smartphone the brute of the computation.

The datasheet for the BNO086 lists performance characteristics in an odd format compared to other sensors, this is because the values shown are what the unit delivers after sensor fusion and drift correction. The “heading drift” a.k.a bias stability is stated to be 0.5 degrees per minute, or 0.008 degrees per second. The accelerometer is stated to be accurate to 0.3 m/s<sup>2</sup> or 0.031 g. There is no data on how the accuracy changes over temperature. The datasheet states a magnetometer accuracy of 1.4 uT.

The maximum gyroscope update rate is 1000 Hz, the maximum accelerometer update rate is 500 Hz, and the maximum magnetometer update rate is 100 Hz. The BNO086 communicates over I2C, SPI, and UART. This unit also has a dedicated UART-RVC connection that is dedicated for Robot Vacuum Cleaners. This interface only transmits heading and sensor information at 100 Hz over the UART TX pin ([BNO08X Data Sheet, 2023](#)). The CEVA BNO086 is a solid choice for our application, given that it performs sensor fusion to generate the most accurate heading by balancing out the gyroscope, accelerometer, and magnetometer drift.

### ST ISM330DHCX

The ST ISM330DHCX is a 6-axis gyroscope / accelerometer combination device. The gyroscope has twice the range of the ICM20948 at 4000 degrees per second, the accelerometer can also support up to 16 g. The gyroscope has a bias instability of +/- 3 degrees per hour, or  $8.3 \times 10^{-4}$  degrees per second. This is an excellent rating. The accelerometer has a zero-g drift of +/- 10 mili-g. The bias instability over temperature is +/- 0.005 degrees per second per celsius, and the accelerometer zero-g drift over temperature is +/- 0.1 mili-g per celsius. In addition, the ISM330DHCX has an internal temperature compensation unit, and communicates over SPI and I2C. The accelerometer has an update rate of up to 6667 Hz, the gyroscope has the same maximum update rate. The ISM330DHCX features a “machine learning core” which processes data from the accelerometer, gyroscope, and even external sensors (such as a magnetometer) which can be connected to the unit via an auxiliary SPI port. The user can define a time window and filters within it to process the data in multiple ways. Overall, the ISM330DHCX is a solid contender for use in the BPS ([ISM330DHCX, 2020](#)). Although it doesn't feature a built-in magnetometer, its accuracy is amazing, and it can support twice the gyroscope range of its contenders.

### IMU Selection

Comparing the three different IMU units, it is clear that the ST ISM330DHCX is the best choice. Although it does not have a built-in magnetometer, the gyroscope and accelerometer are extremely accurate. This unit may lack an onboard processor compared to the BNO086, but for our application, such a feature is not necessarily needed. The BNO086 also lacks a significant amount of performance information in its datasheet compared to the ISM330DHCX, which does not weigh well in its favor. The ICM20948 is a fair competitor, especially since it sports a built-in magnetometer, yet it falls behind the ISM330DHCX by a large factor when it comes to gyroscope and accelerometer drift over temperature, gyroscope bias instability and accelerometer zero-g instability, accelerometer update rate and gyroscope range. Refer to *Table 3.32* for a graphable comparison of the three IMU choices.

**Table 3.32** *IMU Comparison*  
by Authors

|                                      | ICM20948 | BNO086 | ISM330DHCX |
|--------------------------------------|----------|--------|------------|
| Degrees of Freedom                   | 9        | 9      | 6          |
| Gyro Drift over Temperature (dps/°C) | +/- 0.05 | N/A    | +/- 0.005  |

|                                                         |          |           |             |
|---------------------------------------------------------|----------|-----------|-------------|
| <b>Accelerometer Drift over Temperature (mili-g/°C)</b> | 0.8      | N/A       | 0.1         |
| <b>Gyroscope Bias Instability (dps)</b>                 | +/- 5    | +/- 0.008 | +/- 0.00083 |
| <b>Accelerometer Zero-g Instability (mili-g)</b>        | +/- 25   | +/- 31    | +/- 10      |
| <b>Magnetometer Accuracy (uT)</b>                       | N/A      | 1.4       | N/A         |
| <b>Gyroscope Update Rate (Hz)</b>                       | 9000     | 1000      | 6667        |
| <b>Accelerometer Update Rate (Hz)</b>                   | 4500     | 500       | 6667        |
| <b>Magnetometer Update Rate (Hz)</b>                    | 100      | 100       | N/A         |
| <b>Temperature Compensation</b>                         | Yes      | Yes       | Yes         |
| <b>Gyroscope Range (dps)</b>                            | +/- 2000 | N/A       | +/- 4000    |
| <b>Accelerometer Range (g)</b>                          | +/- 16   | N/A       | +/- 16      |
| <b>Magnetometer Range (mT)</b>                          | +/- 4900 | N/A       | N/A         |
| <b>Cost Per Unit (\$)*</b>                              | 8.64     | 16.85     | 9.60        |

\*Prices on Digikey as of 7/21/2024

## 3.4 Software Selection

For this High-Altitude Balloon project, the software selection was crucial for the development and implementation of a microcontroller, which would be responsible for communicating and controlling with the different peripherals to obtain reliable and accurate data, with the final goal of being able to analyze and display all the data collected to the users in a good-looking and organized GUI (Graphical User Interface) once the payload is back on ground.

### 3.4.1 Microcontroller IDE Comparison

When it comes to programming microcontrollers, it is important to understand which IDE (Integrated Development Environment) will be used. For microcontrollers, in general, the most common programming languages used are C and C++, although it is also possible to use other programming languages such as Assembly or Python. Being that C and C++ are the most common programming languages to program a microcontroller, the choice of an IDE mostly relies on which IDE has the best and most compatibility with the microcontroller planned to use.

#### Arduino IDE (C/C++)

One of the most popular and easier IDEs to use is the Arduino IDE, which is a user-friendly IDE for the Arduino family, although it can also be used to program other microcontrollers by finding the libraries needed for the specific microcontroller by searching them within the Arduino IDE. Due to its simplicity to use, it also supports a wide variety of libraries to support different peripherals, such as cameras, temperature, humidity, air pressure, among many other sensors.

Additionally, thanks to its popularity there is also a good amount of resources such as example codes, tutorials, and forums, that can be beneficial when programming a microcontroller. It is also important to note that although the Arduino IDE is one of the easiest IDEs to use, its lack of advanced features using lower-level programming can directly affect the performance and optimization of the microcontroller in use.

#### ESP-IDF (C/C++)

The Espressif IoT Development Framework is the official development framework for the ESP32 series, meaning control and optimization will be maximized to program this microcontroller. The ESP-IDF contains the latest and most optimized features, libraries, and tools needed to make sure the microcontroller is programmed in the most effective and optimized way possible. ESP-IDF is open-source, meaning it can be found for free in platforms such as GitHub. Similarly to the Arduino IDE, the ESP-IDF also supports various software components such as peripheral drivers (cameras, temperature, humidity, and air pressure sensors, among others), and it contains an extensive amount of documentation that can be used by the general public as a tutorial on how to

implement their different software components and hardware peripherals to their projects, which can be very convenient for beginners and amateurs.

Finally, similar to PlatformIO (VSCode), it can be challenging for beginners to start using the ESP-IDF if they do not have any previous experience, mainly because of the extensive feature sets they provide. However, the ESP-IDF is also a solid option to consider to work on projects that require developers to have more control over the microcontroller and develop more complex applications.

### **Simulink (MATLAB )**

Although MATLAB is mainly used for data analysis and computation, the capabilities of MATLAB are not limited to only that. Simulink is a MATLAB extension that provides a graphical programming environment, meaning that a microcontroller can be programmed using graphical modeling and simulation (graphical block diagramming tool). Interesting features from Simulink include a graphical editor for modeling all components of a system, and an automatic code generator from the graphical block diagrams. Finally, it can be helpful to program a microcontroller for a project that might require complex data analysis and computation being that MATLAB is mainly used for that purpose, making the implementation of the functions into the project easier.

### **PlatformIO and Visual Studio Code (C/C++)**

PlatformIO is a user-friendly IDE which can be integrated with Microsoft Visual Studio Code (VSCode) that includes and provides an extensive amount of powerful features, tools, and libraries that simplifies the process of programming a microcontroller, in addition to supporting multiple microcontrollers. One of the features that makes PlatformIO a better option compared to other IDEs is its advanced debugging tools, variable monitoring, and breakpoint setting, which is very useful when working on more advanced projects that require users to debug their program to understand the behavior of the code in order to track errors within the code.

As mentioned before, when it comes to advantages, PlatformIO with Visual Studio Code has an extensive list of tools and features that makes it stand out from other IDEs, however, as a consequence of all the features provided by this IDE, it may be difficult for beginners and amateur projects to start working with this IDE with no previous experience, meaning the process of programming the microcontroller will be extensive and tedious rather than simpler and more flexible. Finally, when it comes to bigger and more complex projects, the demand of the IDE may increase, meaning system performance may be affected, which as a result will make it run slower and will possibly make it more difficult and time consuming to debug.

### **STM32CubeIDE (C/C++)**

STM32CubeIDE is an advanced IDE developed for STMicroelectronics microcontrollers, more specifically for the STM32 microcontrollers and microprocessors. Since this IDE was designed for the STM32, it includes the most reliable and optimized libraries to control the microcontroller. The

STM32CubeIDE provides an extensive amount of tools and features developed for peripheral configuration, code generation, code compilation and advanced debugging features such as CPU core, peripheral register, and real-time tracing, which are very helpful to track problems within the project. In addition to that, STM32CubeIDE integrates the STM32CubeMX, which is a graphical tool that allows users to easily configure the STM32 microcontroller, making peripheral configuration, initialization codes, and setup easy. STM32CubeIDE is also a good option for beginners due that is well documented, meaning there are plenty of resources useful for the correct use of this IDE, including example codes and videos, and the IDE is designed to be user-friendly with a simple interface. Finally, similar to PlatformIO and ESP-IDF, the STM32CubeIDE is an excellent option to program a microcontroller for both beginners and experienced developers, and some of the few downsides are the incompatibility with other microcontrollers, due that this IDE might not be compatible for most microcontrollers, and it might require some time to fully learn and understand how to use this IDE to program a microcontroller.

### **Other IDEs/Frameworks(C/C++)**

Other than the four previously mentioned IDEs/Frameworks, there is a wide variety of other IDEs/Frameworks that can be used to program a microcontroller, which will allow the users to interact with the microcontroller in different ways and provide unique and sophisticated features to communicate and program a specific microcontroller to achieve a project's goal. Finally, some of the most famous microcontrollers already have specific IDEs/Frameworks that were designed for that specific microcontroller, providing helpful features and tools for optimization and efficiency of the microcontroller.

### **Comparison and Decision**

Due to the fact that the main programming languages to program a microcontroller are C and C++, although it can also be programmed with Python, Java, or Assembly, C and C++ are going to be the choice for the microcontroller programming language for this project. C and C++ are the standard programming languages for embedded systems due to their efficiency and hardware control. The main difference between C and C++ from the rest of programming languages is that they provide the necessary tools for low-level access to control the peripherals connected to the microcontroller.

The IDE decision mainly relies on the factor of which microcontroller is going to be used for this project, and even though there are extensions and libraries that can be used to maximize the compatibility of the different IDEs and microcontroller options, it was decided to use the IDE which does not require the most amount of knowledge to use due to lack of programming experience in the group and also for time management reasons, therefore the Arduino IDE will be the IDE used to program the microcontroller. The Arduino IDE was designed to provide the most reliable tools and features to achieve a proper programming of almost all popular microcontrollers available in the market, and including all the documentation that can be found online, it will allow the group to explore features

that allows to easily configure and initialize peripherals, making the microcontroller programming easier.

In conclusion, considering the main and most used programming languages to program a microcontroller, and due to the fact that a ESP32 microcontroller will be used, the decision of using C and C++ as the programming language and Arduino IDE as the IDE seems to be a great fit for our project.

### **3.4.2 Data Analysis / GUI Development Software Selection**

For this High-Altitude Balloon project, one of the main goals is to collect and analyze data, to then present it to the users in a good-looking and simplistic GUI (Graphical User Interface). For data analysis, the most common programming languages used are Python and Java, although sometimes C++ or JavaScript can also be used for data analysis. For GUI development, the most used programming languages are Python and JavaScript, although C#, Java and HTML can be used for GUI development. For this reason, the software selection is important to be able to interpret and display the data to users, leading to the understanding of the environmental conditions recorded by the balloon.

#### **MATLAB (Simulink/Data Analysis)**

MATLAB is a programming language for data analysis, which can be used for numerical analysis and data visualization. With the implementation of Simulink, different data formats can be obtained such as graphs, charts, plots, simulations, among others. An unique feature about MATLAB, and its implementation with Simulink, is that a GUI would not be required because MATLAB itself would be the user interface. However, this would not provide the most pleasant user experience, mainly because users would have to have some knowledge on how to manipulate and analyze the raw data saved by the peripherals.

#### **Python (Data Analysis/GUI Development)**

As previously mentioned, because of its versatility and wide variety of libraries and public resources, Python is a powerful tool that can be used for both data analysis and GUI development. Among the different libraries included with Python, some of the most useful towards the project are NumPy and Pandas for data analysis and manipulation. Numpy is a library that supports a large collection of high-level mathematical functions, which are going to be useful to this project for numerical data processing from the raw data and datasets collected, which will be beneficial for further data analysis and visualization. Pandas is a library used for data manipulation and analysis, it offers data structures for handling structured data, meaning Pandas is useful for cleaning data, making it easier to manage for future and further data analysis and visualization.

In addition to the data analysis and manipulation libraries, there are different libraries such as Matplotlib, PyGame and Tkinter for GUI development. Matplotlib is a plotting library used to create static, animated, and interactive visualizations such as plot graphs, histograms, and charts that can be generated from the

processed data from the balloon. PyGame is a Python library used primarily to create and develop games, however, for this project, PyGame can be used to develop a simple and user-friendly GUI and implement the different types of visualizations generated from the balloon data. Finally, Tkinter is a Python library used to create and develop simple and efficient GUIs, providing various controls such as buttons, labels and text boxes for example. Twinker can be used to create an application, or executable file, that can be used by any Microsoft Windows computer, providing compatibility for user interaction with the data collected.

### **C# (.NET/GUI Development)**

C# is a high-level programming language that is commonly used for web app development, game development, and applications. More specifically, .NET, that uses C#, is the platform used to create and develop desktop, web, and mobile applications. Multi-platform applications supported by different operating systems such as Windows, Linux, macOS, IOS, and Android can be developed by using .NET MAUI (.NET Multi-platform App UI), by simply using a single C# codebase and project system for all devices.

### **Comparison and Decision**

Due to the fact that Python requires the least amount of experience and has more variety of documentation compared to the other programming languages, it was decided that Python will be used for both the data analysis and GUI development. Python offers different tools and libraries, as mentioned before, that align with the goals of this project of interpret and manipulate data from the peripherals to later on display it in a simple user-friendly GUI so user can visualize the data in different formats such as graphs, charts, plots, simulations, among others. Although compatibility with other platforms such as mobile applications for Android or IOS, or even desktop applications for macOS can be achieved, the aim of this project mainly relies on using a Windows computer, therefore the decision of using Python for both data analysis and GUI development seems to be the best fit for this project.

## **Chapter 4 Standards and Design Constraints**

### **4.1 Industrial Standards**

#### **4.1.1 PCB Design Standards**

Given that this project is taking place within the borders of the United States of America, it must conform to American National Standards Institute (ANSI) standards. For PCB design, ANSI has adopted the standard set forth by the Institute of Printed Circuits (IPC), specifically IPC-2221. This standard is designed to be a generic, wide-coverage guideline for PCB design. The objective of the IPC-2221 standard (and IPC as a whole) is to universalize reliable, manufacturable, and safe printed circuit boards across all manufacturers ([\*Working With PCB Design Standards, 2021\*](#)).

Although it is a given that the team's design will be governed by the IPC-2221 standard, there are additional IPC standards that may apply as well. For example, IPC-4101 will apply, as it defines what materials should be used for the physical construction of the PCB board such as laminate. IPC-2152 will also apply, as it governs the thickness of copper traces based on the amount of current it will carry. IPC-4761 will apply as it covers proper via protection methods, our circuit boards will be relatively dense with components so vias will be a necessity. IPC-A-600 will apply as it presents the standards by which a PCB should be accepted or rejected. In addition, it defines the three classes of circuit board assemblies, our PCBs will fall within one of these classes.

IPC-A-600 defines three different classes for PCB products: Class 1 is for more generic products that have a short lifespan and limited use cases. Class 2 is for products that typically are part of a larger system and have to perform in an on-demand environment such as a graphics card in a PC, an embedded system on a smart TV, or an infotainment system in an automobile. Class 2 products must be able to perform for an extended period of time compared to Class 1 products. Class 3 products are held to very strict PCB manufacturing tolerances, and must reach heightened reliability targets. Class 3 specifies a plating thickness for the PCB top and bottom layers and through-hole vias, it also specifies the overall cleanliness of the assembly and teardrop profiles for trace to via connections ([Peterson, 2024](#)).

The goal for this project is to meet Class 2 criteria, given we don't have the facilities to tightly control PCB cleanliness during assembly, we also do not have control over PCB plating thickness, which falls under our fabrication provider, JLCPCB. JLCPCB has their own set of standards, which we are bound to as their customer. These standards are the following:

- 1) Dimension tolerance: +/- 0.1mm
- 2) Board thickness tolerance: +/- 10%
- 3) Drill Hole Size: 0.15mm - 6.30mm
- 4) Drill Hole Tolerance: +0.13mm / -0.08mm
- 5) Minimum via dimensions: Hole, 0.2mm Pad, 0.25mm
- 6) Plated Through Hole (PTH) size: 0.20mm - 6.35mm
- 7) PTH pad size: 0.5mm larger than hole
- 8) Minimum non-plated hole size: 0.5mm
- 9) Non-Plated Through Hole (NPTH) minimum size: 0.2mm
- 10) Minimum plated slot width: 0.5mm
- 11) Minimum non-plated slot width: 1.0mm
- 12) Minimum castellated hole size: 0.60mm
- 13) Plated hole size tolerance: +0.13mm / -0.08mm
- 14) Non-plated hole size tolerance: +/- 0.2mm
- 15) Minimum annular ring on 1oz copper: 0.13mm
- 16) Minimum annular ring on 2oz copper: 0.2mm
- 17) Hole to hole clearance: 0.5mm
- 18) Via to via clearance: 0.254mm

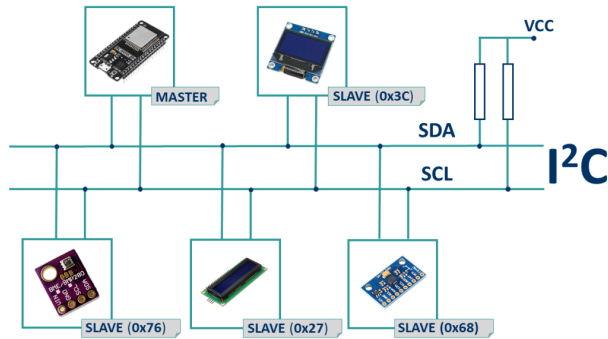
- 19) Pad to pad clearance without hole: 0.127mm
- 20) Pad to pad clearance with hole: 0.5mm
- 21) Via to track clearance: 0.254mm
- 22) Plated Through Hole (PTH) to track: 0.33mm
- 23) Non-Plated Through Hole (NPTH) to track: 0.254mm
- 24) Pad to track: 0.2mm
- 25) Minimum trace width (1-2 layers): 0.127mm
- 26) Minimum trace spacing (1-2 layers): 0.127mm
- 27) Minimum trace width (4-6 layers): 0.09mm
- 28) Minimum trace spacing (4-6 layers): 0.09mm
- 29) Minimum trace width / spacing on 2oz copper: 0.2mm / 0.2mm
- 30) Minimum BGA pad size (1-2 layers / 4-6 layers): 0.25mm / 0.25mm
- 31) Minimum BGA pad spacing (1-2 layers / 4-6 layers): 0.127mm / 0.127mm
- 32) Soldermask expansion: 0.038mm
- 33) Minimum solder bridge: 0.10mm
- 34) Soldermask dielectric constant: 3.8
- 35) Soldermask ink thickness: 10-15  $\mu\text{m}$
- 36) Trace to board outline: 0.3mm

Ultimately, these constraints will govern our PCB design ([PCB Manufacturing & Assembly Capabilities - JLCPCB, n.d.](#)). While we will strive to meet IPC Class 2 standards, those standards are not openly available and must be purchased for a significant price from IPC. In addition to this, we cannot control every aspect of our board's production. Given this is an experimental project, using JLCPCB to affordably produce our PCBs is the best option for us. If this project becomes a viable product, it is understood that we will invest in IPC documentation and locate a fabrication house that can meet their standards.

#### **4.1.2 I2C Protocol Standards**

The I2C, Inter-Integrated Circuit, protocol is one of the most widely used communication standards within PCB design. This will be the device communication of choice, as it is a simple, easy to implement design. The complexity doesn't scale with many devices and easily accommodate all our components. The I2C architecture has 3 defining characteristics, the bus structure, the master-slave set up, and the bitwise communication.

In terms of the Bus Structure, I2C is a 2 wire (plus ground), bidirectional, open drain system. This means any component that wishes to communicate only needs 2 wires connected to a bus system, as shown below, and will be able to both transmit and receive data.

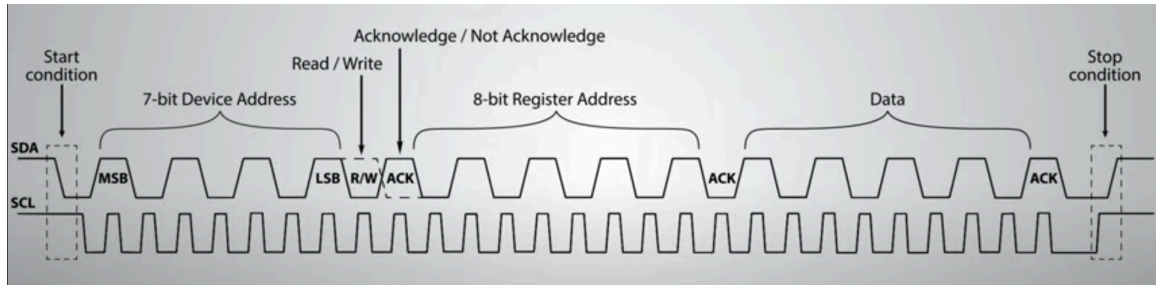


Source: <https://randomnerdtutorials.com/esp32-i2c-communication-arduino-ide/>

Each Device on the I2C bus connects to the Serial Data (SDA) and the Serial Clock (SCL) lines. The SDA line is for transmitting data between the devices, while the SCL line is for synchronization of the data transfer, to ensure the proper bits are received. Proper communication between devices occurs when connected to the bus lines are pull up resistors, which cause the system to be an Open Drain system. An Open Drain system is one in which a device must pull a line to ground. The resistance of these resistors affect the switching speed of the lines. A lower resistance means faster switching times, which means the rate of communication can be faster. This comes at the cost of noise and power usage, as the voltage is usually fixed at 3.3V or 5V (3.3V in our case), so a higher resistance means less current, thus more power efficiency.

All of the devices connected to the bus are categorized as a master or slave. A master is the device that controls the flow of data. It sends out signals to a slave device in order to read or write information to the device. The master communicates with multiple slaves and slaves never communicate with each other. Typically, there is one master and as many slaves as needed and our case is no exception. However in systems with redundancies, multiple masters may exist. In our case, since there are no safety concerns, a redundancy such as this will add more complexity than necessary. Our master device will be the STM32F446 microcontroller identified in chapter 3, and our slave devices will be every peripheral that we need to communicate with, including but not limited to the temperature and humidity sensors, as well as the GPS and Altimeter. Each slave needs an address for the master to be able to address it, which are either 7 or 10 bit addresses, while masters do not need an address, except in the rare instance there is slave functionality to the master's devices. When a Master wants to address a slave, it sends out a message to a slave, and awaits a response, before sending out another message to a slave.

A timing diagram of the communication between a Master and Slave is shown below.



Source: <https://www.youtube.com/watch?v=6IAkYpmA1DQ>

Typically the SDA and SCL are meant to be static high when the bus is not in use. As I2C is an open drain system, they will rest high due to the pull up resistors, until driven low by a master or slave. In order to signal that it is time to communicate, a start bit must initialize the entire process. This is done by having the master cause a high to low transition across the SDA, which is called the “START” bit while the SCL is high, which activates the clock to begin pulsing. Next, the bit address of the device is sent across the bus, usually 7 or 10 bits, across the SDA line, starting with the MSb. The SDA will transition high or low to the appropriate bit while the SCL is low, and remain at the value while the clock is high. The address is sent from MSB to LSB with one extra bit sent after the address. This is the read/write bit, where 0 is sent for the write operation and 1 is sent for the read operation. Then an “Acknowledge” bit is sent from the slave with the corresponding address to the master. Once addressed, 8 bit sets called data frames are sent between the master and slave, with each frame ending with an acknowledgement from the receiver of the message. In most cases, the receiver will be a peripheral while the sender will be the microcontroller. Once the data is all sent, the sending device, most likely the microcontroller, will send a STOP bit. The STOP bit, similar to the START bit is a transition from low to high on the SDA line while the SCL line is low, which causes the cessation of the communication.

### 4.1.3 Optical Standards

#### 4.1.3.1 Lens Manufacturing Standards

In the same context as the PCB and I2C requirement specifications, the optics portion of the project must follow the national standards established by the international standards put forth by the International Organization for Standardization (ISO) and military specifications that trickled down into what optics requirements look like today. Within both versions of constraints, the primary focus is on the initial design of the lenses and other optical elements, rather than the assembly of the system itself. Since the lenses, diffraction grating, and detector for this project will be commercial off-the-shelf (COTS) products then these standards must be implemented by the manufacturers themselves.

There are instances when standards are used without even being aware of them. For example, a typical biconvex lens drawn using popular automated optical

design software often adheres to ASME-Y14.18M-1986 or its predecessor, MIL-STD-34, which outlines the 2D engineering drawing, the notation of the physical measurements, and various common notes. The surface quality requirement, typically given in the scratch-and-dig description (for example, 80-50 or 60-40), originates from OP1.002 or its earlier predecessor, MIL-PRF-13830B, whether explicitly mentioned or not. Surface texture might be specified as Angstroms RMS, which refers to the old MIL-STD-10A that once provided default specifications for spatial bandwidth. Additionally, just about all glass in the US is based on the military standard MIL-G-174B.

The issue is that most of these old MIL standards have been withdrawn from reference or deactivated entirely. In 1994, the Secretary of the Armed Services announced that instead of referencing military standards for contracts, manufacturers should look to the specifications within national or international standards.

Since that day in 1994, over 7000 military specification documents have been redacted from the commercial community. Amongst these, 55 military specifications were related to something optical and so far half have been declined and one-quarter of them declared inactive. Inactive specifications can be grandfathered into current contracts but not for new procurements. The optical manufacturing industry in the United States must adopt the ISO standards or invent new nation standards of their own to fill the void left behind from the decommissioned military specifications.

Another route being taken is the approach of restructuring certain ISO standards to fit American manufacturing practices. For instance, with the deactivation of both MIL-STD-34 and ASME-Y14.18, there is no proper replacement for the American national optics drawing standard. This has resulted in ASC OP producing a new series of notation standards called to be released as OP1.0110: an American counterpart of ISO 10110. Multiple parts of the ISO standards have now been adjusted to fit the vernacular of the American companies. An example for reasoning is a drawing of a lens under the ISO 10110 standard differs notably from the previously used MIL standard format and can be a challenge for manufacturers in the United States to decipher. In an effort to find common ground, the standards intended to be utilized with the notations for roughness, glass grades, or scratch-and-dig quality are denoted by the designated engineer.

With that being said, different companies can vary in the range of intensity when it comes to standards as some can be more strict than others. A priority for this project is quality lenses to achieve readable data but at a reasonable price for the budget constraint. In an evaluation of ethos and practicality, the lens manufacturer for this project will be Edmund Optics. Edmund is a world-renowned optics company that is known to set their standard above the baseline constraints provided by the organizations listed above, but offers a wide range of COTS prefabricated lenses at a reasonable price and honorable availability. The table below lists the manufacturing specifications for Edmund

Optics' spherical lenses which will be used in the spectrometer portion of this project.

**Table 4.1. Spherical Lens Manufacturing Specifications**  
By Edmund Optics

| Spherical Lens Manufacturing Specifications |             |                    |                   |
|---------------------------------------------|-------------|--------------------|-------------------|
|                                             | Commercial  | Precision          | High Precision    |
| Diameter                                    | 4 – 200mm   | 4 – 200mm          | 4 – 200mm         |
| Diameter Tolerance                          | +0/-0.100mm | <b>+0/-0.025mm</b> | +0/-0.010mm       |
| Thickness                                   | ±0.100mm    | ±0.050mm           | ±0.010mm          |
| Surface Sag                                 | ±0.050mm    | ±0.025mm           | ±0.010mm          |
| Clear Aperture                              | 80%         | 90%                | 90%               |
| Radius                                      | ±0.3%       | ±0.1%              | Fix to Test Plate |
| Power (P - V)                               | 3.0λ        | 1.5λ               | λ/2               |
| Irregularity (P - V)                        | 1.0λ        | λ/4                | λ/20              |
| Centering (Beam Deviation)                  | 3 arcmin    | <b>1 arcmin</b>    | 0.5 arcmin        |
| Bevel (Face width @45 degrees)              | <1.0mm      | <0.5mm             | <0.25mm           |
| Surface Quality                             | 80-50       | <b>40-20</b>       | 10-5              |

Source: Edmund Optics "Precision Tolerance for Spherical Lenses" [#]

Due to the fact that this project team does not have any impact on the manufacturing practices of this company, a safe route will be taken with the choice of just the commercially-rated or moderately precision-rated lens class for the two lenses in the established system. In addition to that, this project is under its own constraints: time, money and capability. Although the target spectrum is IR, the system itself does not require extreme precision as displayed in the third class. With that being said, the commercial or low precision class will be a fine choice for the project application.

#### 4.1.3.2 Diffraction Grating Manufacturing Standards

Diffraction grating manufacturing standards are largely around the ISO specifications compared to the fabricating of lenses which often referenced a variety of different sources for standards. ISO manufacturing standards for diffraction gratings primarily focus on quality management and ensuring that products meet stringent requirements. ISO 9001:2015 is the most relevant standard, which provides a framework for quality management systems. This standard emphasizes customer satisfaction, continuous improvement, and the application of a systematic approach to manage processes. [#]

Companies like Wasatch Photonics and OPCO Laboratory, Inc. have achieved ISO 9001:2015 certification for their manufacturing processes, which include the

production of diffraction gratings. This certification ensures that their products meet high-quality standards consistently, utilizing advanced metrology techniques such as interferometry and atomic force microscopy for precision. [#] These companies also adhere to additional industry standards and specifications depending on the application, such as those required for space-qualified components and specialized coatings for high efficiency. [#]

The ISO 9001:2015 is an international standard that specifies requirements for a quality management system. It is used by organizations to demonstrate their ability to consistently provide products and services that meet customer and regulatory requirements. Here are key aspects of the standard:

- 1) Ensures that customer needs and expectations are met, aiming for customer satisfaction.
- 2) Emphasizes the importance of top management's involvement and leadership in developing a quality management system.
- 3) Stresses the importance of competent, empowered, and engaged people at all levels of the organization.
- 4) Encourages organizations to manage activities and related resources as processes, which helps in achieving desired results more efficiently.
- 5) Promotes continuous improvement as a permanent objective.
- 6) Advocates for decisions based on the analysis and evaluation of data.
- 7) Focuses on managing relationships with interested parties such as suppliers.

ISO 9001:2015 uses the High-Level Structure common to other ISO management system standards, making it easier to integrate with other management systems (e.g., ISO 14001). The main sections include:

- 1) Understanding the organization's context and determining the scope of the quality management system.
- 2) Establishing a leadership commitment to the quality management system and defining roles and responsibilities.
- 3) Addressing risks and opportunities, setting quality objectives, and planning changes.
- 4) Managing resources, including people, infrastructure, and organizational knowledge.
- 5) Planning, implementing, and controlling processes for delivering products and services.
- 6) Monitoring, measurement, analysis, and evaluation of quality management system performance.
- 7) Actions to enhance performance, including corrective actions and continuous improvement.

Organizations seeking ISO 9001:2015 certification undergo a rigorous assessment by an external auditor to ensure their quality management system meets the standard's requirements. This involves documentation review, on-site audits, and continual assessments to maintain certification.

A central theme of ISO 9001:2015 is continuous improvement, requiring organizations to regularly assess and improve their processes and overall QMS to enhance performance and adapt to changing circumstances. [#]

The manufacturing guidelines for diffraction gratings also depend on what the customer is looking for. When provided the purpose, the specifications can follow. For example, gratings often have a laser damage threshold, but in the case of this project, only natural light from the sun will be used. The need for a high threshold limit is unnecessary for this reason. The project also requires a transmissive grating versus a reflective grating due to the need of reaching the detector. Within the transmissive diffraction element required a blazed grating versus holographic.

#### **4.1.4 Radio Communication Standards**

Our payload will be equipped with the ability to transmit live data over the air using our RF sub-system. We will be using LoRa as the communication protocol, LoRa stands for “Long Range” and it is designed to be used by amateur radio enthusiasts. LoRa is known for its ability to have operators, these operators deploy antennas operating on the specific LoRa frequency, in our case 915 MHz. In Europe however the dedicated LoRa frequency is 868 MHz. While in Asia the frequency is either 433 MHz or 920 - 923 MHz depending on the country. The operators who are located worldwide then upload information picked up onto the public domain. LoRa is separated into three classes of devices, Class A are devices which are always transmitting and receiving, Class B are devices which transmit and receive in windows of time, and Class C are receive only devices.

The FCC regulations we are looking at are for LoRa devices based in the operating frequency bands of 902 - 928 MHz. For devices in this band the requirements of transmitters can be found in section 15.247 [5].

- 1) Minimum 6 dB bandwidth shall be at least 500 kHz
- 2) Maximum peak output conducted power shall be 1 W (+30 dBm)
- 3) Power Spectral Density (PSD) shall not be greater than 8 dBm in any 3kHz band
- 4) Emissions outside the 902-928 MHz shall be 30dB below the maximum emission

For frequency hopping there are added regulations. This is to prevent LoRa users from over congesting the 902-928 MHz frequency range. With frequency hopping you are able to use narrowband signals as long as you follow the requirements below.

- 1) Frequency hopping systems shall have channel frequencies separated by a minimum of 25 kHz or the 20 dB bandwidth of the hopping
- 2) For any frequency hopping systems operating in the 902-928MHz band, if the 20 dB bandwidth of the hopping channel is less than 250 kHz, the frequency hopping channels shall be at least 50 & the average time of

occupancy on any individual channels shall not be greater than 0.4 seconds within a 20 second period

- 3) For any frequency hopping system operating in the 902-928MHz band, if the 20 dB bandwidth of the system is greater than 250 kHz the system shall use at least 25 hopping channels, and the average time of occupancy on any channel shall not be greater than 0.4 within a ten second period
- 4) For frequency hopping devices in the 902-928MHz band, for devices with at least 50 hopping channels an end device may transmit up to 1 watt; for devices with less than 50 hopping channels end devices can up to 0.25 watts

In some radios that don't meet the requirements of 15.247 either the digital modulation requirements found or the frequency hopping requirements we can look at the requirements in 15.249. This section outlines the requirements based on field strength emissions.

- 1) the maximum permitted field strength of the intentional transmissions shall not be greater than 50mV/m at a 3 meter distance
- 2) the maximum permitted field strength of any harmonics (ie. "spurs") shall not be greater than 500μV/at a 3 meter distance
- 3) Any emissions outside the intentional band of operation, except for harmonics from the intentional radiator, shall be at least 50 dB below the level of the fundamental
- 4) Users may be able to apply a duty cycle correction factor to adjust the maximum permitted field strength measurements

With these requirements in mind we will make sure our transmitter follows these guidelines. We will do this by conducting the necessary tests.

#### **4.1.5 FAA Standards**

Given our senior design project will traverse federal aerospace, we must abide by Code of Federal Regulations Title 14 Chapter I Subchapter F Part 101, which are determined by the Federal Aviation Administration (FAA). FAA Part 101 applies to moored balloons, kites, amateur rockets, and unmanned free balloons. Since our senior design demonstration will consist of the Balloon Payload System being suspended by a moored balloon, and our final goal is to send it up with an unmanned free balloon, Part 101 covers both of our objectives.

Subpart A begins by defining the dimensions of a moored balloon to which the regulations apply. That is, at least six feet in diameter and having a gas capacity of at least 115 cubic feet. Subpart A also defines whether Subpart D applies to an unmanned free balloon. Subpart D applies if any of the following are true:

- 1) The balloon carries a payload that weighs more than 4 lbs and has a weight / size ratio of 3 ounces per square inch on any one of the faces (i.e. the smallest face).

- 2) The balloon carries any individual payload that exceeds 6 lbs.
- 3) The balloon carries two or more payloads that together exceed 12 lbs.
- 4) The balloon utilizes a rope to attach to the payload(s) that exceeds 50 lbs of breaking force.

Subpart A also makes provisions for bypassing any of these regulations via a waiver, and prohibits flight of rocket, balloon, or kite in prohibited areas without express permission from the authority over that area. Subpart A concludes by stating the obvious: no person should operate a balloon, kite or rocket that creates a hazard to others or their property; nor should they drop an object from any of these aircraft if it poses a hazard to others.

Subpart B applies to moored balloons and kites, the regulations that apply to our senior design group for moored demonstration are:

- 1) The balloon should not be operated closer than 500 feet to the base of any cloud.
- 2) The balloon should not exceed 500 feet from the surface of the earth.
- 3) The balloon should not be operated in an area where ground visibility is less than three miles.
- 4) The balloon should not be operated within five miles of the boundary of any airport.
- 5) None of the above apply if the balloon is being operated below the top of a structure and within 250 feet from it, as long as the balloon does not block any illumination from that structure.

If the moored balloon is to be operated more than 150 feet above the surface of the earth, then they must provide the following information to the nearest Air Traffic Control (ATC) tower at least 24 hours before flight.

- 1) The names and addresses of the owner / operators.
- 2) The size of the balloon.
- 3) The location of the moored flight.
- 4) The height at which the balloon will be flown.
- 5) The date and time of the flight, as well as its duration.

If the moored balloon is to be operated at night, it must have proper illumination. This will not be an issue for us, as we will demonstrate during the daytime. In its final section, Subpart B requires that any moored balloon be fitted with a rapid deflation device. This device should be enabled as soon as the balloon escapes its moorings. If this device fails, then Air Traffic Control must be notified of the location and time of the incident and the rogue balloon's estimated flight path.

Subpart D applies to unmanned free balloons that falls within the applicability criteria set forth in 14 CFR 101.1(a)(4). Subpart D begins with operating limitations, those being:

- 1) An unmanned balloon may not be operated below 2000 feet within the lateral boundaries of Class B, C, D and E aerospace without authorization from Air Traffic Control.
- 2) An unmanned balloon may not be operated at any altitude where clouds or any other “obstructing phenomena” cover more than five-tenths of area.
- 3) An unmanned balloon may not be operated at an altitude below 60,000 feet where the visibility is less than five miles.
- 4) During the first 1000 feet of ascent, an unmanned balloon may not be positioned above a congested area or an assembly of people not associated with the ballooning operation.
- 5) Upon making impact with the surface of the earth. The balloon and its payload may not pose any hazards with people or property not associated with its operation.

The unmanned free balloon must be equipped with multiple safety systems, these include:

- 1) At least two payload cut-down systems that operate independently of each other.
- 2) At least two separate systems to terminate the flight envelope of the balloon.

Other requirements are:

- 3) The balloon must be equipped with a radar reflective device or material that will provide an echo to surface radar in the 200 MHz to 2700 MHz frequency range.
- 4) An unmanned free balloon may not be operated under an altitude of 60,000 feet between sunset and sunrise unless the balloon, its attachments, and its payloads are equipped with flashing lights that cycle between 40 and 100 times a minute. If the balloon and its attachments, payloads, etc. become separated during flight, each one of the individual elements must flash independently of each other.
- 5) An unmanned free balloon must not be equipped with a trailing antenna that requires more than 50 lbs of force to break it at any one point. An exception to this rule applies if the antenna is equipped with colored pendants or streamers at no greater than 50 ft intervals down its length. These markers must be visible at a distance of at least 1 mile.
- 6) An unmanned free balloon may not be operated between sunrise and sunset if it is equipped with a suspension device more than 50 feet wide, unless that device is colored with alternate bands of bright colors or has colored pendants or streamers that can be seen from at least a mile away. An exception to this rule is if the balloon is suspended by a highly conspicuous open parachute.

Before launching the unmanned free balloon, a series of notices must be issued. The FAA requires that no one may operate an unmanned free balloon unless

within 6 to 24 hours before beginning the operation, they provide the following information to the nearest Air Traffic Control facility:

- 1) The balloon identification.
- 2) The estimated launch time, accurate to +/- 30 minutes.
- 3) The location of the launch site.
- 4) The cruising altitude.
- 5) The estimated trajectory up to the point the balloon either reaches cruising altitude or 60,000 feet - whichever is lower.
- 6) The diameter and length of the balloon, including the length of the suspension device and trailing antenna, and the weight of the payload.
- 7) The duration of the balloon's flight.
- 8) The estimated time and location of impact.
- 9) An exception to the minimum 6 hour notice window takes effect if the balloon is to be measuring an event which has a critical time element such as a solar or cosmic disturbance. In this case, the window is moved to a minimum of 30 minutes.
- 10) If the launch is canceled, ATC must immediately be notified.
- 11) Upon launching the balloon, ATC must be immediately notified.

The FAA requires that during the duration of the balloon's flight, that its position be monitored and reported to ATC (if requested). The standards pertaining to this are:

- 1) Upon launching the unmanned free balloon, the operator should record its position at least every two hours unless directed otherwise by ATC.
- 2) The operator must forward any balloon position reports requested by ATC.
- 3) One hour before initiating descent, the operator must relay the following information to ATC.
  - a) The coordinates of the balloon.
  - b) The altitude of the balloon.
  - c) If applicable, the estimated time at which the balloon will exceed 60,000 feet.
  - d) The estimated trajectory for the remainder of the flight.
  - e) The estimated time and location of impact.
- 4) If the operator fails to record the position of the balloon for a period longer than two hours, they must immediately notify ATC of the last recorded position and the estimated trajectory. Additionally, ATC must be notified once a connection is re-established with the balloon.
- 5) The operator must notify ATC once the flight operation is ended.

#### **4.1.6 FCC Standards**

Our Balloon Payload System is governed by Title 47 Chapter I Subchapter B Part 22 Subpart H Section 22.925. This standard is authored by the Federal Communications Commission (FCC) and pertains to the airborne operation of cellular telephones. It states that no cell phone should be operated while on an aircraft of any kind, including airplanes and balloons. The maximum altitude

allowed for operation is while it is still on the ground, as soon as an active cellular phone loses contact with earth via aircraft, it is in violation ([47 CFR 22.925 -- Prohibition on Airborne Operation of Cellular Telephones., n.d.](#)). Therefore, it is critical that we do not use an active cell phone for tracking, communication, or any other purpose on our Balloon Payload System.

## **4.2 Design Constraints**

### **4.2.1 Integral Constraints**

#### **4.2.1.1 Environmental Constraints**

The payload has a variety of environmental factors it needs to consider. Firstly, there is a need to make the payload resilient to water. For testing, the launching is going to happen in Florida, a very wet state known for a lot of rain. Additionally, clouds are just dust with water attached to it, meaning even in dryer climates, sudden interactions with a high amount of water will be common. Protecting the electrical components from water within the payload will be important for short and long term functionality.

We have no control over where the payload will land, so it's possible it ends up in a lake or river. The payload needs to be exposed to the environment to the extent necessary for the sensors to read, so it can't be sealed completely. Additionally, the climate gets colder as the altitude increases, meaning that depending on the final altitude and location of launching, insulation of the payload could be necessary to ensure it remains functional. The payload also needs to be fairly secure.

There are two sources of agitation the payload will need to endure through. First is from the wind in the atmosphere. The wind speed will pick up drastically at increasing altitudes until the exosphere, where the air is so thin, the atmosphere is no longer considered an atmosphere. While we are not going anywhere near as high as the exosphere, we will likely be going as far as the troposphere, where the Jet Stream exists, which contains one of the highest wind speeds in the atmosphere. The second source is the landing. Once the max height is reached, the payload will have to survive an impact on the ground, there will be a parachute attached to the payload, but there will be no way to direct its descent in any direction, so it could land in a field, a swamp, or hit a rock formation and the payload need to be recoverable and reusable in each situation.

This is particularly noteworthy for the camera information as that data will not be transmitted, so a recovery of the payload is the only way to obtain that information. It would also be prudent to include enough buoyancy to keep the payload above the water, for easy acquisition, as needing to dive underwater in alligator infested waters is by far, the most dangerous aspect of the balloon.

#### **4.2.1.2 Power Constraints**

Power is the most volatile constraint to deal with. The flight time of balloons is usually a few hours. However, the Telemetry will need to transmit long after the balloon has landed, meaning battery life will need to last much longer than the flight time. If the battery runs out prematurely, this will make the payload undetectable. The software implementation will be key to optimizing the power efficiency of the system. This includes the optimization of the code itself. But more importantly is programming methods that will also save power. This includes putting sensors to sleep when not being polled, and turning off non telemetry systems when battery life is lower.

The power constraint for the balloon and telemetry does not include the camera, as the camera will be outfitted with its own battery and storage system. For the camera, the power constraint is limited to the duration launch so it will not be needed longer than a few hours. Additionally, the power system will need to be able to handle cold temperatures. Care was taken in chapter 3 to account for the different battery technologies' abilities to handle cold environments, however an extra step to insulate the battery itself will be taken to protect it from cold and water.

#### **4.2.1.3 Time Constraints**

This project has multiple deadlines. The first hard deadline is the submission of this paper while the second is the actual showcase of the project. These deadlines occur at the end of the fall and spring semesters, which are 16 week terms, which must be balanced with classes as well, and failure to meet these deadlines results in a failing of the class. Planning the rest of our course schedule in advance is required before even being allowed to sign up for Senior Design.

Additionally, there are a few soft deadlines adding more time constraints. First, the research and design portion has multiple milestone goals. This is to ensure constant progress is to maintain consistent progress throughout the research, to avoid last minute cramming, which will likely lead to many avoidable errors. For the fabrication and testing portion, we have to consider the schedule and timelines of those outside of our group. For example, we need to be cognizant of the shipping of various sensor parts taking time to arrive. Parts purchased and shipped through the Digikey website shipping times can be up to 14 weeks to receive, only 2 weeks less than the Senior Design 2 semester. Therefore, there is a soft deadline on how quickly we must research and purchase our parts so we can begin the actual interfacing and testing of our product mid-flight. The further we push this soft deadline, the more restricted we become with manufacturer shipping options and it could be that we miss our hard deadline all together due a key component not arriving.

The timeline is laid out as such. First, complete the research and design, ending with the first and only hard deadline in Senior Design 1. Once the research is

complete and the paper is turned in, the parts need to be ordered. Once they arrive, the components on the PCB need to be soldered, connected, and tested. Then, the payload needs to be securely fastened to a balloon, which will then require a final round of testing to ensure it will function properly during the showcase. The spring showcases are usually around mid April, as opposed to the end of the semester, cutting our limited time by 2-3 weeks. To further complicate things, to get a complete and robust test, it would be best to record an actual run and use it for the testing, however, that means the deadline will need to be even earlier if we were to do that.

To mitigate this, much of the work, including the formation of the team, the division of labor, as well as the research and creation of the paper over this project has been done in advance over the summer, thus allowing for more time leniency when it comes to time shipping restrictions.

#### **4.2.1.4 Payload Weight Capacity Constraint**

In order to get high altitude readings, the payload designed must be as light as possible. There are three major factors that affect the performance of a weather balloon. The size of the balloon, or how much it expands. Second is the total weight of the balloon and payload, and lastly is the lifting force. The goal for the showcase is a tethered launch, which is around a couple hundred feet. However, for any marketable product, the height will need to be able to reach altitudes that current projects customers are interested in, which is tens of thousands of feet in the air. The more weight of the payload, means the balloon will be limited in its peak height as well as its rate of ascending. This weight can be offset by having a large balloon and adding more helium.

Even with a payload of 10 pounds, there are many balloons from major retailers such as Amazon that can reach upwards of 20,000 feet. However, our stretch goal includes attempting to go as high as 100,000 feet. This constraint requires being very stringent on what will go onto the payload. The sensors themselves must go on, and many electrical sensors are very light, but the spectrogram uses glass lenses, which will add a significant amount of weight, so part of the challenge for the optics team would be to attempt to use smaller and lighter hardware when possible.

Additionally, this constraint creates a challenge in the form of a trade off between sustainability and peak altitude. At high altitudes, parts get cold and may have trouble functioning for extended periods of time if left exposed to the elements. As mentioned under the environmental constraints, insulation and protection of necessary parts will be done, however, this constraint will affect what is considered a necessary part for protection and how much protection is enough.

#### **4.2.1.5 Communication Constraints**

There are lots of factors that make communication difficult on this mission. There are also unpredictable environmental factors that can affect this but we are going

to plan the best that we can. The mission scope is to go up to around 70,000 feet. With wind and other atmospheric conditions the balloon may float even further away. The antennas used must make up for this range and environmental conditions and maintain communication throughout the scope of the flight. The communication is not a single point failure but it is an essential part of the scope to be able to transmit and interpret live data.

At the very worst case we will be retrieving the balloon after flight and can get the data and video manually from the SD card. This is a backup plan and not entirely guaranteed that we will even be able to retrieve balloons after launch. To prevent this we must design the antenna systems to handle the communication range. We are going to do this by using a dipole antenna on the payload, this will get past the weather and environment concerns. This is because the dipole antenna is a lower frequency and can still be transmitted through clouds and rain. This signal transmitted will be picked up from a high gain, high frequency antenna such as a YAGI antenna. This type of antenna will make up for the range.

#### **4.2.1.6 Recovery and Redundancy Constraints**

Due to the grandeur of this project and FAA restrictions in the UCF airspace, the balloon will not be able to be launched during the initial time frame of the capstone season. At most, there will be a tether attached to the base of the balloon and the team will allow it to hover at a set minimal altitude. With this in mind, recovery is not an issue in the capstone time frame, however the team does intend to launch the balloon with the payload in an FAA-approved area in either Ohio or Florida. Recovery of the payload after this post-graduation launch will depend upon the environmental characteristics and region of launch. It will be up to the team to evaluate the weather conditions for the proposed date and determine a proper launch site. Ideally, the weather and region conditions will be minimal to no wind, clear skies, and an open field for launch. The expectation for physical recovery is low as the balloon could drift hundreds of miles before the payload hits the ground. If all goes as planned with the constant communication with the payload from the ground, the data will be transferred in real time without the need of post-crash recovery.

In the realm of redundancy, this term falls under constraints due to the mere size and weight restrictions the project payload is under. Theoretically, it is recommended to have a redundancy plan in place for each operating instrument, however due to the size and budget allowance, the redundancy will be reduced to only a few components. For one, if the live communication fails then a storage card can be recovered from the landed payload. If the landed payload is unable to be found or is retrieved severely damaged, data will not be able to be reclaimed. Redundancy of each subsystem is unrealistic in this case due to the aforementioned budget and size. Adding a second copy of a subsystem adds significant weight and would therefore prompt the need for a larger, more robust balloon, which increases the overall cost. The thought for the actual Senior Design demonstration will be the tethered approach, making it easier to both recover the balloon but also repair or replace components as needed in test.

## **4.2.2 Other Constraints**

### **4.2.2.1 Sustainability**

The payload will be subjected to a cycle of take off and crash land during its lifetime. With so many environmental conditions, a long lasting product will need careful design of the payloads container. The payload will need to be able to be opened and accessible for cleaning, battery/sensor replacement or other maintenance that it might require. But it needs to be sealed in an area tight enough to not allow water. Additionally, parts that can't withstand very cold temperatures and aren't properly, minus forty to minus sixty degrees celsius will have shorter lifespans as well.

Not every part needs to be interchangeable, but there are more likely points of failure in the system compared to others, so making those systems replaceable goes a long way towards the sustainability of the product. The consumer spends far more time with a product than the manufacturer does, so making a product that can easily be fixed would be a huge improvement to customer satisfaction.

### **4.2.2.2 Manufacturability**

Another constraint is equipment and expertise available to us. This group is made up of four electrical engineers. Thus, we are limited in design and optimization of the mechanical aspects that we can accomplish. Fortunately, mechanical design can consist mostly of buying what we need, and keeping our design within what the mechanical part can do.

An example of this is the balloon itself. We cannot design a custom made balloon, so we are limited by what is commercially available. To elaborate, the size of the balloon determines how much helium can be pumped into it which then determines how high and how fast the balloon can ascend. Thus we can attempt to compensate for a heavier product by launching a bigger balloon, but there is a limit to the balloon sizes that vendors are willing to sell.

## **Chapter 5: Chat GPT Comparison with Other Platforms**

Chat GPT and other large language models (LLMs) are artificial intelligence-based softwares that can comprehend the human language and reply with nearly accurate responses in a matter of moments in a human-like fashion. This provides great benefit to the generation of ideas and initial understanding of concepts ranging across a broad spectrum of complexities, and this is what draws many people — especially students — to the platforms.

In the case of Senior Design, the LLMs have both pros and cons. When students might have trouble formulating the flow of a detailed section or grasping a specific topic, these platforms can be incredibly useful as commands such as

“Illustrate that 200 words or less” or “Explain it in bullet points” can be fed into and understood by the program.

The corresponding responses, however, can vary in validity and ethics. As shown below in the following examples, answers provided by the most commonly used LLMs can be plagiarized or wrong entirely. It was found that the more technical the question (aka the complexity or amount of calculations needed) the less likely the response was to be correct. General qualitative questions and whatnot are amongst the more reliable when it comes to correctness, but under a close inspection one notices the parallels in wording between published literature and the reply from an LLM. The direct plagiarism performed by these softwares puts users in danger of unethically using someone else’s work as their own, knowingly or unknowingly.

The following examples will hold a prompt from a team member and a response from an LLM which will be evaluated on accuracy and ethics.

### 5.0.1 Example 1: Microcontroller

Prompt: “list the best microcontrollers, include price and key features, and conclude which one is the best”.

Using ChatGPT was a very strong and helpful tool when doing research for this project because it facilitates the process of gathering data and comparing the different options available to us. In this case, a prompt was given to ChatGPT to list and compare the best microcontrollers available on the market that could be used for this project. The prompt was specifically written to provide the price range of each microcontroller, along with its most relevant features such as performance, memory, connectivity, power efficiency, or any other relevant feature of the microcontroller.

As a result of this prompt, ChatGPT was able to include accurate and relevant details and information regarding the different microcontrollers listed, which in this case were the STM32, ESP32, PIC32, RP2040, and ATmega328PB. Some of the key features and details can be found on *Table 5.1*, where the results provided by ChatGPT were used to compare the microcontrollers listed. The STM32 stood out for its high performance and versatility. The ESP32 was highlighted for its Wi-Fi and Bluetooth implementation and low-power modes. The PIC32 was noted for its high versatility and memory capabilities. The RP2040 stood out for its low price and versatility. Finally, the ATmega328P also stood out for its low price and high power efficiency.

**Table 5.1.** *MCU Comparison (ChatGPT, 2024)*  
*By Authors*

|  | STM32 | ESP32 | PIC32 | RP2040 | ATmega328P |
|--|-------|-------|-------|--------|------------|
|--|-------|-------|-------|--------|------------|

|                         |                        |                        |                              |                            |                       |
|-------------------------|------------------------|------------------------|------------------------------|----------------------------|-----------------------|
| <b>Performance</b>      | Up to 7 CPU cores      | Dual-core 32-bit CPU   | 32-bit MCU                   | NADual-core ARM Cortex-M0+ | 8-bit microcontroller |
| <b>Memory</b>           | Up to several MB flash | 520 KB RAM, 4 MB flash | 512 KB RAM, Up to 2 MB flash | 264 KB RAM, 16 MB flash    | 4 KB RAM, 32 KB flash |
| <b>Power Efficiency</b> | Moderate               | Low-power modes        | Moderate                     | Moderate                   | High                  |
| <b>Versatility</b>      | High                   | Moderate               | High                         | High                       | Low                   |
| <b>Price (\$)</b>       | 5 - 15                 | 3 - 10                 | 3 - 15                       | 1 - 5                      | 2 - 4                 |

From this prompt, ChatGPT was also able to decide based on its own response which microcontroller would be the best choice for this project, which in this case was broken up in three different criteria, which were “IoT (Internet of Things) and wireless communication, general-purpose and educational projects, and high-performance applications”. (ChatGPT, 2024). The microcontrollers selected by ChatGPT were the ESP32 for IoT and wireless communication, the RP2040 for general-purpose and educational projects, and the STM32 for high-performance applications. Even though ChatGPT was not able to give an exact answer on which microcontroller might be the best for this project, the results obtained from this test can be considered as acceptable being that it led us on the right track to choose a microcontroller.

## 5.0.2 Example 2: Sensors

Prompt: “what types of sensors should be included in a high-altitude balloon”.

For this example, ChatGPT was used to explore what type of sensor should be included for this High-Altitude Balloon. In this case, the prompt was somehow specific being that it asked for types of sensors that might be included for a high-altitude balloon, however since the prompt did not ask exactly for the most important sensors to include, we were expecting an extensive list of sensors that might not necessarily be used for this project.

As a result of this prompt, ChatGPT did provide an extensive list of different types of sensors as expected, more specifically, twelve types of sensors were provided by ChatGPT, including temperature, pressure, and humidity sensors. A second prompt was then given to narrow down the initial results for the types of sensors to just consider the three above mentioned, and to include more specific features

such as technology used, operating range, accuracy, power consumption, and price. As a result of this second prompt, ChatGPT was able to list more specific results for the types of sensors and include their key features, which can be found on *Table 5.2*.

**Table 5.2. Sensors Comparison (ChatGPT, 2024)**

*By Authors*

|                          | Temperature Sensor | Pressure Sensor              | Humidity Sensor               |
|--------------------------|--------------------|------------------------------|-------------------------------|
| <b>Technology</b>        | Thermistor         | Piezoresistive               | Capacitive                    |
| <b>Model</b>             | DHT22 (AM2302)     | Bosch BMP388                 | Sensirion SHT31               |
| <b>Operating Range</b>   | -40°C to +80°C     | 300 hPa to 1250 hPa          | 0% to 100% RH                 |
| <b>Accuracy</b>          | ±0.5°C             | ±0.5 hPa                     | ±2% RH                        |
| <b>Power Consumption</b> | 1.5mA max          | 3.4µA (ultra-low power mode) | 150µA (measuring), 2µA (idle) |
| <b>Price (\$)</b>        | ~\$10              | ~\$10                        | ~\$15                         |

From this prompt, it is clear that these results from ChatGPT did not exactly match our previous research for the different types of sensors, neither for the technology used or the model used, other than the technology for the humidity sensor (capacitive). For this example, probably more prompt iterations would have been beneficial to get more accurate results that align with our previous research regarding the types of sensors. However, it is safe to say that if no initial research would have been done for this section, ChatGPT would have been very helpful as a starting point for sensor selection for this project, and ultimately, further research would have been done in order to corroborate the results given by ChatGPT and ensure optimal sensor selection.

### 5.0.3 Example 3: Antenna

Prompt: “what type of antenna is the best for a high-altitude balloon and a base station.”

For this example, ChatGPT was used to look over the types of antennas used in high-altitude balloon applications (59,000 ft to 121,000 ft) for communication and data transmission between the payload and the base station on ground. Similar

to the previous example, the prompt was relatively specific being that it asked for types of antennas relevant for high-altitude balloons (long range applications). In this case a broad range of results was not expected, being that differently than for the sensors, there are fewer options available that comply with the desired specification.

As a result of this prompt, ChatGPT provided a list of four types of antennas: two for on board (Helical and Patch), and two for the base station (Yagi and Ground Plane). Something to highlight about this response was that due to the previous examples run, ChatGPT already included relevant details about each of the antenna types without us having to ask for it in the prompt. In this case, ChatGPT was able to provide details such as gain, radiation pattern, and size, as it can be seen in *Table 5.3*.

**Table 5.3. Antenna Comparison (ChatGPT, 2024)**

*By Authors*

|                          | Helical              | Patch       | Yagi         | Ground Plane    |
|--------------------------|----------------------|-------------|--------------|-----------------|
| <b>Application</b>       | On Board             | On Board    | Base Station | Base Station    |
| <b>Gain</b>              | 6 - 12 dBi           | 6 - 9 dBi   | 10 - 15 dBi  | 2 - 5 dBi       |
| <b>Radiation Pattern</b> | Circularly Polarized | Directional | Directional  | Omnidirectional |
| <b>Size</b>              | Compact              | Small       | Medium       | Small           |

From this prompt, ChatGPT also concluded which antennas should be implemented for our High-Altitude Balloon project, having as a result the Helical antenna for the on board antenna due to its “circular polarization and ability to maintain signal integrity in varying orientations.” (ChatGPT, 2024), and the Yagi antenna for the base station due to its “high gain and directional focus, making it ideal for long-distance communication with the high-altitude balloon.” (ChatGPT, 2024)

#### 5.0.4 Example 4: Software

Prompt: “what type of software should be used for data analysis and GUI development”

For this example, ChatGPT was used to evaluate the types of softwares that should be used for data analysis and GUI development. For this example, the prompt was relatively specific being that it asked for different types of softwares to perform two completely different tasks (data analysis and GUI development),

and in addition to that, context such as current level of coding knowledge was not given, therefore the answer is not expected to be fully personalized.

As a result of this prompt, ChatGPT provided a list of four types of software: PyQt (Python), MATLAB, LabVIEW (Graphical Language), Qt (C++). Following the history of the previous prompts and answers, important factors were highlighted in this response such as use, language, and ease of use, as it can be seen in *Table 5.4*.

**Table 5.4. Software Comparison (ChatGPT, 2024)**  
*By Authors*

|                       | Use                            | Language | Ease of Use |
|-----------------------|--------------------------------|----------|-------------|
| <b>Python with Qt</b> | Data analysis, GUI development | Python   | Moderate    |
| <b>MATLAB</b>         | Data analysis                  | MATLAB   | High        |
| <b>LabView</b>        | GUI integration                | G        | Moderate    |
| <b>Qt</b>             | GUI development                | C++      | Moderate    |

From this prompt, ChatGPT also concluded which software was the best fit for the different aspects of this project, having as a result Python with Qt for “flexible open-source data analysis and GUI development ” (ChatGPT, 2024). Based on ChatGPT, Python with Qt is also the best option due to the fact that it is “recommended for general-purpose tasks requiring a custom interface.” (ChatGPT, 2024)

### 5.0.5 Example 5: Optics

Prompt: “Design a lens system for absorbance spectroscopy of the sun.”

Here, the AI was given a distinct assignment with little restrictions. The LLM recognized that gathering the absorbance spectrum of the sun was to fulfill the goal of understanding the chemical composition of the air. It listed everything from the type of lenses to use to the safety concerns and considerations that would need to be made.

Due to the broad nature of the prompt, the design it produced was also very vague. No specific measurements or values were provided and the spectra analysis software procedure, for example, was described as, “Use software for data analysis to process the recorded spectra and extract absorption features.” (ChatGPT, 2024) The broad response of the language learning model leaves

room for creativity on the students' end, which is beneficial in the long run. This aspect prevents plagiarism and leaves out the potential "copy cat" of the design itself.

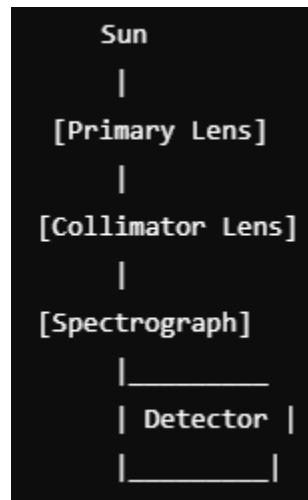


**Figure 5.1.** Optical system diagram (ChatGPT, 2024)

The figure above is the example drawing of a diagram of the system explained in the main body of the LLM response. Here, the spectrograph represents the diffraction grating followed by the detector, but in the main body of the response the spectrograph included both the grating and array detector.

Overall the use of ChatGPT in this example can be very beneficial when in the early research and design phase. Getting a general visualization of an idea has been very helpful on this portion of the project.

## 5.1 Comparison with Other Platforms

In this section we are going to be comparing ChatGPT to other chat AI programs offered from other companies. We will be looking at their quality of responses, experience, tools and other features. With the AI boom happening right before our eyes it's hard to keep track of all the AI apps and startups and what's best for you. This section aims to compare and contrast the top chatbots on the market. When comparing these AI models, it is good to keep in mind that these softwares have to be trained on data. Different AI models will respond differently and have different knowledge bases based on what they are trained on and the prompts they have encountered. A problem for the future is training AI to prevent it from taking in AI generated information, whether this is AI generated papers, graphs, or even art. When this happens, the AI encounters a higher risk of producing errors and its performance declines over time, eventually collapsing; this is called distribution shift. [6]

Below, one prompt will be selected from above and put through the various following platforms. The responses will be recorded and scrutinized for technical correctness and general confirmation of concepts. Since the prompts above were

all cycled through ChatGPT, only Gemini, Copilot, and Claude will be used in the comparison.

### **5.1.1 Chat GPT**

ChatGPT is a conversational AI model developed by OpenAI and is based on the GPT (Generative Pre-trained Transformer) architecture. It can understand and generate human-like text, making it capable of answering questions, offering explanations, and engaging in creative tasks like writing stories or solving problems. It evolved from GPT-1 in 2018, through GPT-2 and GPT-3, with GPT-3.5 and GPT-4 offering significant improvements in conversation, reasoning, and creativity.

ChatGPT excels in versatility, handling casual conversations, educational support, creative writing, business tasks, and even complex calculations. Its training involves analyzing vast amounts of text data to learn language patterns followed by some fine-tuning through reinforcement learning. All steps combined aid in the improvement of output quality and safety.

Despite its capabilities, ChatGPT raises ethical concerns such as biases in responses, the potential spread of misinformation, and security risks like misuse for malicious purposes. The company has claimed to be focused on improving these aspects while continuing to expand the model's functionality and applications. However, ChatGPT remains a versatile tool regardless, with many practical applications across different industries, both technical and nontechnical.

### **5.1.2 Gemini (Google)**

Gemini AI is another powerful language model created by Google. It is designed to understand and generate text, translate languages, write creatively, and answer questions. Trained on a vast amount of data, Gemini can perform a wide range of tasks, from summarizing articles to writing poems. While unable to perform complex calculations, Gemini AI claims to be a helpful resource in understanding concepts.

Prompt: "Design a lens system for absorbance spectroscopy of the sun."

The response from Gemini was quite vague. In an effort to fulfill the prompt, Gemini provided some basic optical components that could be used in the system, but did not provide the order in which they should be aligned. The provided response was not incorrect but it was not detailed or specific enough. In terms of a ground-level fundamental spectrometer setup, one could deduce an outline of a design out of this response. If I needed complexity out of this response, Gemini does not meet the requirements.

### **5.1.3 Microsoft Copilot (Microsoft)**

Copilot is Microsoft's AI platform on the market. Copilot proves to be more of a conversational AI providing help on daily tasks and keeping you up to date on

current news. The primary uses for this version are travel, recipe and entertainment recommendations, image generation, and general task assistance. The platform claims to be able to aid in technical and coding queries, a range of computations, and even large dataset analysis.

Prompt: “Design a lens system for absorbance spectroscopy of the sun.”

Copilot’s response to this prompt was similar to Gemini’s. The general concepts were provided and a basic setup was suggested but the initial instinct of the program is to start with minimal detail then follow up by offering more depending on what the user is looking for. Even after asking for more, the AI does not provide a great deal of in depth information.

#### **5.1.4 Claude (Anthropic)**

Claude is an AI assistant developed by Anthropic, designed to assist with a wide range of tasks, including language processing, problem-solving, creative writing, and technical help like math and programming. Its knowledge spans fields like science, history, literature, and current events (up to April 2024), and can adapt its communication to fit different contexts. A downfall is that Claude can't access real-time information, retain conversations, or interact with the physical world, however its strengths include explaining complex topics, offering personalized assistance, and engaging in creative or analytical tasks.

Prompt: “Design a lens system for absorbance spectroscopy of the sun.”

This was the most detailed response of all the analyzed platforms. Claude provided a similar overview of the various components needed for a sun spectrometer but was more technical in the descriptions of each. For visualization, the LLM provided a script of Python code that translated into a flowchart for the most optimal optical setup. The output of the code is shown below in Figure 5.2.

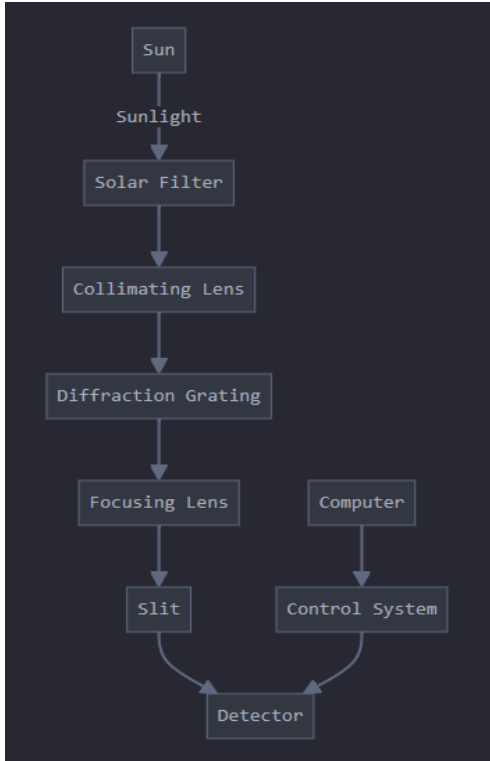


**Figure 5.2.** Optical system diagram (Claude AI, 2024)

This flowchart format is similar to the output provided by ChatGPT in Figure 5.1. The actual order of the components is different from the other platforms' suggestions but is also not entirely incorrect. Due to the vagueness of the provided prompt, the output design is still fairly general like Gemini and Copilot.

## 5.2 Conclusion

Although ChatGPT is very helpful when doing research and can be used as a tool to facilitate the process of gathering data, it is important to keep in mind that ChatGPT should not be considered the primary or most relevant source when researching. Based on our experience with ChatGPT and other LLMs, they can be useful as a starting point to provide relevant information about the topic of interest which is being studied, which can later be corroborated when performing a more formal research about the topic of interest by using more reliable and verified sources.

As shown in the different examples above, ChatGPT was able to provide a quick summary about the different topics of interest such as microcontrollers, sensors, antennas, and softwares. Even though the results did not exactly match our previous research about the different topics, it did help us to know where and what to look for. For example, for the microcontroller section, ChatGPT was able to provide an updated list of the best microcontrollers available on the market and highlight the top features for each of the microcontrollers, and although the response for the features and prices for the microcontrollers might not be exactly

accurate, it still can help us narrow down our future research, allowing us to save time when deciding which microcontroller to use.

Finally, it is important to note that the responses given by ChatGPT may also be affected by different factors. Some of the most obvious factors are how the prompt is formatted, being that the more clear and specific the prompt is, the more accurate and relevant the response will be. The previous chat logs, due that ChatGPT may use similar responses or reference other responses within the same chat log. The model version (GPT-3 or GPT-4) is also a big factor on how the response may be affected, being that more advanced versions such as GPT-4 have more recent and advanced results due to their continuous updates and patches, while GPT-3 is only able to get results up until September 2021. Lastly, language is also a factor, due that ChatGPT is more proficient in English than in other languages, mainly because of the amount of English text in its training data.

## **Chapter 6: Hardware Design**

### **6.1 Mechanical Design**

The C.H.A.N (Climatic High Altitude Navigator) project will consist of two systems. A BPS (Balloon Payload System) and a lift system. The Balloon Payload System will be a rectangular 3D printed payload that houses all of our electronics, experiments and communication devices. We chose to go with a rectangular body design as it will be easiest to manufacture and implement our subsystems into. This body shape will allow us to mount components on all sides outside the body, expanding our working area to more than just inside the payload. Essentially serving as the brains of the project the BPS will be insulated and protected from impact on recovery.

It is important to note that the Balloon Payload System must weigh less than 4 lbs and be suspended by a line that has a breaking force of no more than 50 lbs in order to avoid an extensive set of additional FAA regulations. If we exceed these regulations, then we are required to implement at least two payload cut down systems that need to be triggered by the ground station at the operator's request. This means that we would not only have to implement additional hardware, but ensure 2-way communication with the BPS. The balloon must also be equipped with a radar reflective device that returns signals in the range of 200 to 2700 MHz.

The Lift System is mainly static with only two elements, a balloon and a parachute. The balloon will provide the project with a ride up to the desired altitude. Once the balloon pops due to a loss of pressure in the atmosphere the parachute will deploy. This will ensure the BPS has a smooth ride down back to earth to be recovered. The parachute must be sized appropriately so that the descent rate is approximately 5 meters per second. If the balloon descends much slower than this, it risks being blown far off the estimated trajectory by stray

winds. If the balloon descends much faster than this, it risks causing damage to itself, property, or people upon impact with the surface of the earth [HAS]. As previously mentioned, it is also imperative that the suspension line(s) have a breaking stress no greater than 50 lbs.

Atop the Balloon Payload System will sit the anemometer. Being approximately six inches in diameter, it takes up a significant amount of space. In order to tether the top of the BPS to the parachute and balloon, four arching pillars extending from the corners of the top of the BPS will wrap over the anemometer and meet at the center axis, from this point the mounting hardware will be affixed.

Per FAA regulations for a tethered balloon of a diameter larger than six feet, or a gas capacity of at least 115 cubic feet, we must implement a rapid deflation device. This device is intended to empty the balloon if it breaks free from its moorings. In order to accomplish this, a 3D printed device will be constructed so that it grips around the neck of the balloon. A hot wire will be affixed to this device at a pivot, and a spring will hold it taught against the neck. If the on board altimeter detects that the balloon exceeded 200 feet, the BPS will execute an abort operation which will feed current to the hot wire, subsequently severing the neck of the balloon and rapidly releasing the helium. The parachute will then ensure that the payload does not enter freefall as it returns to earth.

The communication antenna will be mounted to the underside of the Balloon Payload System and point towards the surface of the earth. The antenna must be positioned / constructed in a manner that does not present a risk to person or property upon impact after descent. FAA regulations require that a trailing antenna must be able to be broken at any point with a force no greater than 50 lbs.

## **CAD / DRAFT IMAGE OF OUR PROJECT**

### **6.2 MCU**

The MCU circuitry is based off of Espressif's schematics for their own ESP32 development kit, specifically the ESP32-S3-DevKitC-1 v1.1. The foundation circuitry for the ESP32 includes strategically placed decoupling capacitors, boot and reset buttons, a USB to UART interface, and an auto-programming flip-flop circuit.

The ESP32 requires two decoupling capacitors on its 3.3V input pin. Decoupling capacitors filter out high frequency noise by shunting it to ground; they also act as a temporary power reservoir to ensure constant voltage to the supply pin during load switching [SF]. This particular design utilizes two decoupling capacitors, the one further from the input pin has a higher capacitance rating (22uF) than the one closer to the input pin (0.1uF). The reasoning behind this is that the larger capacitor acts as the main power reservoir and filters out lower

frequencies, but struggles to filter out higher frequencies. Whereas the smaller capacitor presents a low impedance to high frequencies, thus expanding the AC signal filtering range [TW].

In order for the ESP32 to function properly, the Enable (EN) pin must be pulled up to 3.3V. A 10 KOhm pull up resistor is utilized to achieve this task. The reason a pull up resistor must be used is to limit the current flowing into the Enable pin. In addition, a 1uF capacitor is used to ensure the auto-program circuit functions reliably.

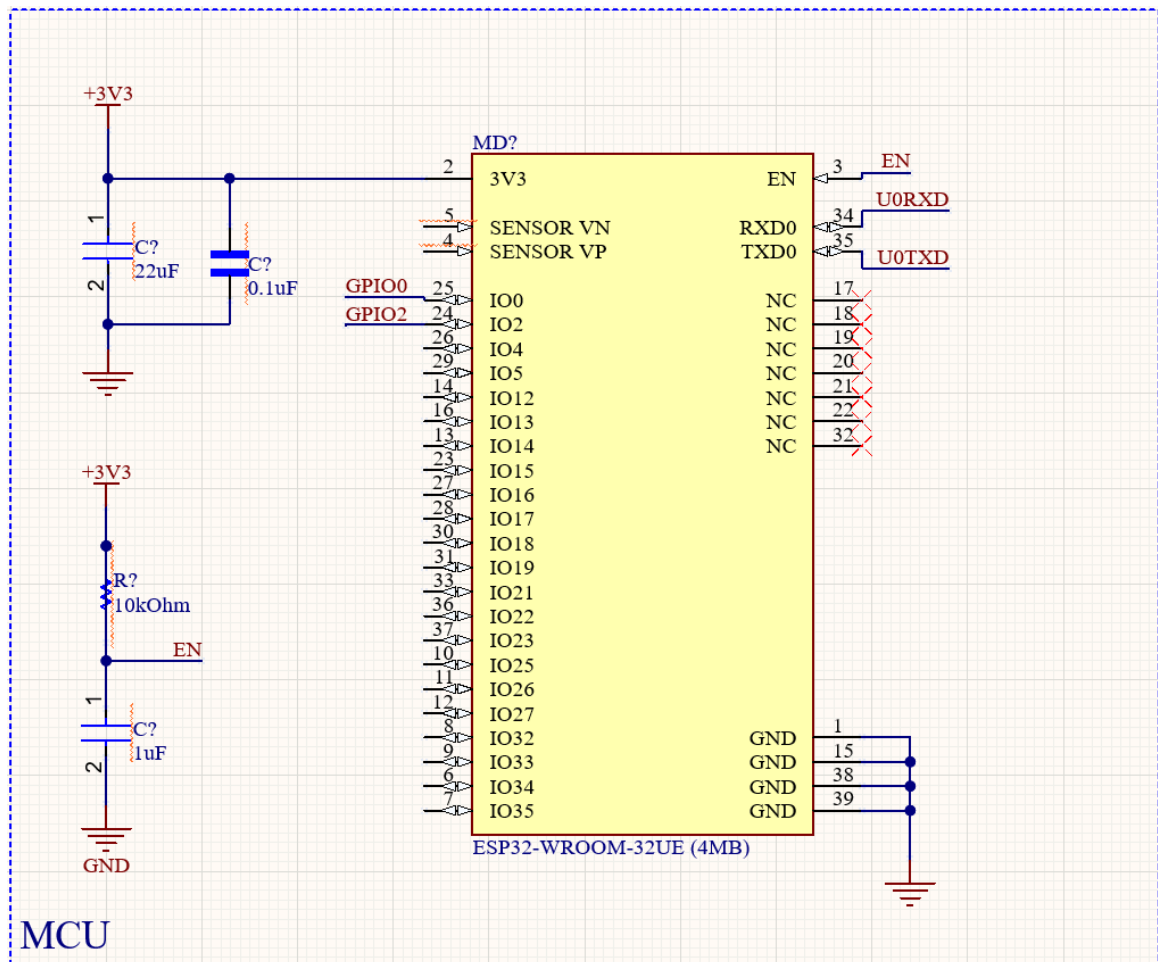


**Figure 6.2.1: ESP32 Baseline Connections Schematic**

In order to program the ESP32 and communicate with it over a PC/MAC/Linux serial COM port, a USB to UART chip was implemented. A CP2102N series chip from Silicon Labs was chosen for this task, as Espressif utilizes it in their development board. This solidifies the CP2102 as a solid choice, and ensures that there will be support if any issues arise. The CP2102 needs a minimal amount of pins connected for it to function as needed. All the power pins are

decoupled by a common 10uF capacitor, reset is pulled to 3.3V by a 1 KOhm resistor, and the RXD and TXD lines are linked straight to the ESP32.

The differential USB pair is routed to the micro USB header, but not before linking to a set of Transient Voltage Spike (TVS) diodes that protect the CP2102 from ElectroStatic Discharge (ESD). A third TVS diode is needed to protect the 5V from the host, which is then fed through a 40V, 1A Schottky diode to the device 5V rail. This is to prevent a defective over-producing 5V supply on the Balloon Payload System from frying a host computer during programming or debugging.

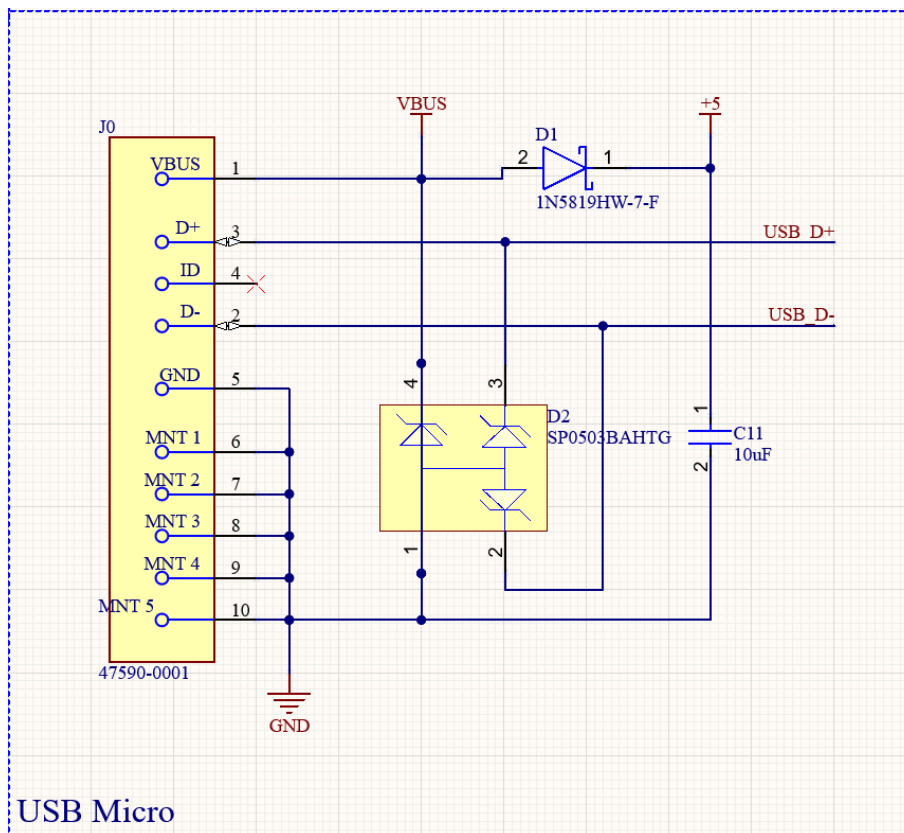


**Figure 6.2.2: Micro USB Header Schematic**

The VBUS pin has strict voltage requirements, it must float no more than 2.5V above logic volcate (VIO), which in this case is 3.3V. It must also be pulled up to no less than  $3.3V - 0.6V = 2.7V$  for it to register connection to a USB host. In order to meet these requirements, the datasheet calls for a voltage divider fed off of the host 5V power rail in conjunction with a 1uF decoupling capacitor [DS].

The CP2102 utilizes a Ready To Send (RTS) output pin which signals the UART target device when its FIFO register is open to receive data, and when it is full. It also utilizes a Data Terminal Ready (DTR) output pin which signals the UART target device when its data terminal is ready. The Espressif development board

schematic details a type of latch circuit used to toggle the EN and GPIO0 pins on the ESP32. This latch circuit is driven by the DTR and RTS pins from the CP2102. In order for the ESP32 to enter serial flash mode, the GPIO0 pin must be held low while the EN pin is toggled low then high. In order to translate the DTR and RTS pin timing (which is configured for general cases), to this specific ESP32 timing, the aforementioned latch circuit is used. There is however one issue: the EN and GPIO0 pins cannot be pulled low at the same time. *Refer to Table 6.2.1.* To solve this issue, a 1uF capacitor is tied to the EN pin which slows the rise time (via charging) of that pin after it is pulled low. This allows enough overlap time for the ESP32 to read the EN and IO pins as low at the same time and enter boot mode [FM].

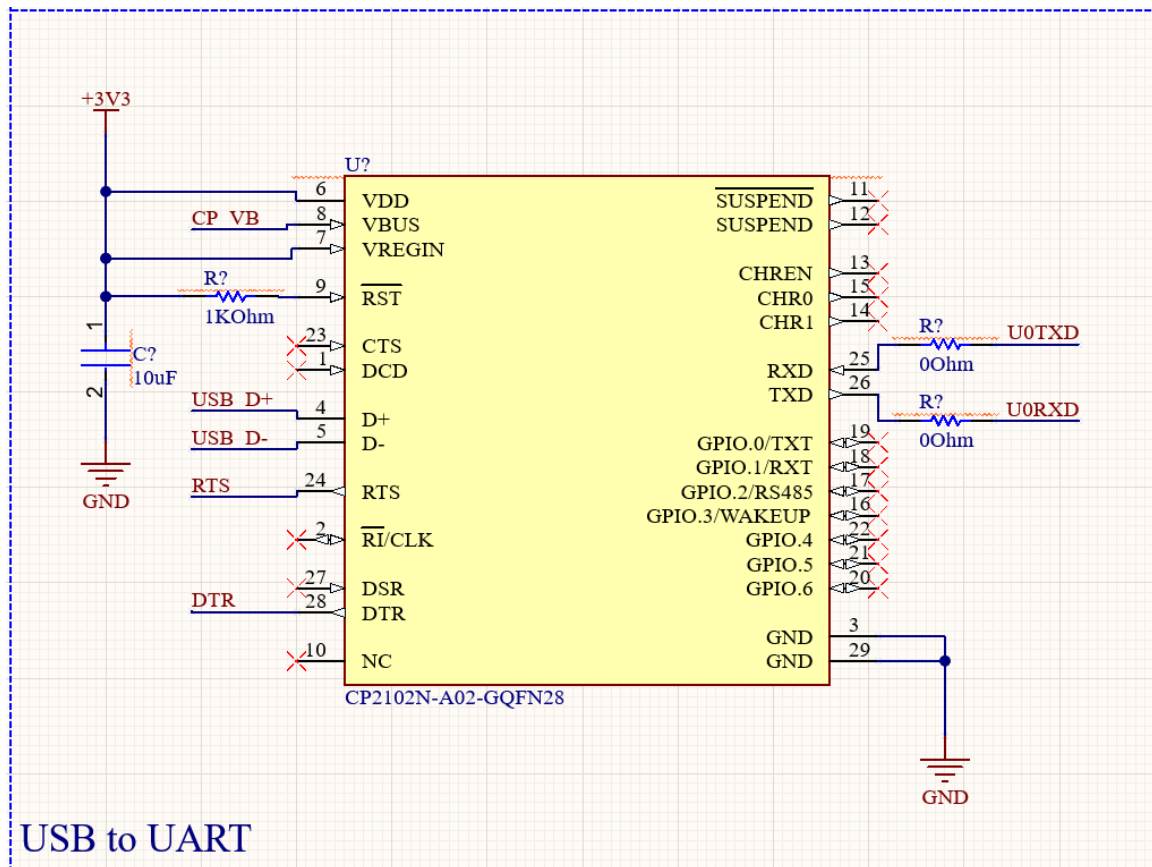


**Figure 6.2.3: CP2102 Schematic**

**Table 6.2.1. Logic Table for AutoProgram**  
by Authors

| DTR | RTS | → | EN | IO |
|-----|-----|---|----|----|
| 1   | 1   |   | 1  | 1  |
| 0   | 0   |   | 1  | 1  |

|   |   |  |   |   |
|---|---|--|---|---|
| 1 | 0 |  | 0 | 1 |
| 0 | 1 |  | 1 | 0 |

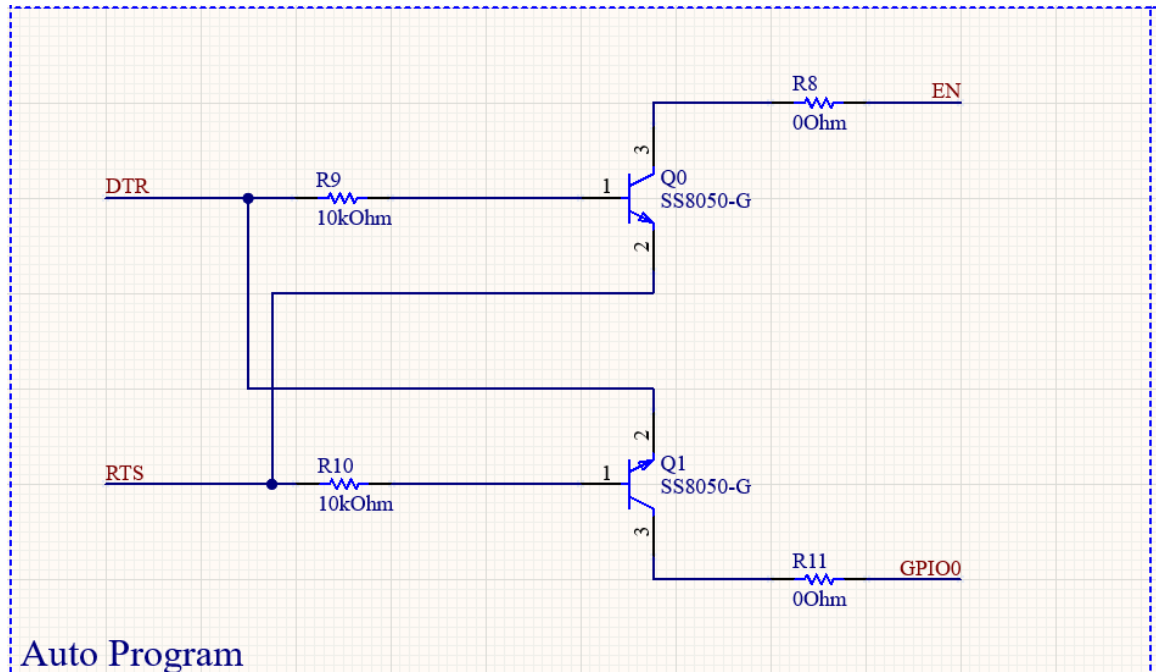


**Figure 6.2.4: Auto Program Schematic**

In addition to the auto program circuitry, two momentary push buttons are wired to the GPIO0 and EN pins. In the event that the auto program circuitry fails, the 0 Ohm resistors can be removed, and the ESP32 can be manually forced into boot mode with the push buttons. This is done by holding the GPIO0 (BOOT) pin low while momentarily pushing the EN button *Refer to Figure X*. If all else fails, the ESP32 supports JTAG which can be used for debugging and programming. Refer to *Figure 6.2.5*.

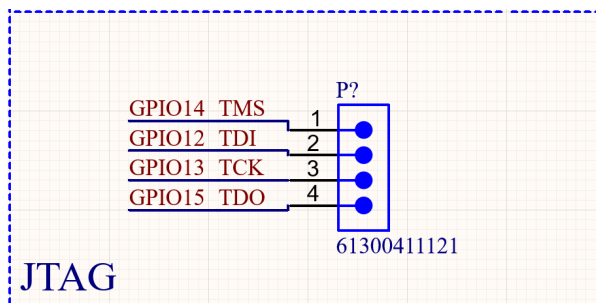


**Figure 6.2.5. JTAG Schematic**

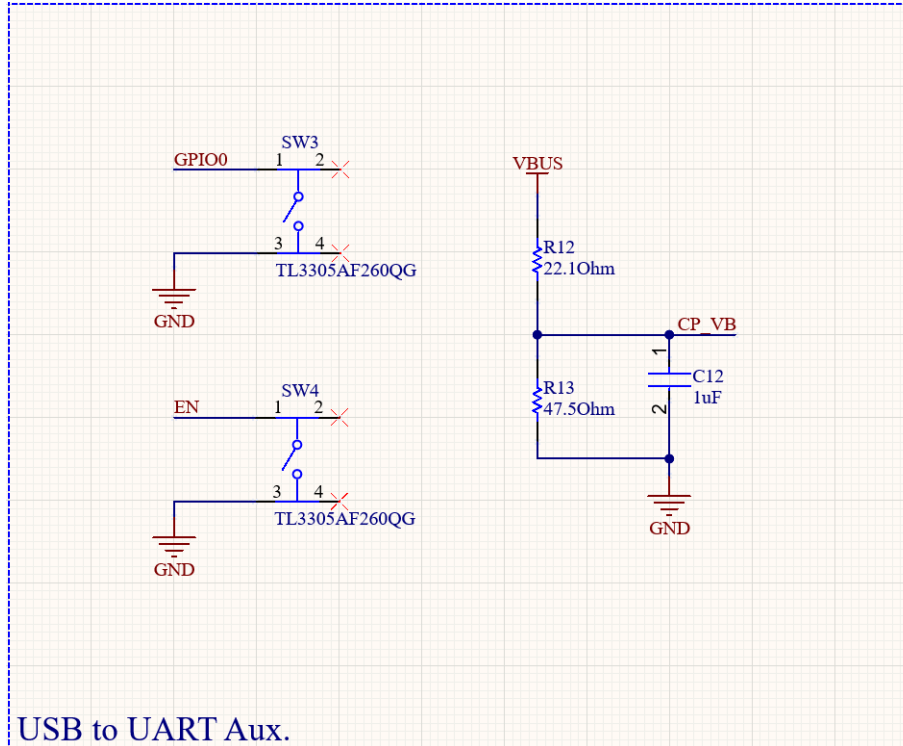


**Figure 6.2.6.** *USB to UART Auxiliary Schematic*

In order to easily test the operation of the ESP32, and provide quick and easy indication of the Balloon Payload System status under bench testing, three serial-addressable RGB LEDs are wired to the MCU. Adafruit private labels these LEDs and sells them as *Neopixels*, but their technical name is SK6812MINI-02, manufactured by Opsoo Optoelectronics. These LEDs house a microcontroller which interprets serial data to determine which Red, Green, or Blue LED to power and at what level. Their serial nature allows them to be daisy chained, which is how they are configured in our system. The datasheet calls for a 5V power input and 5V logic, which would require logic level shifters in our case. Fortunately, Neopixels can work with 3.3V, albeit the maximum brightness is reduced. Knowing this, Espressif designed their development board with a direct connection from the 3.3V rail and MCU logic to the Neopixels, and we opted to do the same to reduce complexity. Refer to *Figure 6.2.7*.

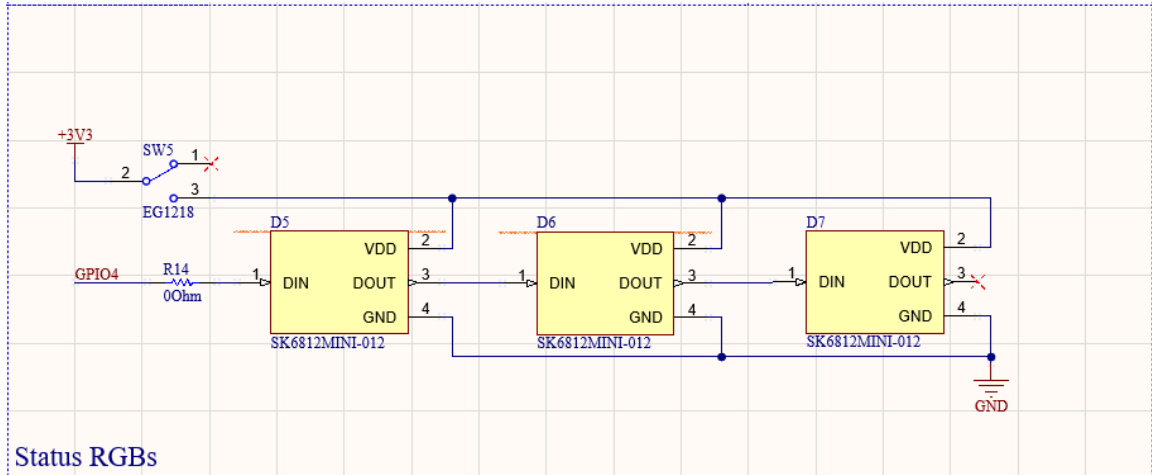


**Figure 6.2.7: Status RGBs Schematic**

One of our main goals is to store atmospheric and telemetry data to local storage during flight. To accomplish this, we are utilizing a micro SD card. Communication with the SD card is conducted over SPI. While this is not the fastest way to write to an SD card, it takes up the least amount of pins on the MCU, which is far more important. The SD card is connected to the 3.3V rail, and is decoupled with 0.1 $\mu$ F and 10 $\mu$ F capacitors. Refer to *Figure 6.2.8* for the SD card schematic.

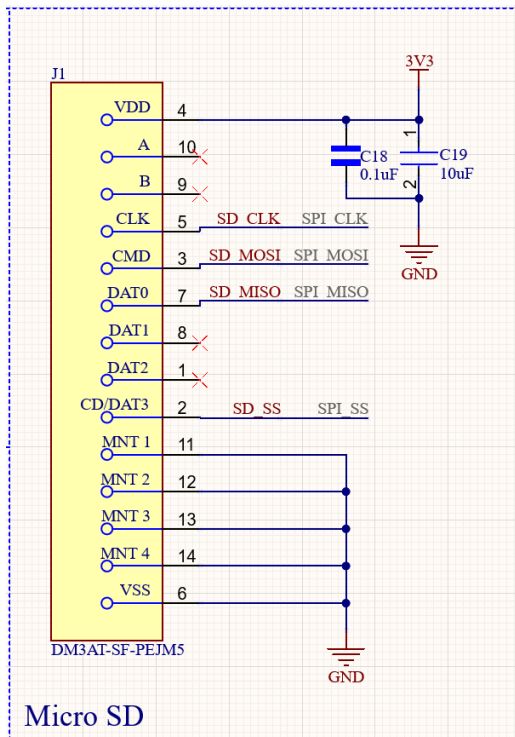


**Figure 6.2.8: Micro SD Schematic**

The data we save to the SD card does not mean much if we cannot accurately timestamp it. To do this, we implemented a Real Time Clock (RTC), specifically

the Analog Devices DS3231. This chip is pre-packaged with a crystal oscillator, and communicates over I2C, making it extremely easy to implement into our design. The RTC requires a backup battery to keep the clock running when the MCU is off, so it is connected to the same 3V rechargeable battery as our GNSS module. Refer to *Figure X* for the RTC schematic.

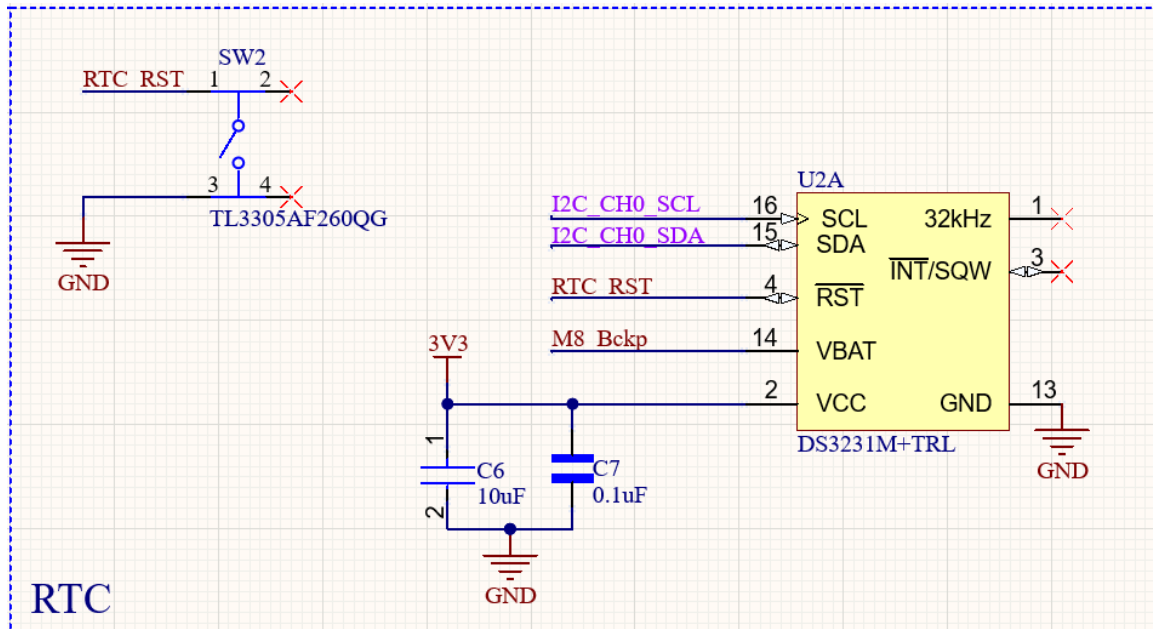


**Figure 6.2.9:** *RTC Schematic*

## 6.3 RF Subsystem

The RF subsystem has two parts, the transmission components located on the payload and the receiver located on the base station. The transmitter will consist of a radio module that will modulate and transmit the signal. This signal will be sent to the dipole antenna via coaxial cable which will be connected to the radio module by an SMA connector. This signal once sent over the air by the dipole will be picked up by the base station.

The receiver on the base station will have another dipole antenna that will pick up the signal from the payload. On the stretch launch we will use a yagi antenna for a more directional receiving antenna to make up for the farther distance of transmission. Both antennas, the transmit and receive will be running LoRa at 915 MHz. We chose to go with LoRa over APRS due to the accessibility of LoRa devices as well as the public support LoRa has. In a worst case situation if we lose contact with the vehicle LoRas public “operators” receive signals operating at LoRa frequency and upload their information to a public website.

Looking at the schematic below we can see the radio module. It takes in a 5 volt input. On the input power line there are four decoupling capacitors, a 47 microFarad, 1 microFarad, .22 microFarad and .1 microFarad. The chip operates on an SPI protocol, we know this by looking at the pins of the EBYTE 915M30S

module we are using. We can see there are SCK, MISO, MOSI, and NSS pins. These are common SPI pin heading names; sometimes the MISO and MOSI pin may be called PICO or POCI or some other similar naming convention. SPI operates by taking in a clock signal from the master device, in our case the ESP32. Once the clock signal hits a rising edge or falling edge (depends on what is configured and what the device specifies) the data will then be sampled and returned to the master. For the radio module the SPI pins we are using are named SPI\_CLK, SPI\_MISO, SPI\_MOSI, and SPI\_SS\_ANT. These are going to hook up to the MCU for control. The TXEN and RXEN are for transmit and receive enable.

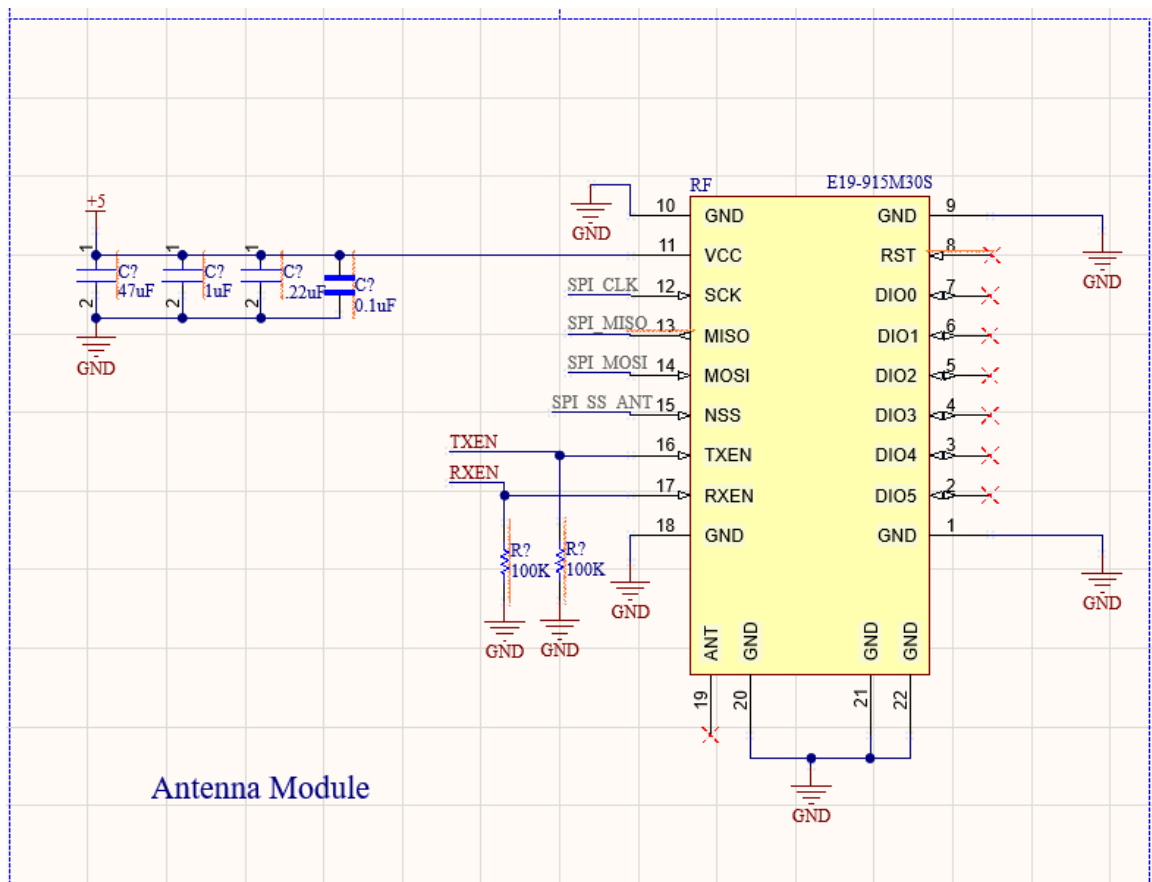


**Figure 6.3.1** RF Transmitter Schematic

## 6.4 Atmospheric Peripherals

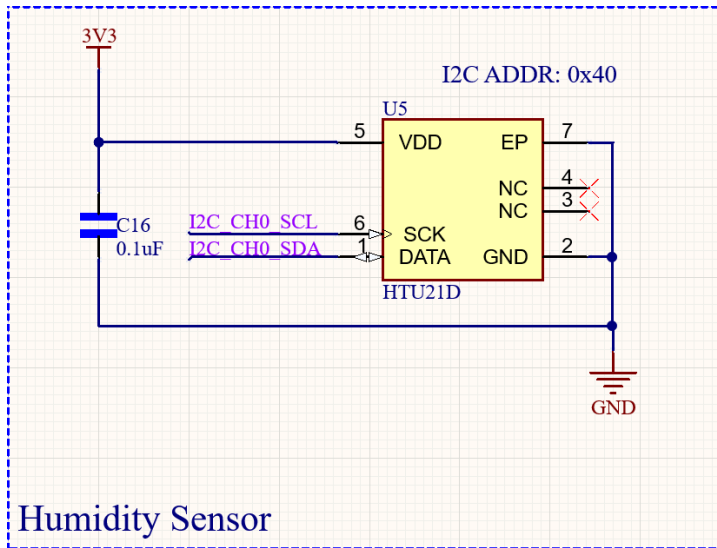


**Figure 6.4.1** Temperature and Humidity Sensor Schematic

The HTU21D temperature and humidity sensor is a 2 in 1 device connected via I2C. It is powered by the 3V3 bus (VDD). The I2C DATA pin and SCK pin are connected to the I2C buses for channel 0, to MCU pins 33 and 36 respectively (IO21 & IO22). Additionally, there are 2 hanging No Connection (NC) pins as well as an Exposed Pad (EP), which is tied to ground along with the ground (GND) pin. Lastly, the datasheet instructs that a 100nf bypass capacitor be connected between VDD and ground as close to the pins as possible

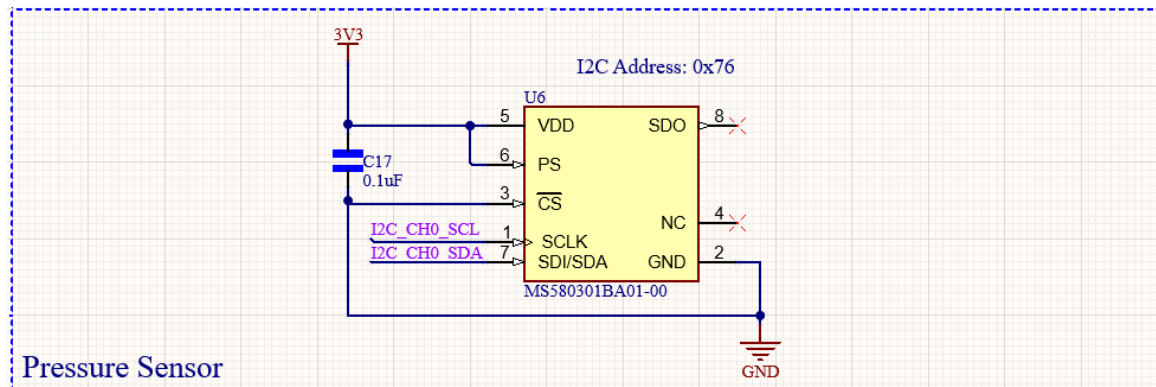


**Figure 6.4.2** Pressure Sensor Schematic

The MS5803-01BA Pressure sensor is also powered from the 3V3 bus and a ground pin. The sensor comes with I2C and SPI functionality which is selected by either tying the Protocol Select (PS) pin to ground or VDD. We are using I2C channel 2 in this case, so it is tied to VDD. The SDI is the data bus for the sensor, while the SDO is left unconnected for I2C operations. The SDI and SCLK are connected to the I2C buses for channel 0, to MCU pins 33 and 36 respectively (IO21 & IO22). The Chip Select (CS) pin allows some freedom when

it comes to I2C addressing. The CS pin acts as the LSb for the address. The address of the bus is 0x76 or 0x77 which can be useful for possible conflicts with other devices. We have no address conflicts so may use either and we chose to tie it to ground. This datasheet also requires a 100nf bypass capacitor be connected between VDD and ground as close to the pins as possible.

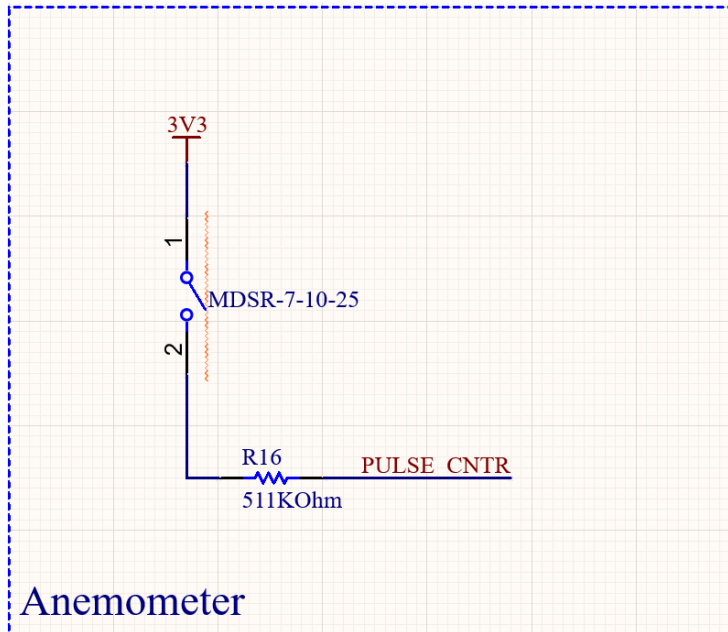


**Figure 6.4.3** *Anemometer Schematic*

The Inspeed Classic Anemometer is connected and only utilizes a Reed switch in its circuitry. It is powered by the 3V3 bus. This is fed into a current limiting resistor to limit the power consumption though the anemometer when the circuit is closed. This output voltage of the pulse, which is within 95% of the value of the power bus, will be fed into the pulse counter, MCU pin 6 (IO34).

## 6.5 Telemetry Peripherals

### 6.5.1 GNSS Module

The Ublox SAM-M8Q consists of an antenna, RF circuitry, and a microcontroller. This makes it extremely easy to interface with, as it calculates latitude, longitude, and altitude internally, and sends that data over I2C. The VCC pin is connected to the 3.3V rail and is decoupled with a 0.1 $\mu$ F capacitor, the VCC IO pin is connected to the same rail as VCC.

The SAM-M8Q features “hot start” capability. Upon startup, this allows it to lock onto satellites in as little as 1 second, compared to up to 30 seconds for a “cold start.” In order to take advantage of hot start, a 3V backup battery needs to be routed to the V BCKP pin. The 3V battery is rechargeable, so a current-limiting circuit is utilized to maintain charge during power-on.

The SAM-M8Q uses an active-low reset pin, which is connected to a momentary push-button switch. In addition, it also supplies a TIMEPULSE pin which outputs a high signal every second, in synchronization with the GPS or UTC timegrid. This pin is routed through a 1 KOhm resistor to a yellow LED. The I2C SCL/SDA lines utilize 22 Ohm resistors to reduce the risk of interference from RF signals. Refer to *Figure 6.5.1* for the GNSS Module schematic.

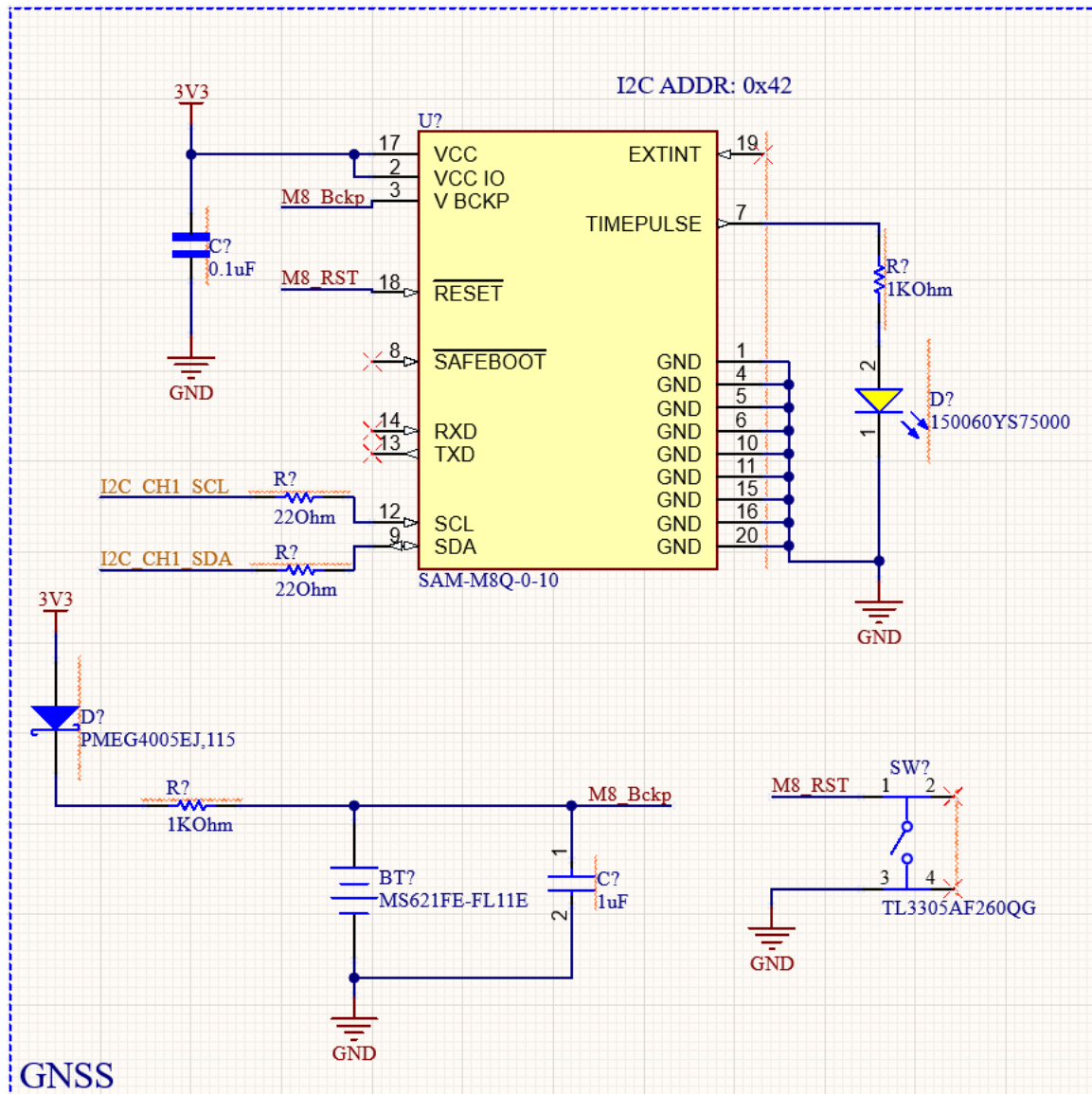


**Figure 6.5.1: GNSS Schematic**

## 6.5.2 Altimeter

The Xtrinsic MPL3115A2 Altimeter is connected to the 3V3 bus. The signal is stabilized with a 10uF decoupling capacitor and high frequency noise is filtered with a 100nF bypass capacitor. The VDDIO is the reference for digital high signals, and is tied to VDD. There are 2 external interrupt pins (INT1 & INT2). The sensor will be polled at constant intervals without the need for interrupts, so they are left hanging. The SCL and SDA pins connect to the appropriate I2C channel 2 buses, which are the MCU pins 8 and 9 respectively (IO32 & IO33). The CAP pin connects to an external capacitor for internal voltage regulation, which goes to ground alongside the GND pin. Refer to *Figure 6.5.2*.

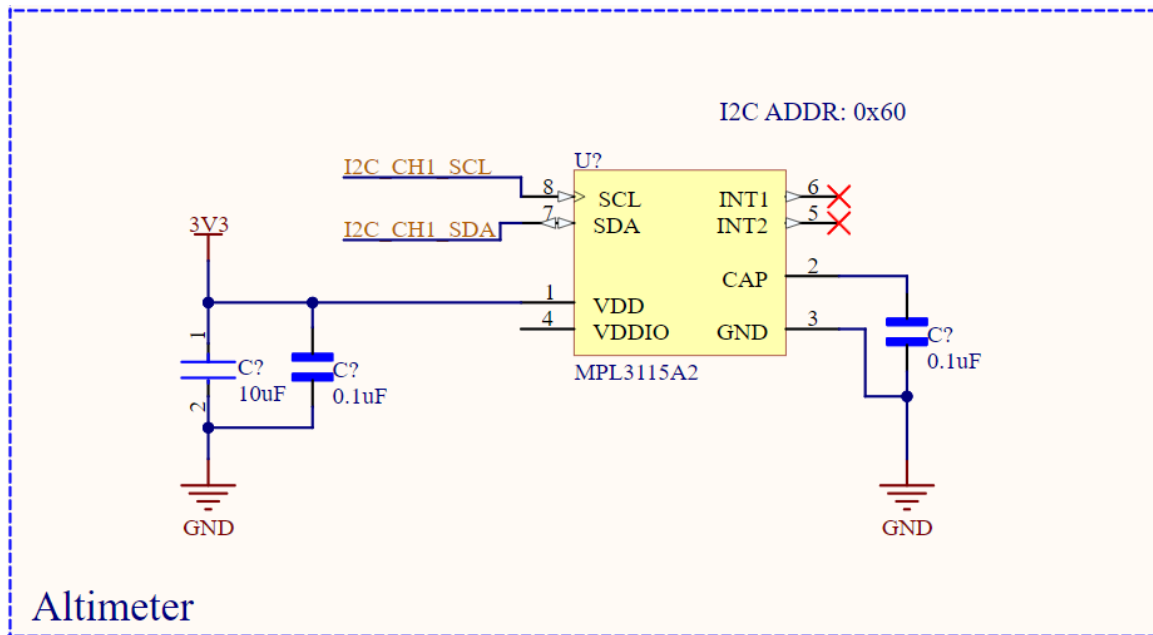


**Figure 6.5.2** Altimeter Schematic

## 6.5.3 IMU

The ISMDHCX is powered by the 3V3 bus for its VDD and VDDIO. Both have a 100nF bypass capacitor, while the VDD pin also has a 10uF decouple capacitor. The sensor has I2C and SPI functionality, but it is configured for I2C. The SCL and SDA pins connect to the appropriate I2C channel 2 buses, which are the MCU pins 8 and 9 respectively (IO32 & IO33). Due to this, the OCS and SDO Aux pins are left unconnected. The SCx and SDx are also unused in this configuration, but are tied to VDD. There is no mention in the datasheet as to why, but a similar model, ISM330DLC, mentions letting these pins hang will increase current consumption in its datasheet. [CITE, sheet in drive] The CS pin selects I2C/SPI and connects to VDD to select I2C. There are 2 INT pins left hanging and 2 GND pins. Refer to *Figure 6.5.3*.

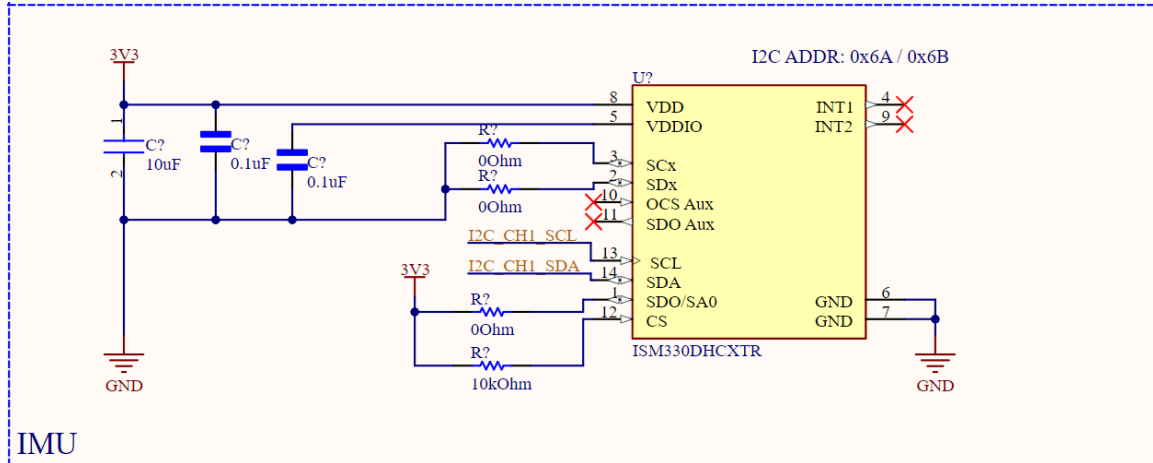


**Figure 6.5.3** *IMU Schematic*

## 6.6 Optical Subsystem

The optical design of the spectrometer involves two lenses, a pinhole, a transmissive diffraction grating, and two photodiodes. The total length of the system shown in the figure will be roughly 14 cm in length. The system in Figure 6.6.1 is the Ray Optics simulation model of how light will pass through the various spectrometer components and behave throughout until reaching the detector interface. The white LED represented by the point source on the left of the figure will likely emit in a wider angle as shown so a pinhole is used after the LED to limit the FOV for the light source and help with the focus aspect towards the end of the system. The whole system will be enclosed to prevent particles or stray photons from entering the setup and contaminating the experiment. The diode, however, will be contained even more on its own with the pinhole being the only escape for light.

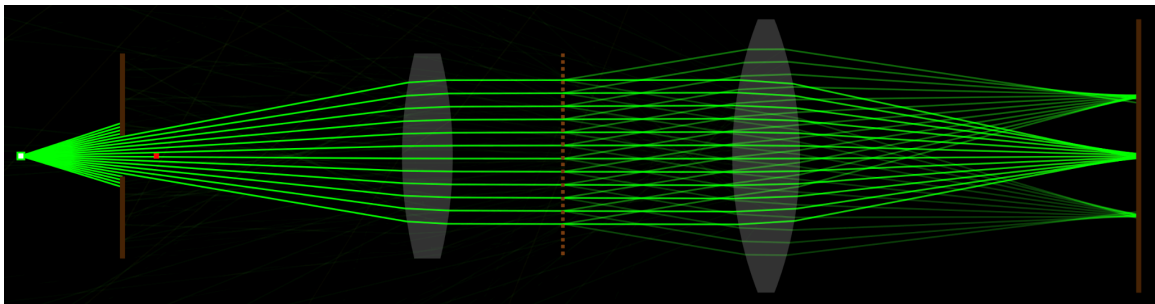


**Figure 6.6.1** *Spectrometer Lens System Layout*

Due to the project needs, only two specific wavelengths will need to be detected to obtain the results desired. Since we are going to be detecting mere oxygen gas presence, a photodiode at 750nm will be used for the molecule detection, and one photodiode at 550nm to be used as a reference. The white LED will be purchased from Adafruit, the pinhole will be made in-house, both plano-convex lenses will be purchased from Edmund Optics, and the transmissive diffraction

grating will be obtained from Omega Optical. Lastly, the photodiodes will be ordered from Thorlabs.

The photodiodes will be interfaced onto the XXX and implemented with a high-pass passive filter and bias voltage source. The high-pass filter will increase our SNR to a visually distinguishable level and the bias voltage source will allow us to tune the sensitivity of the photodiodes. The data collected will be voltage readings at each wavelength. The 550nm detector should always be transmitting heavy readings if the subsystem is working, and the 750nm detector will transmit something only if oxygen gas is not present.

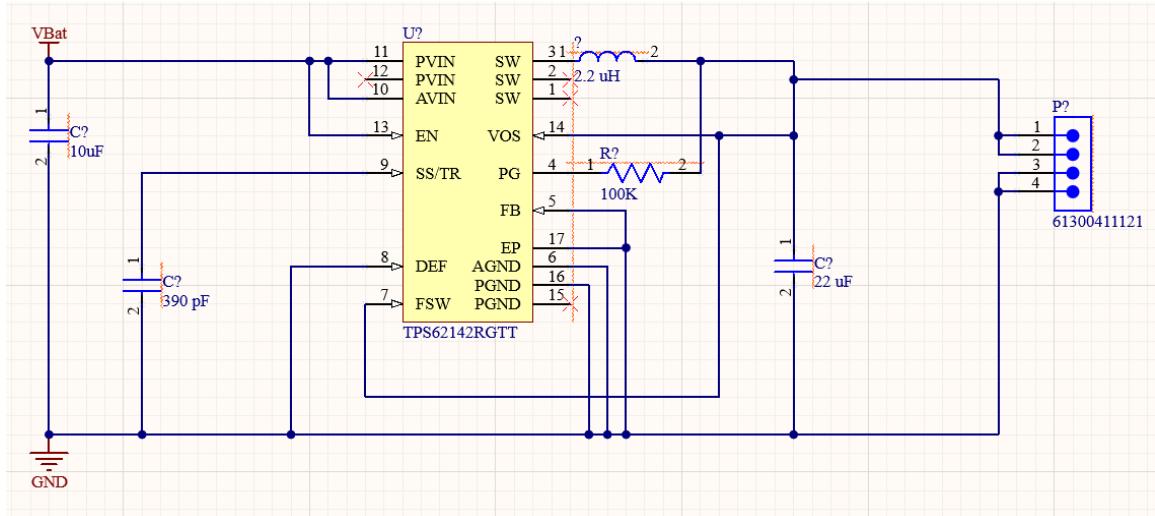
## 6.7 Power

The power subsystem for this project consists of a power supply and we are using a 2 cell 5000 mAh 7.4 volt battery. This is denoted by VBat in our schematics. The battery and power subsystem is a huge part of our project as without power nothing will be powered and nothing will work. Being a single point failure of our design this system needs to be carefully designed, manufactured and tested thoroughly. After power leaves the battery it is then fed into two voltage regulator circuits which drop the voltage from the current battery voltage output. To either 3.3 or 5 volts. The battery has a minimum output voltage of 7.4 volts and a maximum of 8.4 volts. These voltage regulating circuits are able to take in the entire range of voltage from the battery output allowing for a smooth transition from battery output to the power busses.

Lets dive into the voltage regulators, below we have the schematic for our 7.4 volt to 3.3 volt buck converter, designed from Webench Power Designer. The chip used in the step down circuit is a TPS62142 offered from Texas Instruments. The device operates with pulse-width modulation in continuous-conduction mode. This means that the inductor, in our case 2.2 uH connected to the load will never reach zero and always stay positive even when switched off. The FSW pin on the chip stands for Frequency Switching, when this pin is powered high the device operates at 1.25 MHz and when the pin is powered low it operates at 2.5 MHz. These frequencies represent at what frequency the switching occurs at while pulse width modulation represents how long of the switching cycle to stay on for.

The pulse width modulator is then managed by control loop circuitry which takes in the input of the VOS pin. VOS stands for Voltage Output Sense and compares the output voltage to the desired output voltage. It then reports this to the control loop which adjusts the pulse width modulation to reach the desired output voltage. A concern of the power system is how it will operate under the extremely cold environment found in the stratosphere. With the insulated payload we will be able to keep our electronics at the optimal operating temperatures, we will also have a battery sensor to measure output voltage from the battery before being sent to the buck converters. With VOS at the end of the voltage regulator we will be supplying consistent reliable voltage through the buses to be used for all other electronics on board the payload.

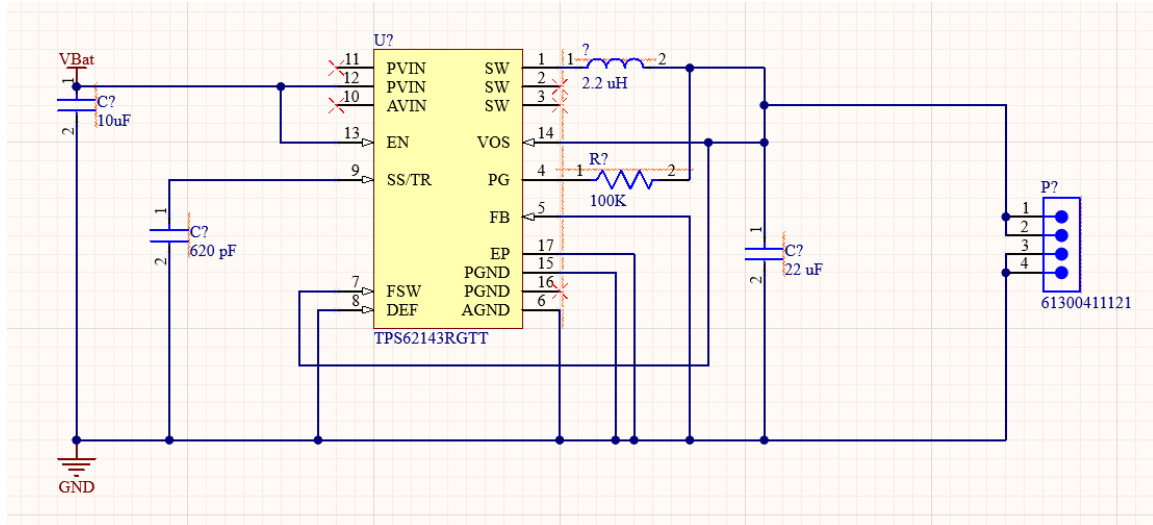
## 7.4 to 3.3 Volts



The voltage regulator for the 5 volt bus is similar to the 3.3 volt version just with some external components changed. The 5 volt buck converter below also uses a different texas instruments chip from the same family. As we can see below the TPS62142 used in the 7.4 to 3.3 volt voltage regulation circuit has an output voltage of 3.3 volts. On the other hand the 7.4 to 5 volt voltage regulation circuit found below the chart uses a TPS62143 with an output voltage of 5 volts.

| PART NUMBER | OUTPUT VOLTAGE | POWER GOOD LOGIC LEVEL (EN = LOW) |
|-------------|----------------|-----------------------------------|
| TPS62140    | Adjustable     | High Impedance                    |
| TPS62140A   | Adjustable     | Low                               |
| TPS62141    | 1.8 V          | High Impedance                    |
| TPS62142    | 3.3 V          | High Impedance                    |
| TPS62143    | 5.0 V          | High Impedance                    |

## 7.4 to 5 Volts



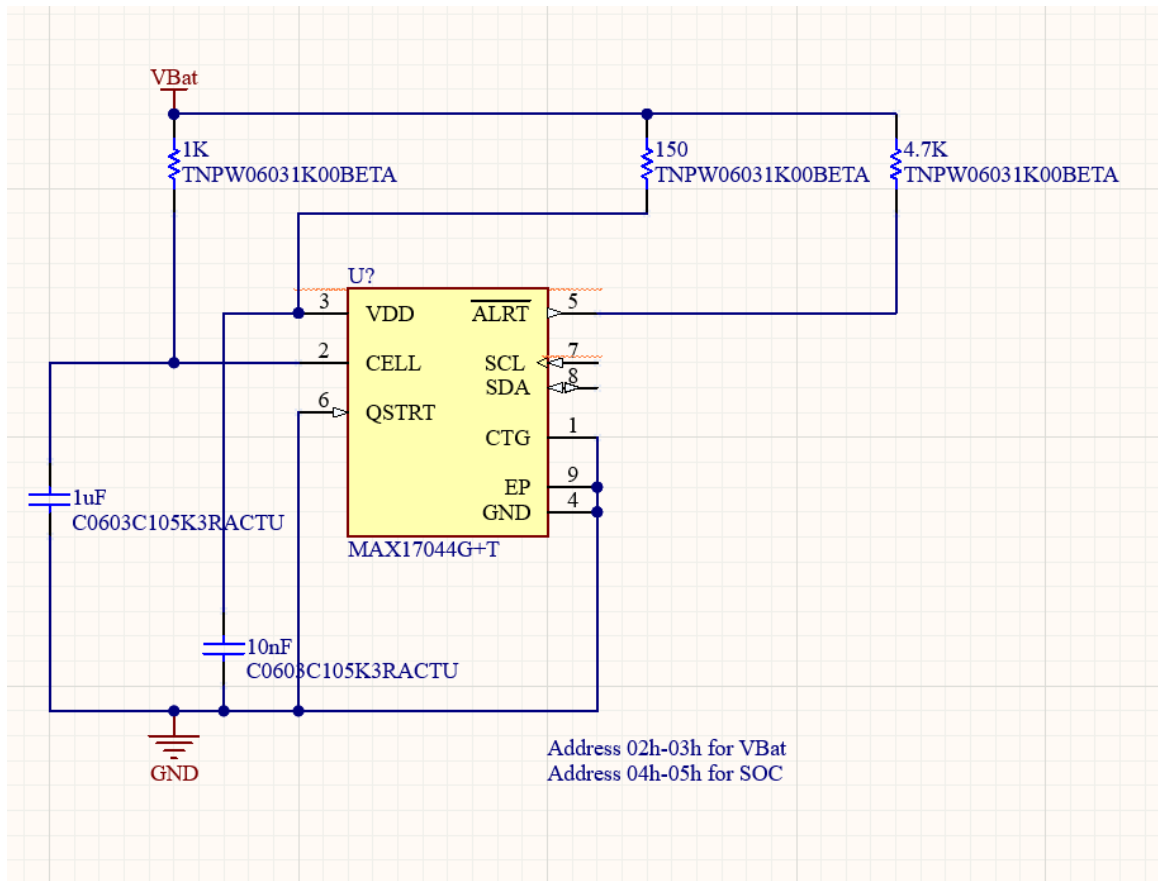
We can also analyze the external components when looking at these voltage regulators. Looking at the 5 volt schematic above, we can see there are two input capacitors: 10 microFarads and 620 picoFarads. These are decoupling capacitors that take in the input voltage and filter it out, smooth it, as well as reducing noise. Without these the input signals would be a lot more messy with lots of noise and ripple. Reducing this allows for the chip and system to operate reliably without leaving any of the performance to chance. We talked about the 2.2 microHenry inductor above and its role in the continuous conduction mode output voltage system. This inductor is responsible for storing and outputting energy. When the switch is on the inductor charges and when the switch is off the inductor outputs energy. This provides a smooth transition from one voltage to the desired voltage.

The last element in the power supply system is the battery sensor. The battery sensor is located between the battery and the voltage regulating buck converters. This sensor takes in the battery power and transfers it to the two buck converters. In the process it takes in the current voltage of the battery as well as how much energy the battery has left. The chip does this by simulating the battery chemistry, impedance and time effects of the battery. Usually other battery sensors accumulate error as time goes on, the MAX17044 that we use does not. In coulomb counters which are typically used in battery sensing applications they get less accurate as time goes on and a state of charge drift occurs.

To communicate with this chip and poll the current data we have to use I2C. The two addresses we will be polling from this chip are 02h - 03h which coordinates with VCell, the current voltage of the battery. We are also going to polling 04h - 05h SOC, which is the current state of charge. These two I2C address are connected to **PUT WHAT PINS THEY ARE CONNECTED TO ON THE MCU.**

<https://www.analog.com/media/en/technical-documentation/data-sheets/MAX17043-MAX17044.pdf>

## Battery Sensor



## Chapter 7: Software Design

The high-altitude balloon will require a series of software designs to achieve proper and reliable functionality among the different sections that make up the entirety of this project. For proper and reliable functionality, the High-Altitude Balloon project will be separated into two different sections, one section will be dedicated for the payload, which is going to be in the sky, and the other section will be dedicated for the base station, which is going to be in the ground. In addition to that, each section can be separated into subsystems to ensure proper and reliable software design, making sure each component is being used as intended.

The first section can be defined as the payload, where the MCU and all of the atmospheric and telemetry peripherals will be located to collect data along the trajectory of the flight to later communicate with the MCU, which is going to process the data from each atmospheric and telemetry peripheral and later store them into the SD card. In addition to reading and storing the data, the software should also be designed so it is able to identify whether the data is telemetry or not, being that telemetry data needs to be transmitted to the base station in order to be able to locate the payload in real time to track its path and successfully recover the payload once it lands back. It is important to mention that although a camera is also being used to record the trajectory of the flight, a software design to implement this component is not required, being that the camera is going to be set to record manually before launching the High-Altitude Balloon, in addition of having an independent SD card dedicated to store all footage recorded along the flight.

The second section can be defined as the base station, where the computer and communication peripherals will be located to receive data from the payload during its flight, and process the data stored in the SD card once the payload is recovered. The base station software design can be splitted into two different subsections, one for the communication and one for the GUI implementation. For communication, the base station software is designed so it guarantees reliable real-time communication with the payload in order to receive essential telemetry data such as location or altitude that will ease the process of tracking the balloon during its flight and once it lands back. Finally, for the GUI implementation, the base station software is designed to provide a fully customized user interface where all the data acquired during the flight, stored in the SD card, can be visualized and analyzed in multiple ways and settings, providing plots, maps, tables, and any additional analysis relevant to this topic. It is important to mention that although a communication software design is mentioned, in reality open source softwares will be used and integrated to the GUI.

### 7.1 Payload Software Design

The first section that compose this software design section, as mentioned above, is going to be the payload software, and along the most important tasks there is

MCU and peripheral communication, proper data formatting and separation, convenient for data processing on the base station once the payload lands back, and periodic real-time communication with the base station for tracking purposes. Figure 7.1 shows the overlap software design structure for the payload, showing all relevant activities that will be performed, mainly by the MCU and the modules. A more detailed explanation will be provided to describe the design of the payload software.

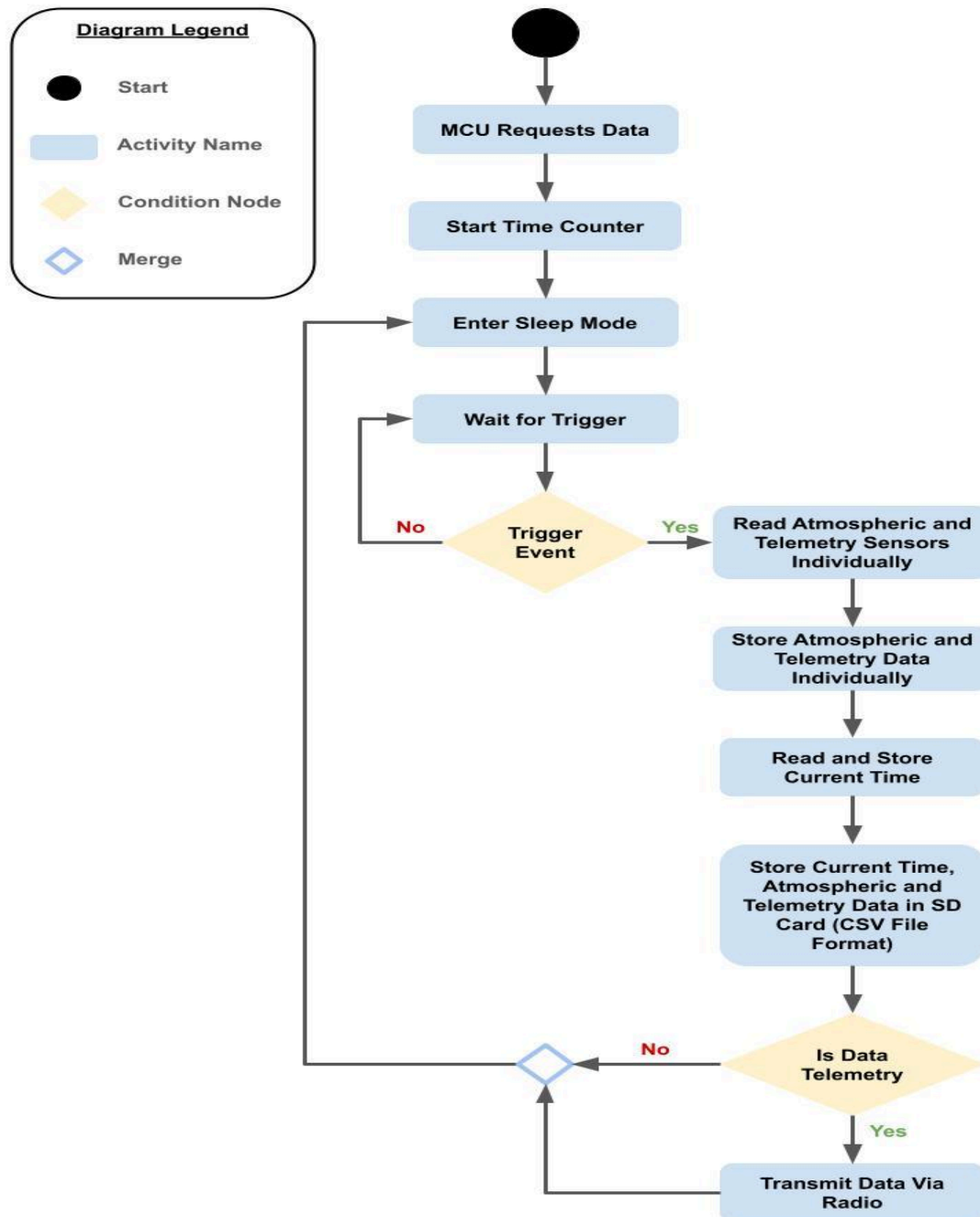


**Figure 7.1** Payload Software Activity Diagram

## ESP32

The ESP32 is the brain and most important component of this payload. Among its many responsibilities, the more important tasks are to communicate with and store data from the different peripheral and sensors, format and separate the data received to ease future data processing at the base station, and communicate via radio with the base station to provide live and reliable data such as atmospheric data and location of the payload. In this case, due to familiarity and convenience factors, the ESP32 was programmed using the Arduino IDE, using C++, providing a simple yet effective proper MCU development, being that due to its popularity and amount of resources available online, the ESP32 can be easily integrated and programmed with the Arduino IDE.

### 7.1.1 Atmospheric and Telemetry Sensors

One of the main goals of this High Altitude Balloon project is to be able to collect atmospheric data that will be used to later perform a series of analyses on how the atmosphere changes due to the change in altitude. In order to observe these atmospheric changes, a total of three sensors will be used to collect temperature, pressure, humidity and wind speed. When programming the ESP32, it is important to know which protocol each of the sensors uses, to provide proper interface and guarantee proper data collection. Based on the data sheets, it was found that the temperature and humidity sensor, the HTU21D, will use I2C. Similarly, the pressure sensor, which can also be used as a temperature sensor, the MS5803-01BA, will be using I2C. Finally, the anemometer, the Inspeed Classic, will provide an analog output in the form of a pulse, depending on the frequency of each spin.

For time and simplicity reasons, open libraries from Github will be used for both the HTU21D and MS5803-01BA sensors. Once both libraries are imported into the main MCU file, only one command is going to be necessary to communicate and collect a reading from one of the sensors. On the other hand, for the anemometer, a function will have to be created to properly read the output pulses and translate them into wind speed. Most of the information regarding how to program a pin for the ESP32 as a pulse counter can be found on the Espressif website. However, due to its difficulty to implement, and pulse false reading, we decided to simply read the analog signal and create a custom setup so every time the pin reads a voltage within a reasonable range, it will count it as a pulse. Finally, to transform each spin into frequency we simply count the number of spins per second, then convert the frequency to wind speed (in miles per hour) using the formula provided by the manufacturer.

The other main goal of this High Altitude Balloon project is to be able to collect and transmit telemetric data for live tracking of the payload from the base station and later data processing. In order to collect the telemetry data, a total of three telemetry sensors will be used to measure altitude, velocity and location. Based on the data sheets of each sensor, it was found that the altimeter sensor, the MPL3115A2, uses I2C. Similarly, the GPS module, the SAM-M8Q, uses I2C.

Finally, the 6 axis IMU, the ISM330DHCX, also uses I2C. Since all telemetry sensors use I2C, and for time and simplicity reasons, open libraries from Github will be used for all telemetry sensors. All files will be revised to double check all commands and addresses are set up correctly, and once the revision is done the sensors would be able to be read from the MCU by simply running a few lines of code by importing and calling each of the libraries for each sensor into the main MCU file.

### **7.1.2 Radio (Transmitter), SD Card and RTC**

The radio module is essential for reliable long-distance data transmission and communication between the payload and the base station. The SD card module will store data from each individual sensor, which will be crucial when the payload is recovered and the data is analyzed via the GUI. The RTC module ensures proper data organization by recording the current time at which data is collected, providing accurate timestamps that enable users to track how atmospheric factors change throughout the flight's trajectory. This is essential for effective data analysis through the GUI. Based on the datasheets of each module, it was determined that the radio module, the E19-915M30S, utilizes SPI communication. Similarly, the SD card module, the DM3AT-SF-PEJM5, also uses SPI. The RTC module, which is integrated with the SAM-M8Q GPS module, employs I2C communication. As in previous sections, open-source libraries from GitHub will be utilized, as these libraries are already compatible with the modules used in this project.

## **7.2 Base Station Software Design**

The second section that compose this software design section, as mentioned previously, is going to be the base station software, and along the most important tasks that need to be performed there is constant and live communication with the payload, and post-recovery data processing, which will be integrated with a graphical user interface. Figure 7.2.1 and Figure 7.2.2 shows the overall software design structure for both subsections of this base station section, showing in detail how the base station receiver is going to communicate with the payload, and how the GUI is going to be used by users to display and analyze all data collected. A more detailed explanation will be provided to describe the design for each of the base station software subsections.

### **7.2.1 Receiver and Communication Software Design**

Since the payload and base station are two different systems, a new ESP32 will be needed to integrate all the modules which are going to be used for the base station. The ESP32, as previously mentioned, is the most important component for the base station also, due to the fact that it will ensure communication between peripherals and proper functionality of each component such as the radio module and the LCD screen. The radio module, as previously mentioned, is essential for reliable long-distance data transmission and communication

between the payload and base station. The LCD screen will allow users to see the live data that is being transmitted from the payload to the base station. Being that the radio module that will be used for the base station is the same as the radio module from the payload, a similar code will be used, with the only difference that instead of transmitting data and sending packages, this radio module will wait until a package is received to trigger an interrupt and from there display all the data received. Based on the data sheet of each module, it was found that the radio module, the E19-915M30S, uses SPI. On the other hand, the LCD display module, the [NAME], uses I2C. Finally, a series of buttons will be added to the base station system to scroll through the different sets of data that can be displayed on the LCD screen. Example programs can be found online via Github, where existing libraries for all the modules used are already well structured.

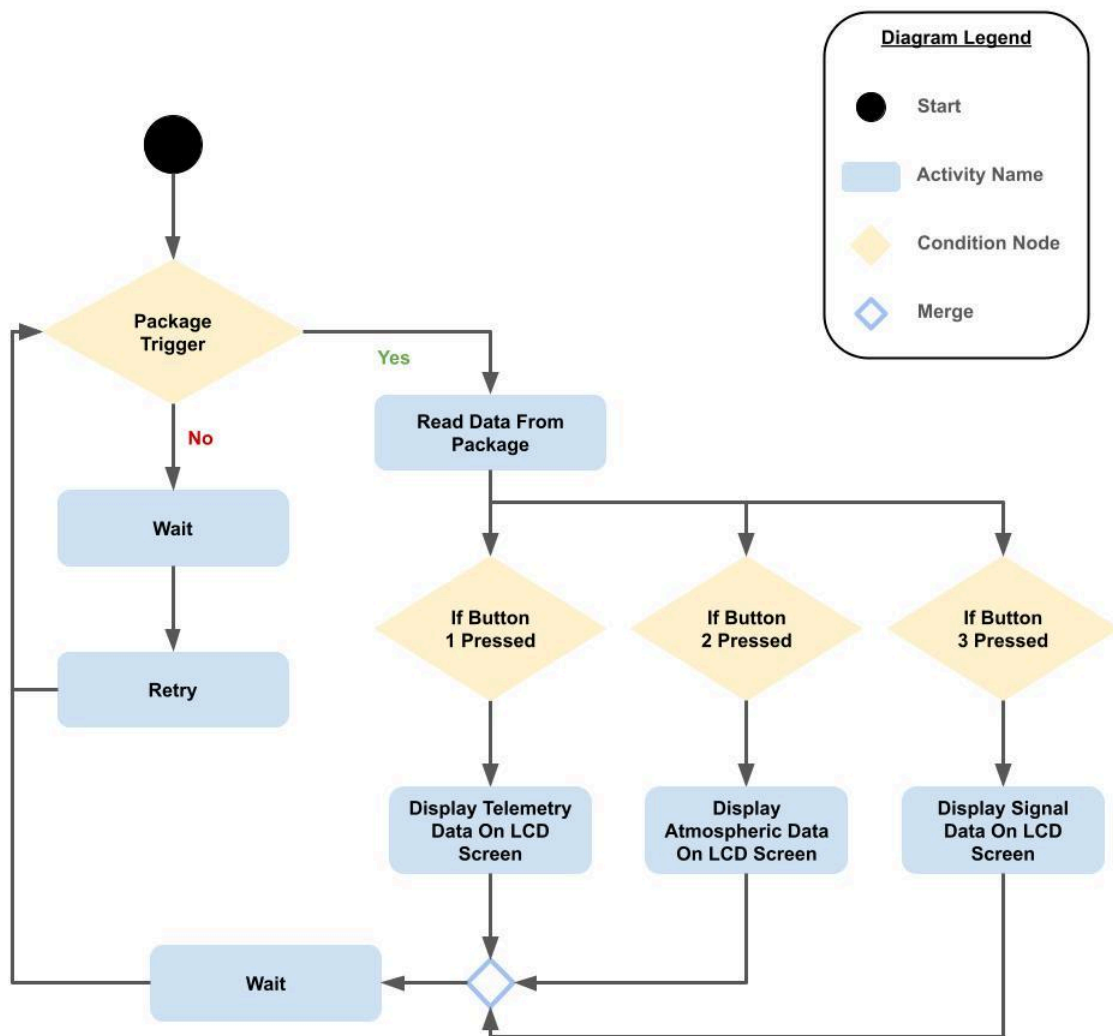


**Figure 7.2.1** Base Station Software Activity Diagram (Communication)

### 7.2.2 GUI and Data Processing Software Design

The last software design section for this project is the Graphical User Interface (GUI), which will be responsible for displaying all the collected data to the users. To achieve a professional and custom design for the GUI, multiple libraries to allow customization were added such as tkinter and customtkinter, which in addition of providing all the customization tools needed, it also has different online resources and examples that can be used to have a more clear idea of how to work with said libraries. As it can be seen in Figure 7.2.2, the logic that this GUI follows is very simple, as it starts in a windowed screen with two buttons to either plot data or exit the program. If the plot data button is pressed, then the program runs a separate full windowed screen where all data can be plotted as long as the data is available in the selected CSV file. To select CSV files, the user only needs to press the green “Select CSV File” button, which is linked to a function that triggers a file dialog which asks the user specifically to browse and select a CSV file, practically the CSV file will be selected from the payload SD card to ensure the program reads the data properly. Once a CSV file is selected, users can start pressing different buttons to display and see the different data collected using data plotting and analysis libraries such as matplotlib and pandas. Finally, once the user wants to exit the GUI, the red “Exit” button can be pressed, which will trigger a built-in function from customtkinter that will make the app stop running and close it.

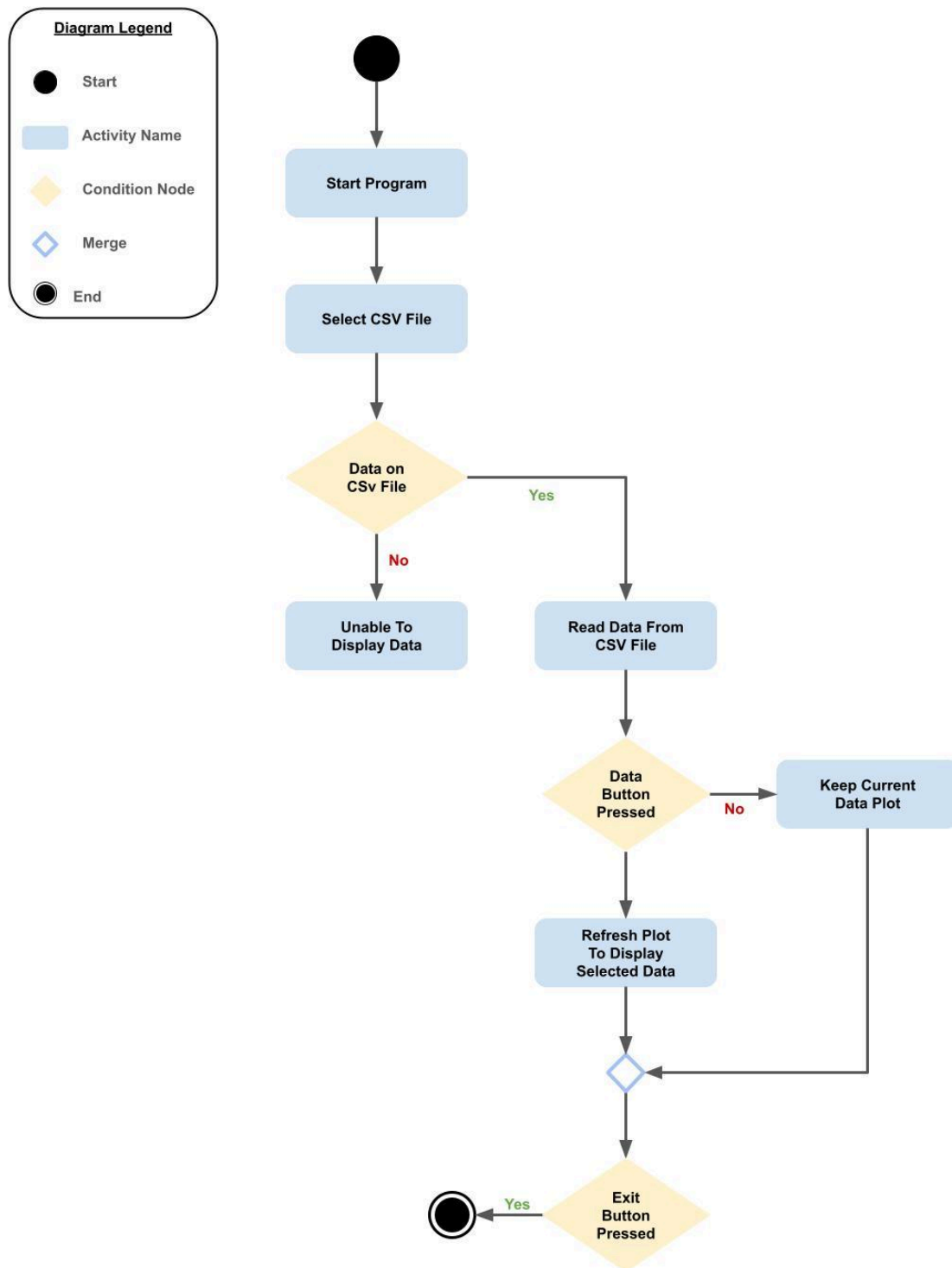


**Figure 7.2.2 Base Station Software Activity Diagram (GUI)**

## Chapter 8: System Fabrication/Prototype Construction

### 8.1 MCU Board Layout

The MCU board houses the ESP32, Ebyte E19 LoRA module, altimeter, IMU, pressure sensor, SD card slot, and temperature / humidity sensor. The MCU board is the most critical component of the Balloon Payload System. In order for our project to function, the MCU board must meet the following goals:

- **Programmability:** *The MCU board must include circuitry that allows the ESP32 to be programmed over USB with or without an external power supply.* This was accomplished by utilizing the auto-program circuitry featured in Espressif's official ESP32 development board and implementing an LDO that allows all the on-board 3.3V components to function on USB power.
- **Connectability:** *The MCU board must provide an ample amount of connections to external boards and sensors.* The MCU board features 5 different headers. Three are screw terminal headers which connect to the anemometer, external temperature sensor, and rapid deflation circuitry. One is a JST SH connector which connects to the GNSS board, and one is a 4-pin 2.54 mm pitch auxiliary header.
- **Low-Noise:** *The MCU board must shield traces from noisy components. It must also be able to shield traces from external noise.* This was accomplished by using a 4-layer stackup with 3 ground pours: one on the top layer, one on the inner 1 layer, and one on the bottom layer. All three layers are connected with stitching vias.
- **Diagnosability:** *The MCU board must be designed in a way that individual components can be isolated from data buses without removing them from the board.* This was accomplished by utilizing 0 Ohm jumper resistors on the data lines leading to every component on the I2C and SPI buses.

Refer to *Figures 8.1 & 8.2* for the MCU board layout.

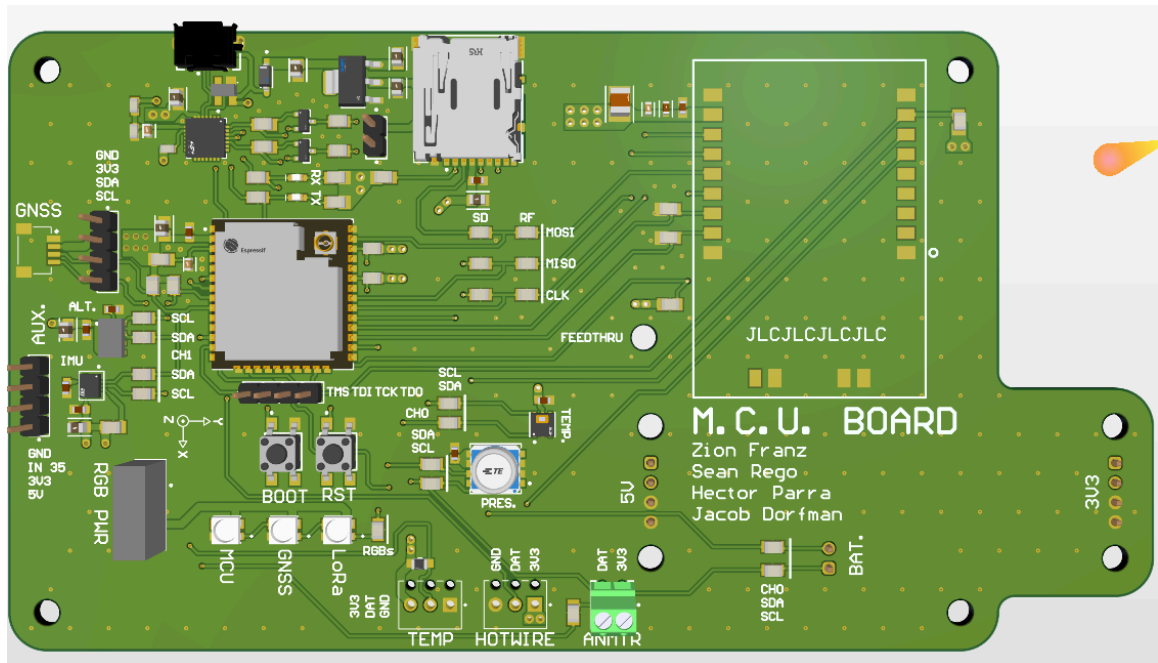


**Figure 8.1: 3D MCU Board Layout**

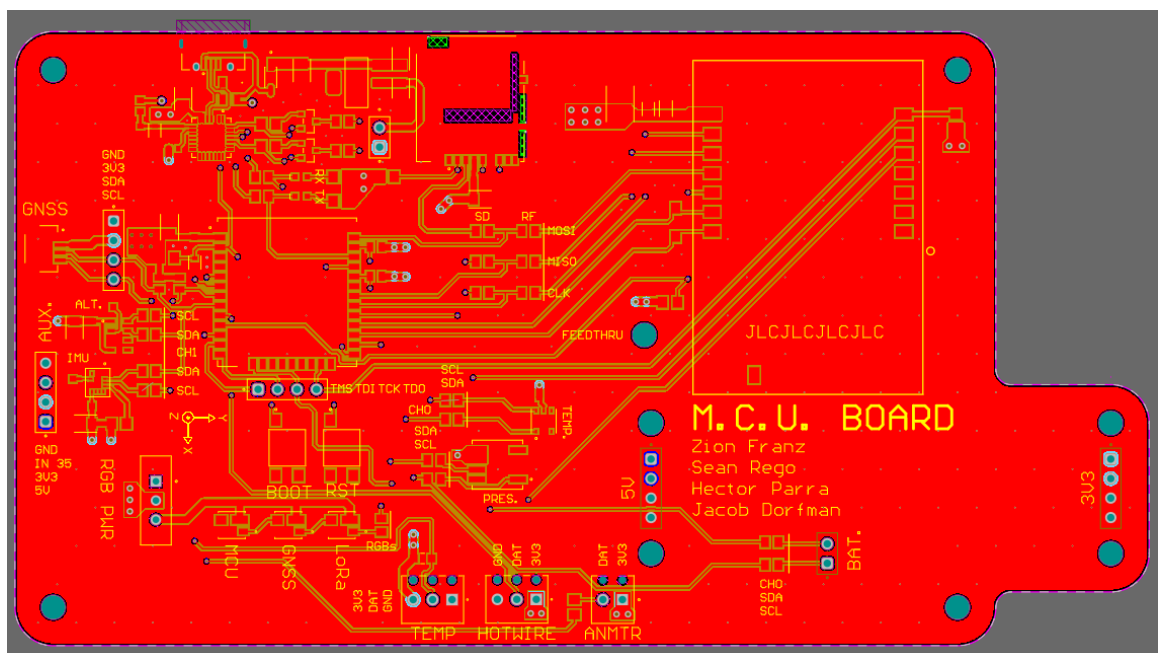


**Figure 8.2: 2D MCU Board Layout**

## 8.2: Power Board Layout

The power board houses the 5V and 3.3V buck converters, and the battery charge monitor. The power board must meet the following goals to ensure project success:

- **Current Output:** *The power board must be able to supply an ample amount of current to the MCU and GNSS boards.* To achieve this, the power board was designed to deliver 1.5 A to each of the rails. This is an ample amount of current to support all systems on the B.P.S.
- **Battery Charge Monitoring:** *The power board must provide a way to monitor the state of charge of the 2 cell LiPo battery.* To achieve this, the MAX17044 battery fuel gauge chip was integrated onto the power board. This chip measures the output voltage of the battery and relays it over I2C to the ESP32. From there, the state of charge can be logged onto the SD and sent over LoRa to the base station.
- **Overvoltage and Overcurrent Protection:** *The power board must prevent overvoltage and short circuit events.* To achieve this, PTC resettable fuses and zener diodes were implemented on both the 3.3V and 5V rails. When an overvoltage event occurs, the zener diode shunts all current to ground, which blows the PTC resettable fuse. This ensures the voltage rails will never exceed the safe voltage limits set by the zener diodes. The PTC resettable fuses also protect against short circuits.
- **Efficient Buck converter layout:** *The power board must allow the 3.3V and 5V buck converter circuits to function at maximum efficiency.* To achieve this, components such as inductors and capacitors were placed as close to the switching IC as possible. Additionally, large copper pours were used to ensure high current flow with minimal heat.

Refer to *Figures 8.3 & 8.4* for the power board layout.

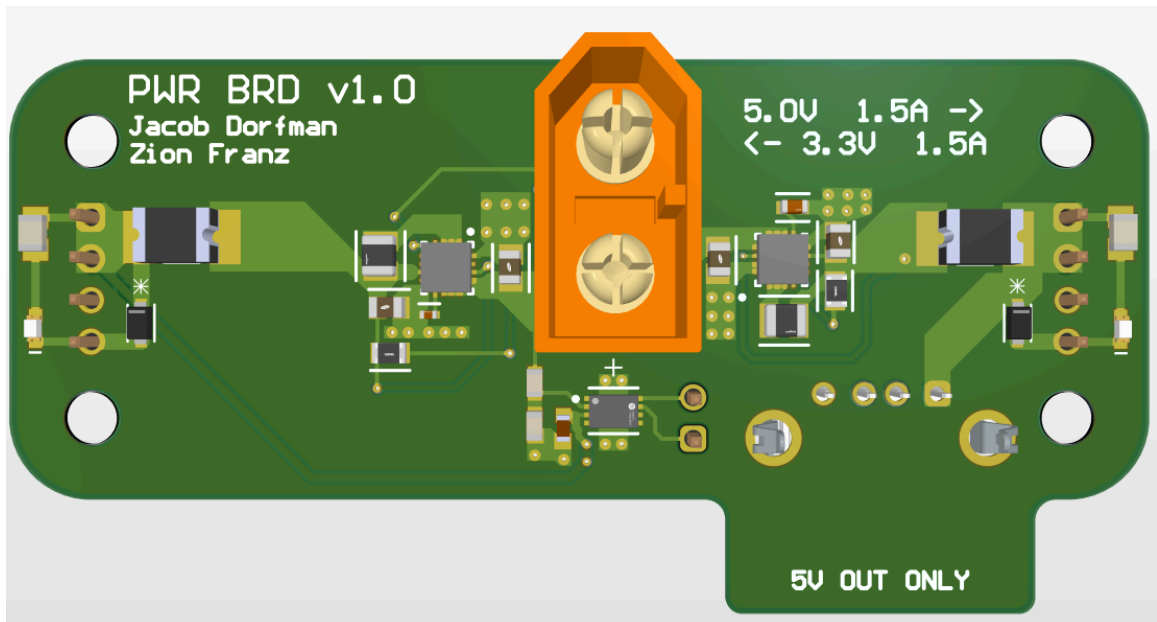


**Figure 8.3:** 3D Power Board Layout

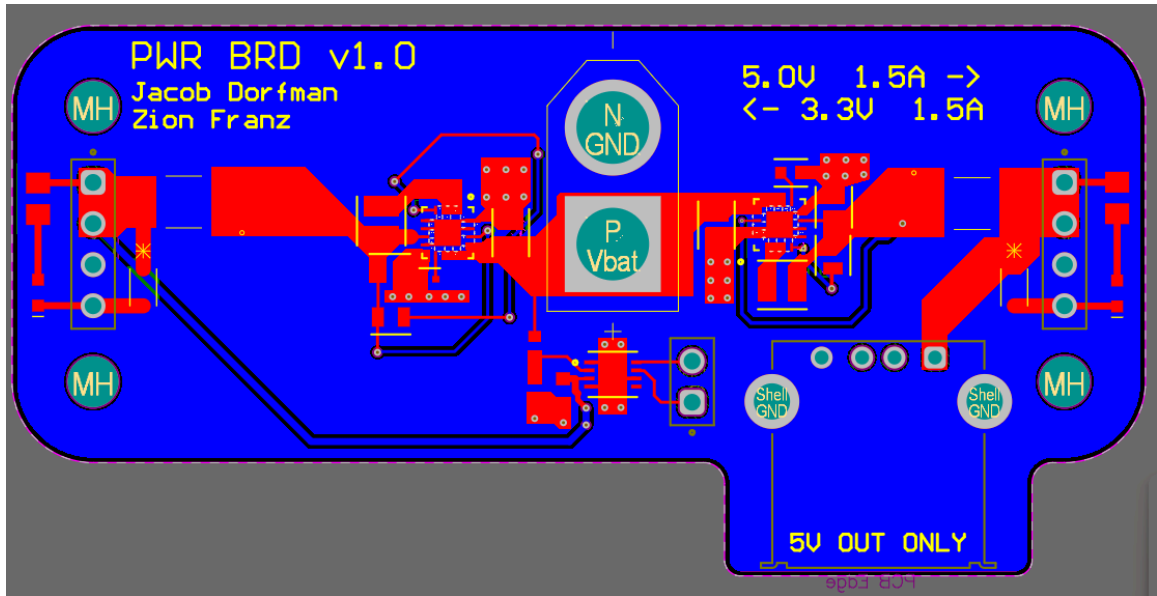


**Figure 8.4:** 2D Power Board Layout

### 8.3: GNSS Board Layout

The GNSS board houses the Ublox SAM-M8Q GNSS module / antenna. The GNSS board was designed to provide the SAM-M8Q with an ample ground plane for its onboard patch antenna to function properly. The GNSS board communicates with the MCU board over I2C with a JST SH connection. Refer to *Figures 8.5 & 8.6* for the GNSS board layout.

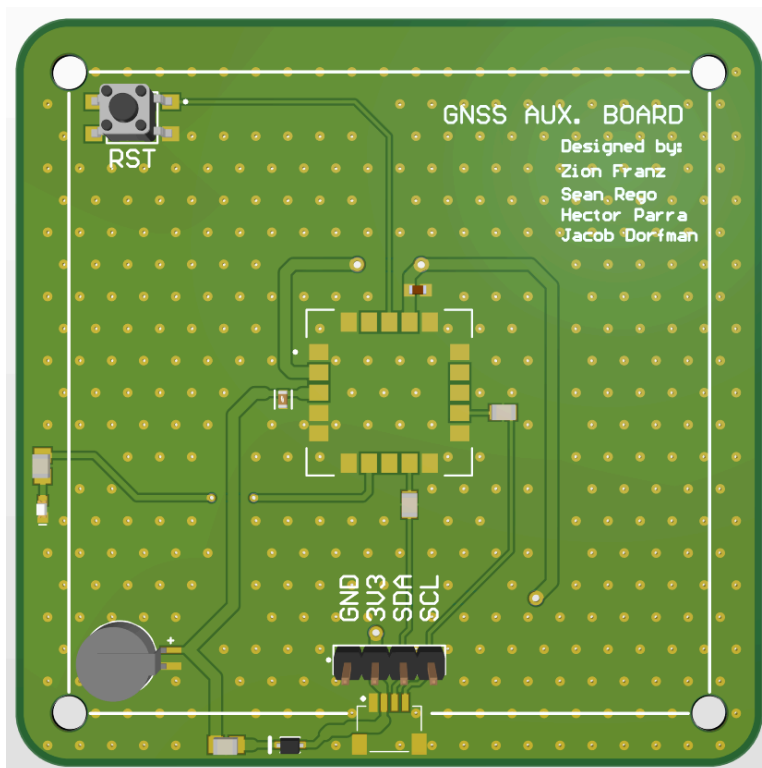


**Figure 8.5:** 3D GNSS Board Layout

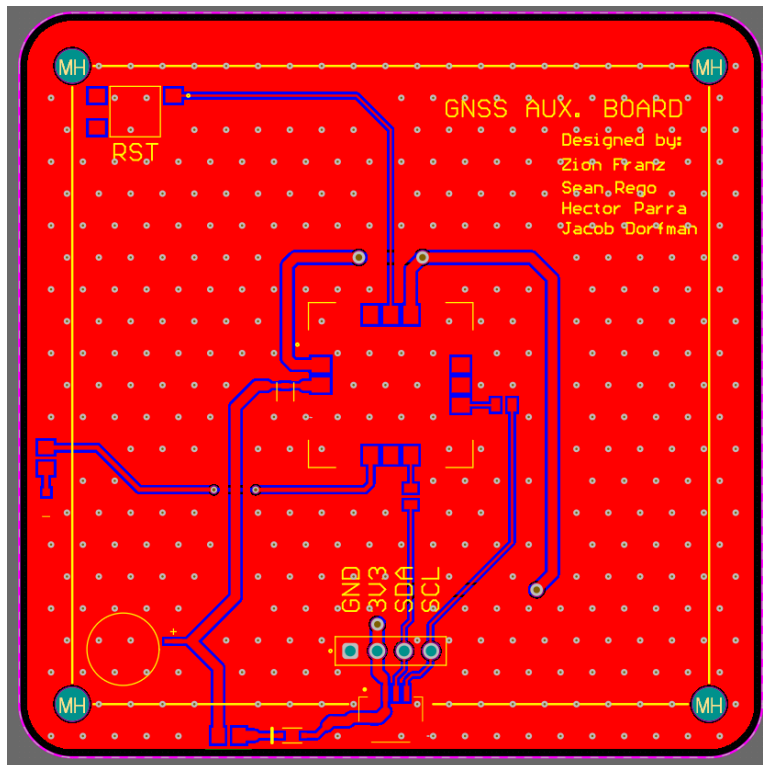


**Figure 8.6:** 2D GNSS Board Layout

## Chapter 9: System Testing and Evaluation

### 9.2 Software Testing

#### Temperature and Humidity Sensors

The temperature and humidity sensors were evaluated against a Siemens QAA2280.FWSC room sensor as a reference. The development board version of our sensor was polled at regular intervals without skips or delays. The sensor maintained a stable performance of 23.36 °C and 57 %RH, while the reference measured 22.5 °C and 60% RH, indicating a small high bias in our sensor. However, all measurements remained within  $\pm 2$  °C and 7% RH as listed on our specification sheet.

#### Air Pressure and Altimeter

The development board version of the air pressure sensor and the altimeter tests ran against a UCF air pressure sensor. While the air pressure sensor initially

performed closely to the reference, an error in the design caused a burnout to the sensor. The Altimeter values remained close as well and had no burnout issue. To test altitude change, measurements were taken while traveling between the first and third floors of the UCF Research 1 building. In the US, the height between floors of a US commercial building is about 10 feet (3 meters). Traveling between 3 floors would result in a 9 meter altitude change, while our instrument recorded a 10m change.

### **Anemometer**

The anemometer is the only part requiring testing which does not use a development board part. The Inspeed reference was tested against a reference anemometer using an air compressor as a wind source. The recorded Inspeed values differed by less than 2mph of each other. The reference anemometer consistently measured 13.8 mph, indicating either a low bias or natural deviation from minor wind speed variation between the anemometer locations. Nevertheless, the measurements remained comfortably within the 0.57 mph range listed in the specification sheet.

### **GPS & IMU**

The GPS was tested using code from the ESP32 library, generating coordinates in text form, which were compared to Google Maps and were found to be extremely close to the reference.

The gyroscope and accelerometer were tested against an Android phone for reference. The reference Physics Toolbox Samsung Galaxy S21. The reference and sensor were placed on a shared, flat surface, which was tilted and moved to get a similar change. The gyroscope values remained stable when still and a 2 degrees radian tilt on the reference was met with a similar reading on the IMU. The Accelerometer displays a rate of 8-12  $\text{m/s}^2$ , while the reference oscillates between  $\pm 3\text{m/s}^2$ . This difference in value is because the reference corrects for  $9.8\text{m/s}^2$  due to Earth's gravity. Applying the correction resulting in the reference values closely matching the reference, confirming the accuracy of the sensor.

### **SD Card and RTC**

The SD Card was tested by saving CSV files and transferring them to a computer. After multiple trials, the files were saved and transferred and opened as Excel files without issue.

The RTC was run against a testing PC clock for reference. Both kept a similar pace, but the RTC lagged by 11 seconds. This 11 second delay is not significant enough to be concerned with. A constant delay of 11 seconds can easily be accounted for in post processing or within the code.

## Radio

The radio system was tested by transmitting a 'message counter #' signal, with the counter incrementing every few seconds from a distance of up to 5 feet. The messages were successfully sent and received without any issues. The second round of testing involved 2 people, one on transmission, the other at the receiver. The transmission tester moved around the UCF campus in a semi circular path from the receiver. A signal was read from up to 100 meters (430 feet) through cars, trees and other impediments. The data was plotted using Google Earth to verify the accuracy location.

## GUI

The GUI was tested by opening CSV files and displaying. Csv files were either manually created, or imported from the test run mentioned above. All files open properly all long as all data cells are filled in. There is also a noticeable, but non-significant delay in opening larger files.

# Chapter 10: Administrative Content

## 10.1 Budget Allocation

The budget for this project was determined in a very liberal manner, as to present a worst-case-scenario cost. For example, the PCB and electrical component budget allows for multiple PCB revisions, thus the \$500 allocation. The goal of the team is to never exceed this inflated budget. Refer to *Table 10.1* for the Overall Budget allocation.

**Table 10.1:** Overall Budget Allocation  
By Authors

| Sub-System              | Cost  |
|-------------------------|-------|
| PCBs / Electrical       | \$500 |
| Sensors                 | \$200 |
| Sun Spectrometer        | \$200 |
| Base Station / Antennas | \$200 |

|                     |                |
|---------------------|----------------|
| Balloon & Parachute | \$400          |
| Payload Box         | \$150          |
| Ground Equipment    | \$200          |
| Helium              | \$500          |
| <b>Total</b>        | <b>\$2,350</b> |

## 10.2 Bill of Materials

The Bill of Materials itemizes every expense, thus providing a much more tangible method of tracking where money is spent. One may note that the Bill of Materials sums up to much less than the Budget Allocation table. This is because the Budget Allocation table provides a worst-case-scenario cost, while the Bill of Materials provides a more practical cost, given there are no major unexpected expenses. Refer to *Table 10.2* for the Bill of Materials.

**Table 10.2: Bill of Materials**  
*By Authors*

| Component                     | Quantity | Allocation (\$) |
|-------------------------------|----------|-----------------|
| MCU                           | 1        | \$10            |
| Temp./Hum. Sensor             | 1        | \$10            |
| Pressure Sensor               | 1        | \$10            |
| Anemometer                    | 1        | \$100           |
| Altimeter                     | 1        | \$10            |
| GNSS Receiver                 | 1        | \$30            |
| IMU                           | 1        | \$10            |
| SD Card (64GB)                | 1        | \$40            |
| Custom PCBs                   | 2        | \$200           |
| Various Electronic Components | 10+      | \$50            |
| Camera                        | 1        | \$200           |
| Optical Detector              | 1        | \$20            |
| Payload Radio Transmitter     | 1        | \$30            |
| Payload Antenna               | 1        | \$30            |
| Battery                       | 2        | \$40            |
| Station Radio                 | 1        | \$100           |
| Station Antenna               | 1        | \$50            |

|                      |   |                |
|----------------------|---|----------------|
| Balloon              | 3 | \$100          |
| Parachute            | 1 | \$50           |
| Suspension Line      | 1 | \$20           |
| 3D Printing Filament | 4 | \$100          |
| Insulation Foam      | 2 | \$50           |
| Helium               | 1 | \$500          |
| Miscellaneous        | 1 | \$200          |
| <b>Total</b>         |   | <b>\$1,960</b> |

### 10.3 Distribution of Work

The distribution of work was carefully constructed by discovering each team member's strengths and weaknesses. After this was done, tasks were assigned to members based on how well they meshed with that member's abilities. Each task was also assigned a secondary person to provide a "second pair of eyes" in order to ensure no detail was missed. Refer to *Table 10.3* for the distribution of work.

**Table 10.3:** *Distribution of Work  
By Authors*

| Department                | Task                          | Primary Person | Secondary Person |
|---------------------------|-------------------------------|----------------|------------------|
| <b>Design / Schematic</b> | MCU                           | Michael Franz  | Sean Rego        |
|                           | Temperature / Humidity Sensor | Sean Rego      | Michael Franz    |
|                           | Pressure Sensor               | Sean Rego      | Michael Franz    |
|                           | Anemometer                    | Sean Rego      | Michael Franz    |
|                           | Altimeter                     | Jacob Dorfman  | Michael Franz    |

|                      |                                     |               |               |
|----------------------|-------------------------------------|---------------|---------------|
|                      | GNSS Receiver                       | Michael Franz | Sean Rego     |
|                      | IMU                                 | Michael Franz | Sean Rego     |
|                      | SD Card Slot                        | Michael Franz | Sean Rego     |
|                      | Debug Header                        | Sean Rego     | Michael Franz |
|                      | 5.0 V Power Supply                  | Jacob Dorfman | Michael Franz |
|                      | 3.3 V Power Supply                  | Jacob Dorfman | Michael Franz |
|                      | Optical Detector Interface          | Lily Sigg     | Sean Rego     |
|                      | Optical Detector Software Interface | Lily Sigg     | Hector Parra  |
|                      | Optical Mirror Layout               | Lily Sigg     | Lily Sigg     |
|                      | Payload Radio Transmitter           | Jacob Dorfman | Michael Franz |
| Software             | Payload Runtime Software            | Hector Parra  | Sean Rego     |
|                      | Payload Sensor Interpretation       | Hector Parra  | Sean Rego     |
|                      | Payload Communication Software      | Hector Parra  | Jacob Dorfman |
| Board Layout         | Main PCB                            | Jacob Dorfman | Michael Franz |
|                      | Power PCB                           | Jacob Dorfman | Michael Franz |
| Payload Construction | Payload Antenna Integration         | Jacob Dorfman | Michael Franz |
|                      | Payload Physical Design             | Hector Parra  | Michael Franz |
|                      | Payload 3D Printing                 | Hector Parra  | Jacob Dorfman |

|                 |                                        |               |               |
|-----------------|----------------------------------------|---------------|---------------|
|                 | Payload Insulation                     | Jacob Dorfman | Hector Parra  |
|                 | Payload Sensor Integration             | Sean Rego     | Michael Franz |
| Base Station    | Base Station Antenna Integration       | Jacob Dorfman | Michael Franz |
|                 | Base Station Radio Integration         | Jacob Dorfman | Michael Franz |
|                 | Base Station Software Integration      | Hector Parra  | Jacob Dorfman |
| Recovered Data  | Recovered Data (SD Card) Presentation  | Hector Parra  | Sean Rego     |
|                 | Recovered Footage (GoPro) Presentation | Sean Rego     | Jacob Dorfman |
| Tethered Launch | Tethered Launch Coordination           | Michael Franz | Jacob Dorfman |
|                 | Rapid Deflation Device Implementation  | Michael Franz | Hector Parra  |
|                 | Helium Filling                         | Michael Franz | Sean Rego     |
|                 | Launch Train Construction              | Sean Rego     | Lily Sigg     |
|                 | FAA Communications                     | Michael Franz | Sean Rego     |

## 10.4 Milestones

In order to ensure timely completion of our project, milestones were established to prevent falling behind and missing critical deadlines. These milestones were chosen to be both punctual and practical. Time was allocated for unexpected delays, yet the spacing between deadlines was minimalized. Our milestones will serve as a guiding beacon of time management, eliminating the possibility of *procrastination*. Refer to *Table 10.4* for our project milestones.

**Table 10.4: Project Milestones**

*By Authors*

| Week | Date              | Description                                                                                                                                                                                                                                                                                                           |
|------|-------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1    | 8/19/24 - 8/25/24 | <ul style="list-style-type: none"><li>- Schedule biweekly meetings with Chan</li><li>- Continue to complete Chapter 3</li><li>- Begin choosing optical detector</li><li>- Begin hardware diagrams for Chapter 6</li><li>- Begin software diagrams for Chapter 7</li><li>- Begin ordering development boards</li></ul> |
| 2    | 8/26/24 - 9/1/24  | <ul style="list-style-type: none"><li>- Finish preliminary budget</li><li>- Finish SD I &amp; SD II plan</li><li>- Finish division of labor</li><li>- Complete Chapter 3</li></ul>                                                                                                                                    |
| 3    | 9/2/24 - 9/8/24   | <ul style="list-style-type: none"><li>- Submit Divide &amp; Conquer</li><li>- Finish Chapter 6</li><li>- Finish Chapter 7</li><li>- Begin testing components</li><li>- Choose an optical detector</li></ul>                                                                                                           |

|          |                     |                                                                                                                                                                                                                                                                                                               |
|----------|---------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>4</b> | 9/9/24 - 9/15/24    | <ul style="list-style-type: none"> <li>- Divide &amp; Conquer meeting</li> <li>- Finish Chapter 2: Project Description</li> <li>- Finish Chapter 5: Chat GPT</li> <li>- Begin Chapter 8: System Fabrication</li> <li>- Begin Chapter 9: System Testing</li> <li>- Begin Chapter 10: Admin. Content</li> </ul> |
| <b>5</b> | 9/16/24 - 9/22/24   | <ul style="list-style-type: none"> <li>- Divide &amp; Conquer revision</li> <li>- Begin PCB Design</li> <li>- Finish Chapter 8: System Fabrication</li> </ul>                                                                                                                                                 |
| <b>6</b> | 9/23/24 - 9/29/24   | <ul style="list-style-type: none"> <li>- 60 Page Draft Report</li> <li>- Quiz A</li> <li>- Quiz B</li> <li>- Finish Chapter 9: System Testing</li> </ul>                                                                                                                                                      |
| <b>7</b> | 9/30/24 - 10/6/24   | <ul style="list-style-type: none"> <li>- Quiz C</li> <li>- Quiz D</li> <li>- Finish Chapter 10: Admin. Content</li> <li>- Finish Chapter 11: Conclusion</li> </ul>                                                                                                                                            |
| <b>8</b> | 10/7/24 - 10/13/24  | <ul style="list-style-type: none"> <li>- Quiz E</li> <li>- Quiz F</li> <li>- Begin hardware fabrication</li> </ul>                                                                                                                                                                                            |
| <b>9</b> | 10/14/24 - 10/20/24 | <ul style="list-style-type: none"> <li>- Quiz G</li> <li>- Begin seeking FAA / UCF tethered launch clearance</li> </ul>                                                                                                                                                                                       |

| <b>10</b>   | 10/21/24 - 10/27/24 | - Finish PCB design<br>- Order PCBs                                                |
|-------------|---------------------|------------------------------------------------------------------------------------|
| <b>11</b>   | 10/28/24 - 11/3/24  | - 60 Page Draft Revision<br>- Continue hardware design / redesign                  |
| <b>12</b>   | 11/4/24 - 11/10/24  | - Finish Anemometer Mounting                                                       |
| <b>13</b>   | 11/11/24 - 11/17/24 | - Submit Mini Demo Video<br>- Receive PCBs                                         |
| <b>14</b>   | 11/18/24 - 11/24/24 | - Submit Final Report<br>- Begin PCB assembly                                      |
| <b>15</b>   | 11/25/24 - 12/1/24  | - Finish hardware design                                                           |
|             |                     |                                                                                    |
| <b>Week</b> | <b>Date</b>         | <b>Description</b>                                                                 |
| <b>1</b>    | 1/6/25 - 1/12/25    | - Schedule biweekly meetings with Chan<br>- Schedule multiple weekly team meetings |
| <b>2</b>    | 1/13/25 - 1/19/25   | - Finish PCB assembly                                                              |
| <b>3</b>    | 1/20/25 - 1/26/25   | - Begin PCB testing                                                                |
| <b>4</b>    | 1/27/25 - 2/2/25    | - Finish hardware construction & assembly<br>- Finish PCB testing                  |
| <b>5</b>    | 2/3/25 - 2/9/25     | - Procure Helium<br>- Final ground test                                            |
| <b>6</b>    | 2/10/25 - 2/16/25   | - <b>Tethered launch demonstration</b>                                             |
| <b>7</b>    | 2/17/25 - 2/23/25   | - Begin high altitude launch preparation                                           |

|           |                   |                                                                                         |
|-----------|-------------------|-----------------------------------------------------------------------------------------|
| <b>8</b>  | 2/24/25 - 3/2/25  | - Finish preparation<br>- Finish flight plan                                            |
| <b>9</b>  | 3/3/25 - 3/9/25   | - Travel to Dayton, Ohio<br><b>- Launch &amp; recover Balloon Payload System</b>        |
| <b>10</b> | 3/10/25 - 3/16/25 | -Begin Senior Design showcase preparation<br>-Begin editing high altitude video footage |
| <b>11</b> | 3/17/25 - 3/23/25 | - Continue Showcase preparation                                                         |
| <b>12</b> | 3/24/25 - 3/30/25 | - Continue Showcase preparation                                                         |
| <b>13</b> | 3/31/25 - 4/6/25  | - Continue Showcase preparation                                                         |
| <b>14</b> | 4/7/25 - 4/13/25  | - Senior Design Showcase                                                                |
| <b>15</b> | 4/14/25 - 4/20/25 | <b>- Finished</b>                                                                       |

## Chapter 11: Conclusion

# Chapter 12: Appendices

## Appendix A: References

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## Appendix B: Copyright Permissions

I2C Bus (Figure 4.

Your message has been sent

Select your contact reason:

**Other...**

Name:

**Sean Rego**

Email Address:

**seanerego@gmail.com**

Confirm Your Email Address:

**seanerego@gmail.com**

Subject:

**Permission For Image Use**

Describe Your Question Briefly:

**Hello, I would like to request your permission to include a picture in my groups Senior Design Project. It will of course be cited as your property The image in question is on this web page. <https://randomnerdtutorials.com/esp32-i2c-communication-arduino-ide/>**

**It is the second picture on the web page and it is under the "Introducing ESP32 I2C Communication Protocol" Section. Its a visual of the I2C bus and how the devices connect to the I2C bus.**

Li  
E  
pr

## Appendix C: Software Code

## Appendix D: Testing Outputs

Figure 10.1 Temperature and Humidity Breakout Board Test

```
Temperature: 23.87 °C  
Humidity: 50.79 %  
Temperature: 23.86 °C  
Humidity: 50.64 %  
Temperature: 23.86 °C  
Humidity: 52.75 %
```

Figure 10.2 Pressure Sensor Breakout Board Test

```
Temperature C = 24.32  
Temperature F = 75.76  
Pressure abs (mbar)= 999.30  
Pressure relative (mbar)= 1220.48  
Altitude change (m) = 0.00
```

Figure 10.3 Anemometer Breakout Board Test

Number of Spins in Last 5 Seconds: 23  
Wind Speed: 13.11 mph

Number of Spins in Last 5 Seconds: 23  
Wind Speed: 13.11 mph

Number of Spins in Last 5 Seconds: 25  
Wind Speed: 14.25 mph

Figure 10.4 Gyroscope Breakout Board Test

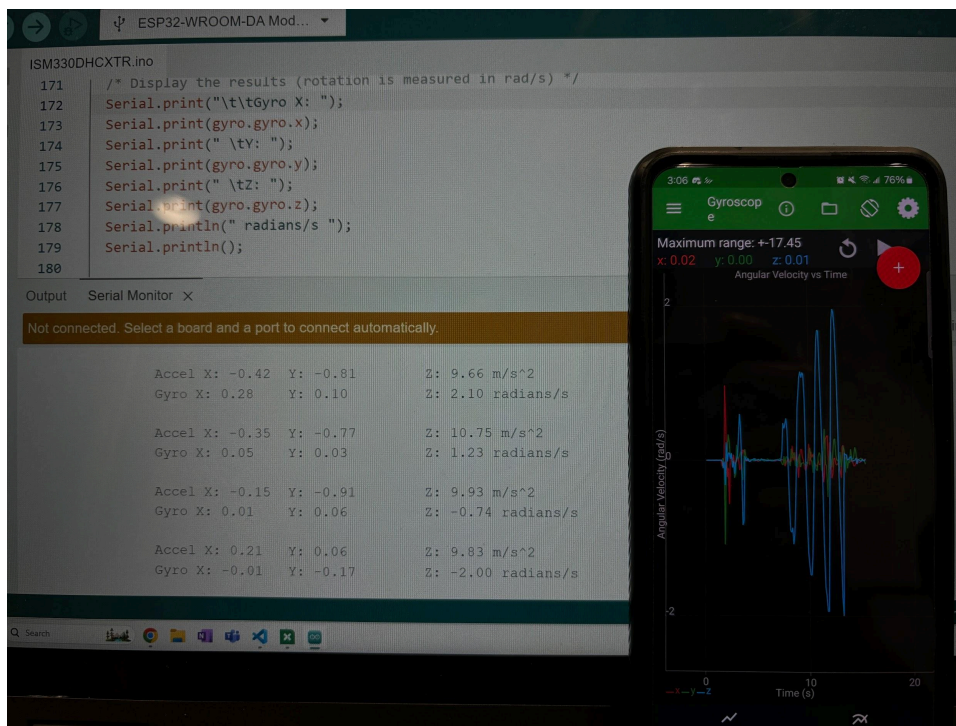


Figure 10.5 Accelerometer Breakout Board Test

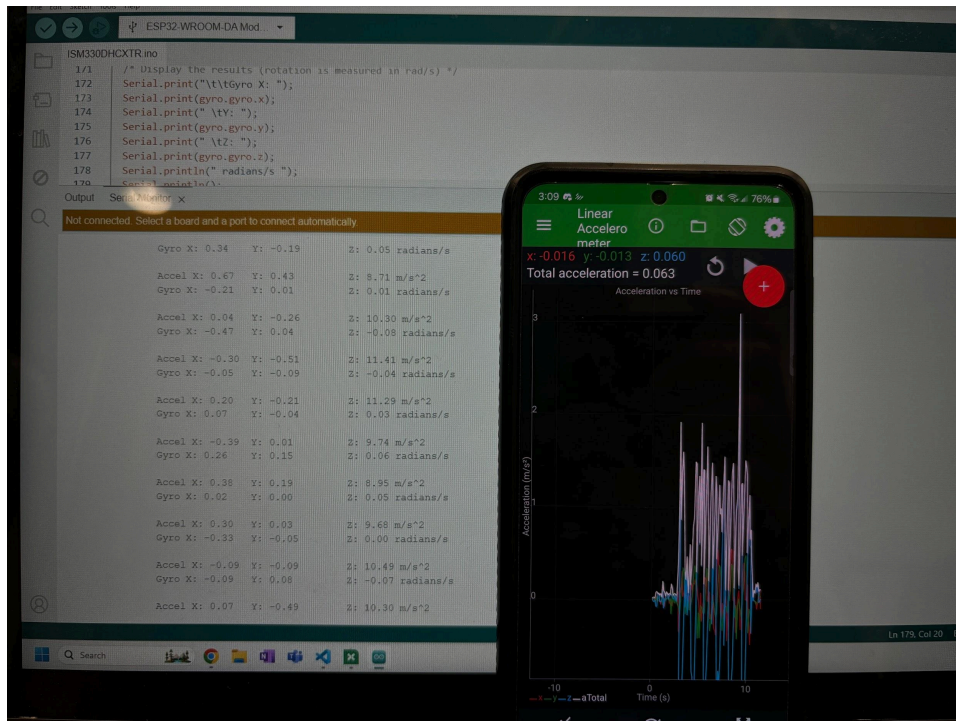


Figure 10.6 Radio Breakout Board Test

```
[SX1276] Received packet!
[SX1276] Data: 22.71,44.13,6855.50,0.00,-29.56,0.02,0.24,-0.03,-2.56,-0.76,9.87,28.60,-81.20,16:20:27
[SX1276] RSSI: -125.00 dBm
[SX1276] SNR: -2.00 dB
[SX1276] Frequency error: -6316.62 Hz
Latitude: 28.60
Longitude: -81.20
Altitude: -29.56
Time: 16:20:27

[SX1276] Received packet!
[SX1276] Data: 22.69,44.29,6855.50,0.00,-28.87,0.24,0.28,0.20,-1.69,-0.15,6.07,28.60,-81.20,16:20:42
[SX1276] RSSI: -120.00 dBm
[SX1276] SNR: 0.75 dB
[SX1276] Frequency error: -6383.73 Hz
Latitude: 28.60
Longitude: -81.20
Altitude: -28.87
Time: 16:20:42

[SX1276] Received packet!
[SX1276] Data: 22.68,44.93,6855.50,0.00,-30.19,0.26,-0.30,-0.14,-1.05,0.73,9.66,28.60,-81.20,16:20:57
[SX1276] RSSI: -121.00 dBm
[SX1276] SNR: 0.00 dB
[SX1276] Frequency error: -6366.95 Hz
Latitude: 28.60
Longitude: -81.20
Altitude: -30.19
Time: 16:20:57
```

Figure 10.7 RTC Breakout Board Test

```
15:26:29.718 -> 2024/9/20 15:26:18
15:26:30.708 -> 2024/9/20 15:26:19
15:26:31.718 -> 2024/9/20 15:26:20
15:26:32.727 -> 2024/9/20 15:26:21
15:26:33.702 -> 2024/9/20 15:26:22
15:26:34.718 -> 2024/9/20 15:26:23
15:26:35.718 -> 2024/9/20 15:26:24
15:26:36.708 -> 2024/9/20 15:26:25
15:26:37.716 -> 2024/9/20 15:26:26
15:26:38.720 -> 2024/9/20 15:26:27
15:26:39.737 -> 2024/9/20 15:26:28
15:26:40.734 -> 2024/9/20 15:26:29
15:26:41.718 -> 2024/9/20 15:26:30
15:26:42.748 -> 2024/9/20 15:26:31
15:26:43.714 -> 2024/9/20 15:26:32
15:26:44.712 -> 2024/9/20 15:26:33
15:26:45.719 -> 2024/9/20 15:26:34
15:26:46.723 -> 2024/9/20 15:26:35
15:26:47.723 -> 2024/9/20 15:26:36
15:26:48.726 -> 2024/9/20 15:26:37
15:26:49.728 -> 2024/9/20 15:26:38
15:26:50.727 -> 2024/9/20 15:26:39
15:26:51.725 -> 2024/9/20 15:26:40
15:26:52.710 -> 2024/9/20 15:26:41
15:26:53.711 -> 2024/9/20 15:26:42
15:26:54.731 -> 2024/9/20 15:26:43
15:26:55.727 -> 2024/9/20 15:26:44
15:26:56.749 -> 2024/9/20 15:26:45
15:26:57.752 -> 2024/9/20 15:26:46
15:26:58.734 -> 2024/9/20 15:26:47
15:26:59.718 -> 2024/9/20 15:26:48
15:27:00.750 -> 2024/9/20 15:26:49
15:27:01.746 -> 2024/9/20 15:26:50
15:27:02.737 -> 2024/9/20 15:26:51
15:27:03.749 -> 2024/9/20 15:26:52
15:27:04.747 -> 2024/9/20 15:26:53
15:27:05.724 -> 2024/9/20 15:26:54
```