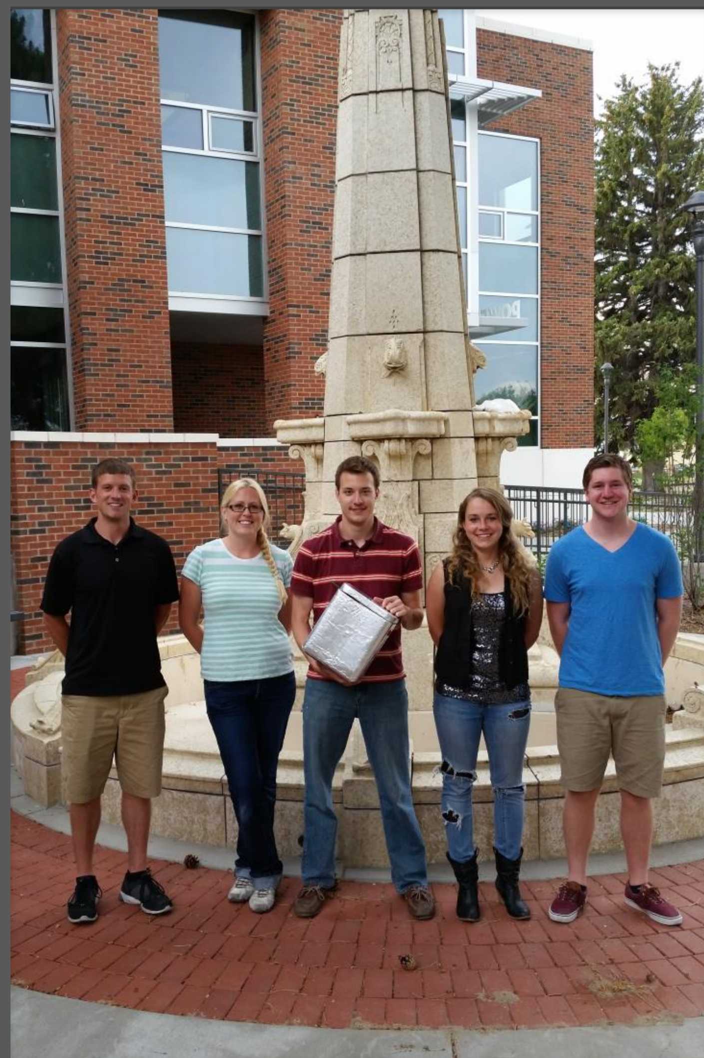
Colorado Space Grant Consortium

Colorado State University
Summer 2014
Design Document



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1 August 2014

CSU DEMOSAT B

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1.0 Mission Overview

1.1 Mission Statement

The mission is to provide a system that is reusable, low cost and mobile that will map the vertical profile of Carbon Dioxide at high altitudes and locate CO_2 emission origins to bring attention to the effects of man-made CO_2 emissions.

The goal of Colorado State University's Colorado Space Grant Consortium project is to accurately measure Carbon Dioxide levels with an increase in altitude up to 45,000 ft. This is achieved by launching a high-altitude balloon payload that will take readings by operating a system which filters and heats air intake before it reaches the IR sensor that detects CO_2. An altimeter is used to take pressure readings that will translate to altitude. Both readings are then recorded onto a SD card and analyzed to create a carbon dioxide high altitude profile.

The secondary mission is to map the wind speed and direction of the payload's ascent to determine the source of CO_2 plumes noticed during the flight. A GPS module will be implemented to track and create a map of the wind profile as the balloon ascends. This map will correlate to CO_2 plumes noted on the ascent and analyzed to find the probable source of CO_2.

1.2 Mission Background

Recording CO_2 levels in the atmosphere on the balloon's ascent will help map the changes of CO_2 levels both seasonally and spatially around the launching location. Many experiments do not record CO_2 levels at high altitudes.

Carbon Dioxide levels have increased drastically over the past century. CO_2 is the primary greenhouse gas emitted through human actions such as electricity, transportation and industry. Greenhouse gases trap heat in the Earth's atmosphere. Because of increased levels of Carbon Dioxide, the average surface temperature on Earth has grown. If the trend of CO_2 continues over the next century there could be a drastic effect on the quality of human life such as an increase in global temperature. With this data, preventive measures can be implemented from the main sources of emitted CO_2 to ensure the levels of CO_2 do not reach even higher levels in the future, as noted by the pink and orange lines in figure 1.1. By detecting CO_2 in the atmosphere the payload can be used to test a variety of locations for plumes of CO_2 which will help to reduce CO_2 emissions into the atmosphere.

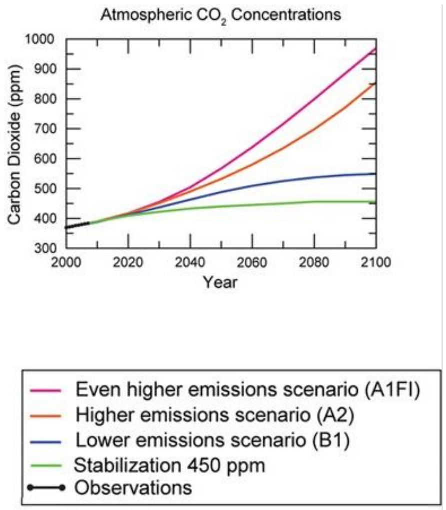


Figure 1.1 Senerio of future CO2 concentrations in the atmosphere
Source: www.epa.gov

2.0 Requirements Flow Down

2.1 Requirements

The project had several constraints taken into consideration when building the payload. These ranged from general requirements established by the Colorado Space Grant Consortium to project specific requirements that were determined by hardware, design, and budget. Requirements are as follows with Level 0 being derived from mission statement and overall guidelines. Level 1 requirements stem from Level 0 requirements.

2.2 Requirements Flow Down

Level 0:

Payload must weigh 1.5 kilograms or less

Budget shall not exceed $1000

Payload must have means of measuring CO_2 levels and wind speed and direction accurately

Payload must have means of recording and storing data received from sensors

All electronics must remain operable during 90 minute ascent and 60 minute descent

Level 1:

Internal temperature of payload must stay above 0°C for sensors to operate (external temperatures can reach -80°C)

Position must be mapped to extrapolate wind speed/direction

Altitude must be taken and recorded up to a height of 100,000 feet

Must have a way to pull air from outside into payload and pumped through CO_2 sensor at a minimum flow rate of .2 Lpm

Internals must be protected and be able to survive an impact of 35 mph

Battery must provide adequate power to all electronics for the entire flight

3.0 Design

3.1 Design Overview

Design of the payload was derived from the requirements flow down chart. Specific components were chosen that best accomplish these goals. Additional parts were found to make sure primary components were working. For example, the most accurate, compact and sensitive CO_2 sensor available was purchased and design decisions were made to ensure this sensor would work properly. The batteries were chosen based on power draw of all components and basic operating temperature range to make sure the payload would remain operable throughout the entire flight. The battery had a considerable margin of safety to account for decreased performance near 0°C.

3.2 Requirements

System	Overview	Power Draw	Operating Temperature Range	Misc.
Power	Lithium Polymer Battery	44.4 W-h	0-40°C	Especially sensitive to impacts
Heating	Three 10 ohm resistors in heating chamber, Two 10 ohm resistors mounted on board	5.4W	PVC melts at 160°C	
Air Flow	Produced by vacuum pump	0.5W	5-45°C	5.9" Hg max vacuum, 0.9-1.0 Lpm max flow,
Filtering	Inline filter			0.6 micron filtering, 99 Lpm max flow
CO_2 Sensing	CO_2 sensor	0.02W	0-50°C	30ppm sensitivity, 0.2-1.0 Lpm flow
Data Storage	Micro SD Card	0.75W	0-70° C	8G storage
Altitude Measuring	Pressure based altimeter	0.01W	-40-85° C	Successfully tested to 120,000 ft
Location Tracking	GPS module	0.01W	-40-85° C	Successfully tested to 32 km, +/- 3m accuracy,

3.3 Structure

The structure of the CO_2 Sat was designed to be lightweight, insulating, and capable of withstanding a 35 mph impact while protecting the electronics inside. To do this, construction of the payload was made out of polystyrene foam. Polystyrene is light, durable, insulating, and could be cut and formed into any shape. Both cylindrical and prismatic shapes were considered. A rectangular prism shape was chosen for its ease of manufacturing, as there were no distinct advantages of a cylinder design. 9”x10”x2” layers of foam were cut and then stacked and glued together using a foam adhesive. Six layers were stacked, giving the payload a height of 12” and leaving just enough space inside for internal systems. The middle was cut out leaving a wall thickness of 2”. A foam lid with the dimensions of 9”x10”x1” was glued to a smaller piece the size of the cut out middle, 5”x6”x1” to close the structure. A hole was added to the lid and bottom of payload for space for a plastic tube. The flight string was run through this tube. The tube was externally threaded and the lid was attached to the rest of the foam by tightening two wing nuts on either end of the structure onto two large plastic washers. Aluminum foil was glued to the outside of the structure to help with insulating the internal electronics.

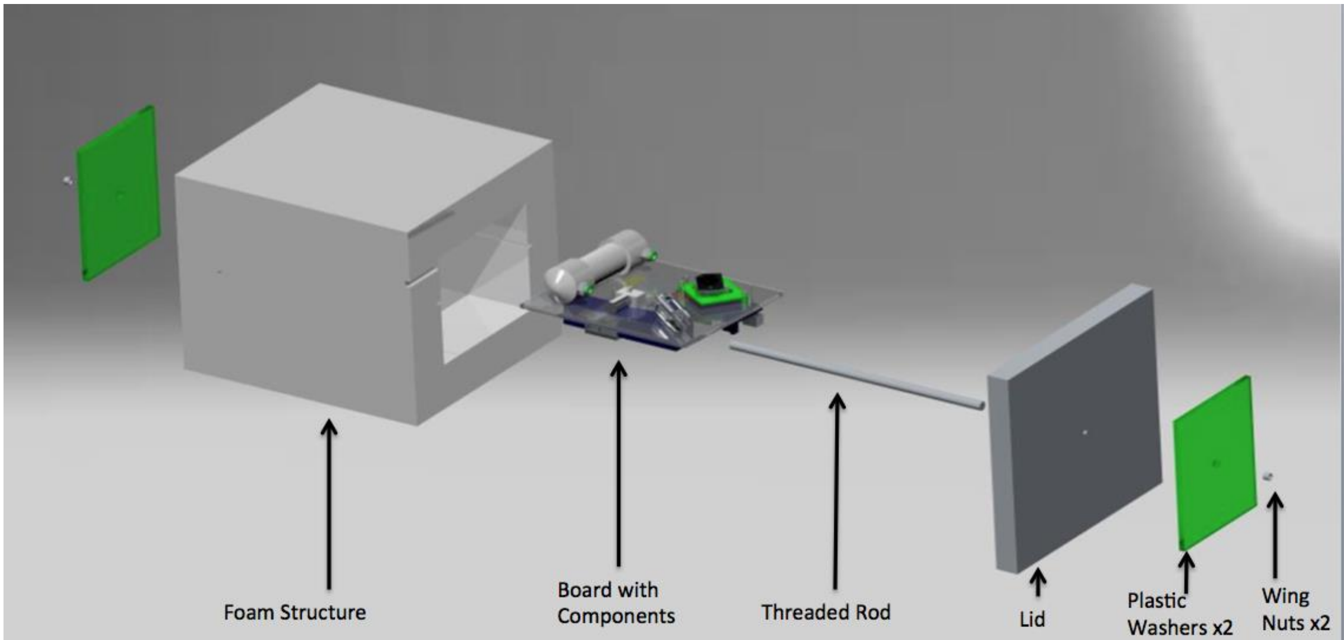


Figure 3. 1: Exploded view of the payload

3.4 Internals

A central polycarbonate board that can be completely removed was chosen to mount all components. This central control board can be completely removed from the payload with ease. This design allowed easy and quick access to all components. Parts can easily be replaced or tweaked within minutes if needed. The internal system consisted of a CO_2 sensing subsystem mounted on one side of a polycarbonate board and microcontroller, battery, GPS, altimeter and data logger mounted on the other side. Below is a functional block diagram of the final design to display air flow, power and data between components (figure 3.2).

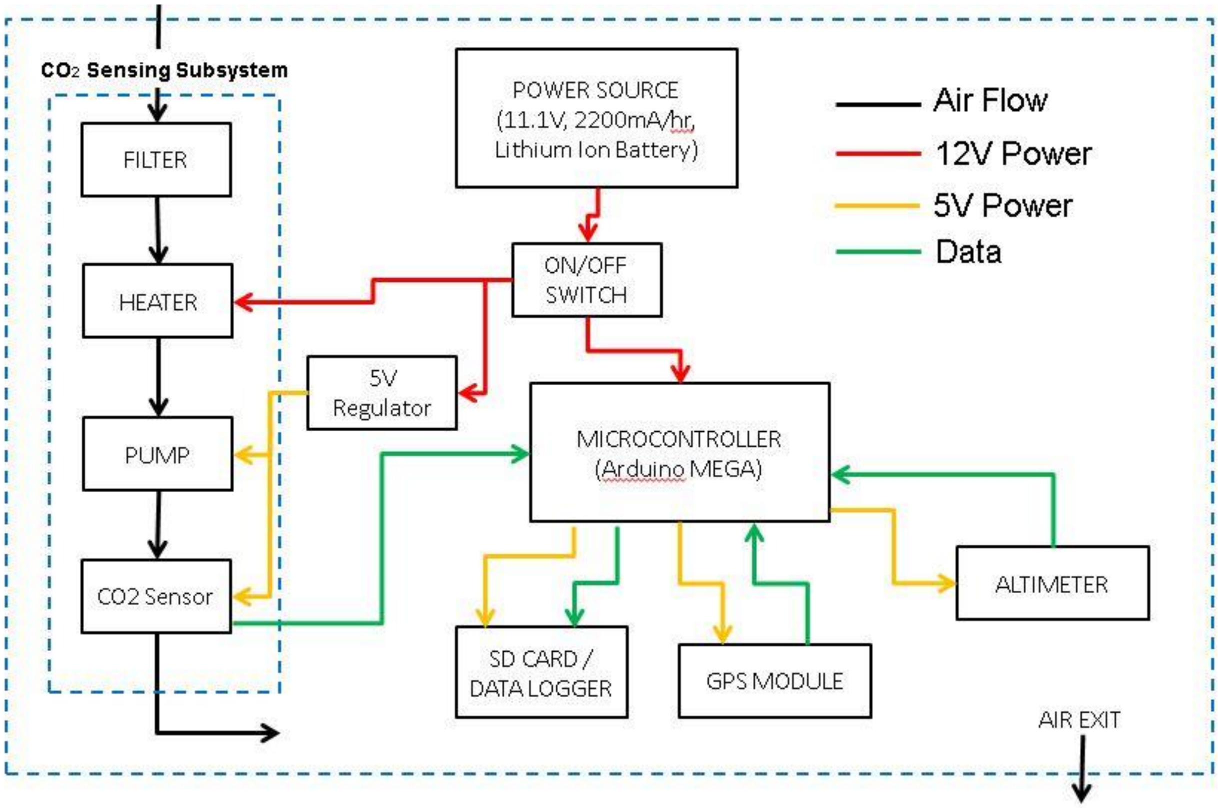


Figure 3.2 Block Functional Diagram of all internal systems

The CO_2 subsystem was composed of the CO_2 sensor, pump, heater, and a filter (figure 3.3). All were connected via tubing. External atmospheric air was pumped into the tubing, which flowed through the filter, then into the heater where the air was heated to within the specs of the sensor. The air was then pumped into the CO_2 sensor to be measured. After CO2 sensor measured the warm air, it was expelled inside the payload. Three ¼" holes in the bottom of the payload allow ambient air flow in order to keep the pressure even between the inside and outside of the payload. Air travels from the inlet to the sensor in 4-7 seconds depending on the air pressure.

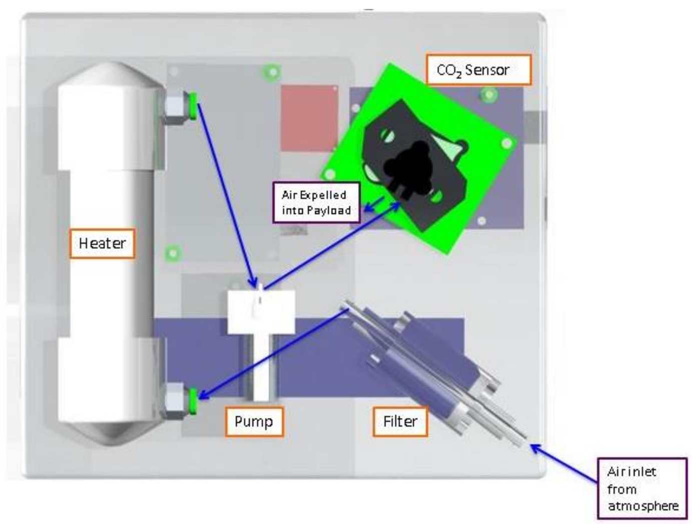


Figure 3.3 Air Flow diagram of the CO_2 subsystem

The other side of the board contained the battery (11.1 V Lithium Ion), the Arduino Mega Microcontroller, an altimeter sensor, a GPS, and a data logger that saved to a Micro SD card. All sensors were run through a code programmed to the Arduino Mega, recording readings from each sensor once every 15 seconds and storing them on the onboard SD card. Components were mounted to the board using either zip ties run through holes drilled in the board, or bolted down into the board with spacers cut from tubing that also absorbed shock.

Both sides of the board required wiring to the microcontroller for communication. Figure 3.4 displays the exact wiring used in the mission. Although there are many unused pins, the MEGA was selected because of its large onboard flash memory.

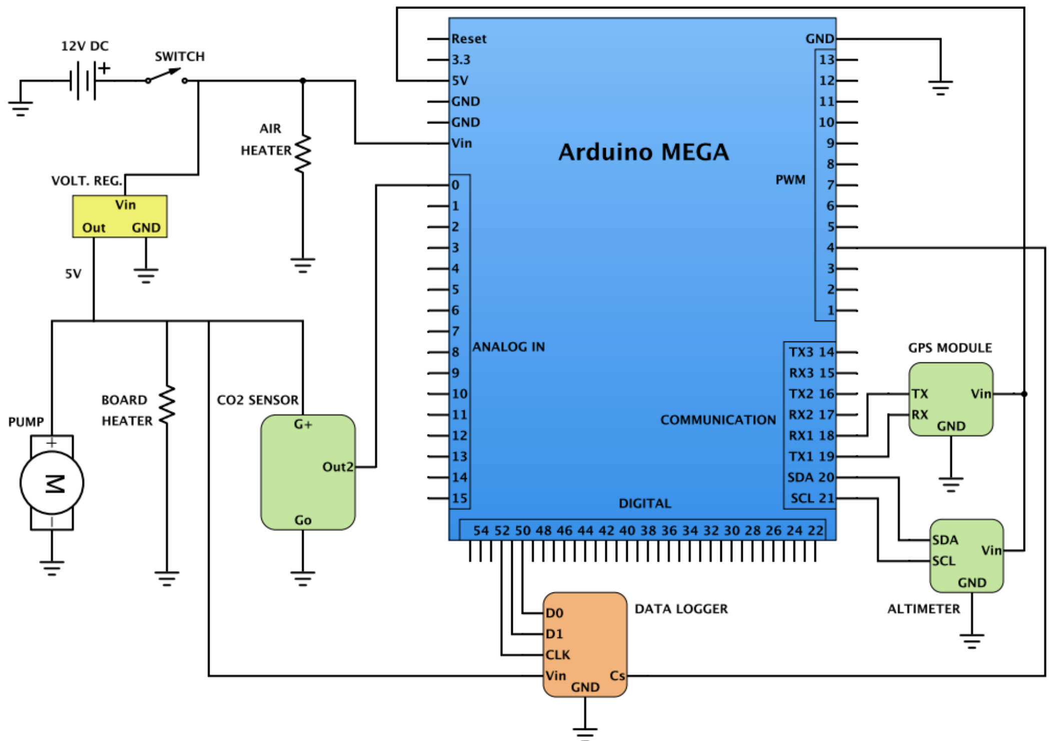


Figure 3.4 Wiring diagram of internal systems

3.4.1 CO_2 Sensor Theory

The CO_2 Sensor used was the K-30 10,000 ppm version from CO2meter.com (figure 3.5). It used a non-dispersive infrared sensor (NDIR) to calculate CO_2 concentrations by sending an infrared pulse at a known wavelength and measuring the amount absorbed by the CO_2. The sensor uses an infrared LED to send light through the gas chamber. The light travels through the air and is then filtered for only the 4.26 micron wavelength. This wavelength is absorbed by CO_2. A thermopile is used to detect the IR pulse intensity. Below is a schematic showing a simplified NDIR sensor (figure 3.5).

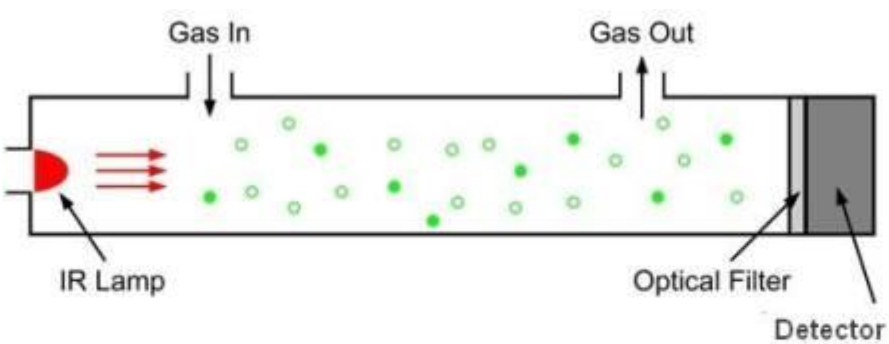


Figure 3.5 Schematic of a simplified NDIR sensor. Source: www.co2meter.com

Beer's Law is used to calculate the concentration of CO_2 from the reading of the thermopile. Creating a longer light travel length is the only physical way to increase the resolution of the sensor.

Beer's Law is $\mathbf{I} = \mathbf{I}_o * \mathbf{e}^{-kcl}$.

Where I is the intensity sensed by thermopile. I_o is the intensity of the light pulse that the LED sends. k is a function of reflectivity of mirrors and the gas specific absorption constant. c is the concentration of the ambient CO_2 and l is the path length of the light pulse.

3.4.1.1 K-30 Sensor Specs:

This sensor was selected for its advertised 0-2000ppm range, a sensitivity of ±20ppm and accuracy of ±30ppm. The sensor outputs a voltage ranging from 1 to 5 volts depending on the concentration of CO2 present inside the chamber. This is a typical NDIR sensor utilizing an IR LED and thermopile to detect light intensity.

Figure 3.6: K-30 CO2 sensor. (co2meter.com)

3.4.1.2 Sensor Improvements

The sensor comes equipped with a .1 micron semi-permeable membrane (figure 3.7). This membrane creates a diffusion barrier so that only gas can get into the sensor. Unfortunately, since the air needs to diffuse through the filter, small ppm changes can have very long response times. The filter was removed (figure 3.8) and filtered air is forced directly into the sensor to increase the response time of the sensor and increase the sensitivity to small ppm changes.

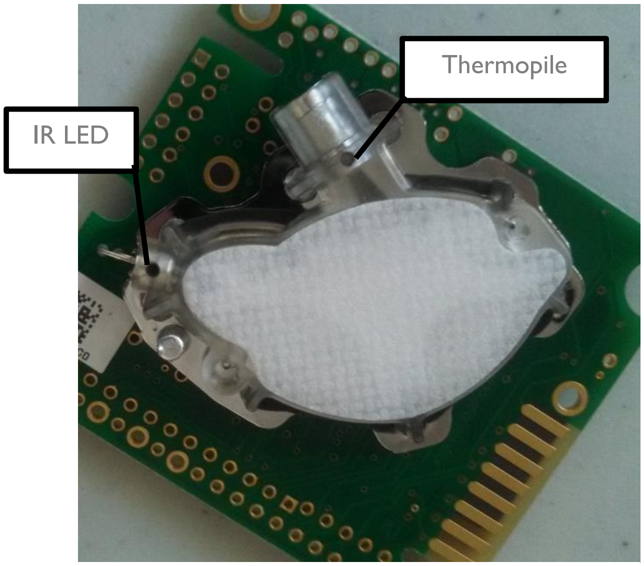


Figure 3.7 Sensor with stock filter installed

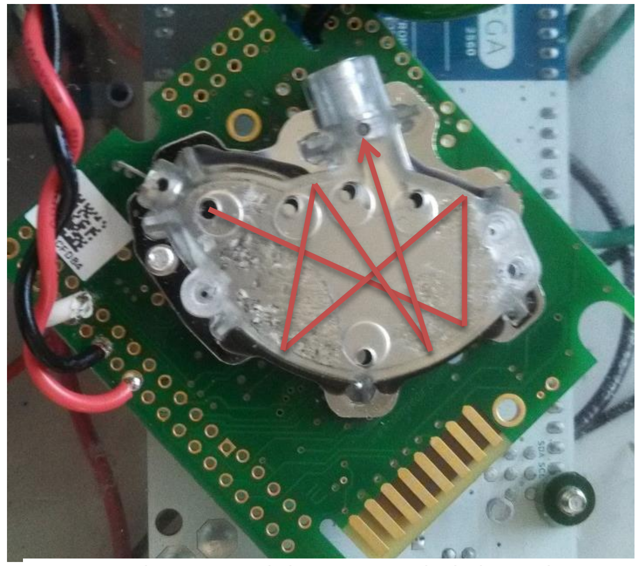


Figure 3.8 Filter removed shows gas intake holes to the chamber. Light path is also illustrated here in red.

The pump will force air flow to the sensor to ensure a quick response time and accurate readings. Below is a comparison between the stock adapter (figure 3.9) and a custom 3-D printed adapter and their air flow paths (figure 3.10). The printed adapter forces air directly into the sensing chamber and forces the air out on the opposite side. With the printed adapter, the air must travel throughout the entire chamber as opposed to the very short path length of the factory sensor.

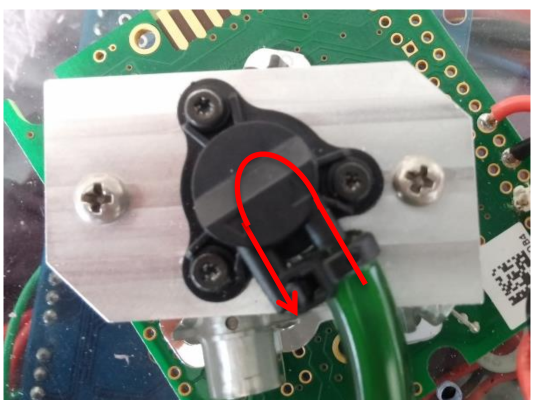


Figure 3.9: Stock adapter does not allow for significant flow path length

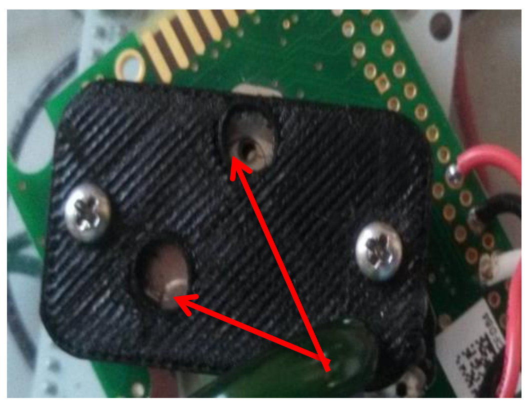


Figure 3.10 Custom adapter allows for air flow of nearly max possible length and two outlets to increase dispersion of air into chamber

3.4.2 GPS Sensor

In order to measure the wind speed and direction of the payload, a tracking system was needed. A GPS sensor was used to map position and derive general trends about the wind speed/direction as the balloon moved. The GPS Sensor chosen was the Adafruit Ultimate GPS Breakout (figure 3.11). It has up to 10 Hz updates, 66 channels, and can track up to 22 satellites at once. The position accuracy of the sensor is listed as within 3 meters.

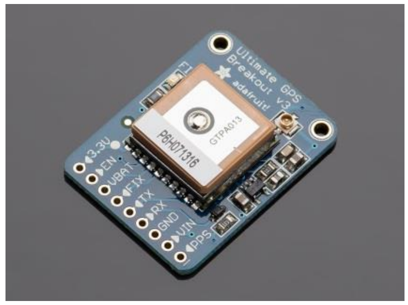


Figure 3.11: GPS Sensor Source: www.adafruit.com

3.4.3 Altimeter Sensor

CO_2 vertical profiling requires an altitude to correspond to a specific CO_2 level. An altimeter sensor was used to measure the altitude of the payload during the flight. The altimeter chosen was the Parallax Altimeter Module MS5607, figure 3.12. The Altimeter was used to measure altitude during both the ascent and descent. The altimeter worked by measuring pressure levels which is related to altitude change, the barometric formula. The altimeter reported functioning up to altitudes of 120,000 feet by Parallax. Our 100,000 foot elevation fell within its range.

Figure 3.12: Altimeter Sensor Source: www.parallax.com

3.4.4 Microcontroller

A microcontroller was required to provide power and communicate with the sensors. The Arduino Mega was chosen over an Arduino Uno because the Uno did not have enough memory to store the larger code which included I2C and SPI communications and averaging functions. The device is shown in figure 3.13

Figure 3.13: Arduino Mega

Source: www.utopiamechanicsus.com

3.4.5 Micro SD Data Logger

On-board data logging was needed to save the results from our sensors during the flight. To save the data, an Adafruit Micro SD Card Breakout Board was used. The sensor was coded to save CO_2, altimeter, and GPS data to an 8GB micro SD card in 15 second increments. A micro SD card slides into the data logger and will record everything to the card which can be plugged into the computer.

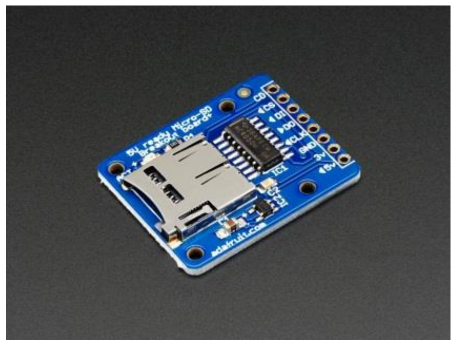


Figure 3.14: Micro SD Data Logger
Source: www.adafruit.com

3.4.6 Battery

To power the device, a battery is needed that would last 90 minutes for the ascent of the payload and the 60 minute descent. A Zippy 11.1 volt 4 amp-hour lithium polymer battery is used. The battery supply of 44.4 W-h is approximately twice as much as needed for a 2.5 hour flight. This is to help compensate for decreased performance of the battery at temperatures close to 0°C.

Figure 3.15: Battery
Source: www.hobyking.com

3.5 Heating Subsystem Design

The payload was expected to function up to an altitude of 100,000 feet. At this altitude, temperature extremes of up to -80°C can be expected. Most of the electronics had an operating temperature of >0°C, so an on-board heater was necessary to make sure the inside of the payload stayed warm enough to keep everything functioning properly.

There were two different heaters on board, one inside the CO_2 subsystem to heat the air that was being taken in and run through the sensor, figure 3.16, and one mounted on the polycarbonate board to keep the other sensors warm. The CO_2 air heater consisted of three 10 ohm resisters mounted in series inside a PVC pipe. A current ran through these resisters which would heat them up. External air will be pumped inside the chamber and heated before travelling to the CO_2 sensor then expelled inside the payload to heat the inside the structure. The board heater consisted of two more 10 ohm resisters in series that were mounted just beneath the GPS and the SD card data logger.

Figure 3.16: Heater unit before being placed inside of PVC Piping

4.0 Management

A project overview schedule was created to ensure there was enough time to complete each task before launch. There was a 10 week deadline for the project. The Gantt chart as shown in figure 4.1 was useful to evaluate if the project was on, ahead or behind schedule. Each group member diligently worked on the payload until all tasks were completed. The chart demonstrates that there is plenty of time for testing and revision before launch. This was beneficial because each component of the project was not rushed and thoroughly tested under flight-like conditions. Having the payload ready for testing at week 6 is beneficial for preforming multiple tests and leaving time for product improvement. After completing a week of extensive testing, there was time to purchase any parts that failed. Another week of testing was planned and conducted after improvements. The project remained on schedule as planned. Finishing the design of the payload early provided confidence into launch that every aspect of the design was tested and ready to launch to 100,000 ft.

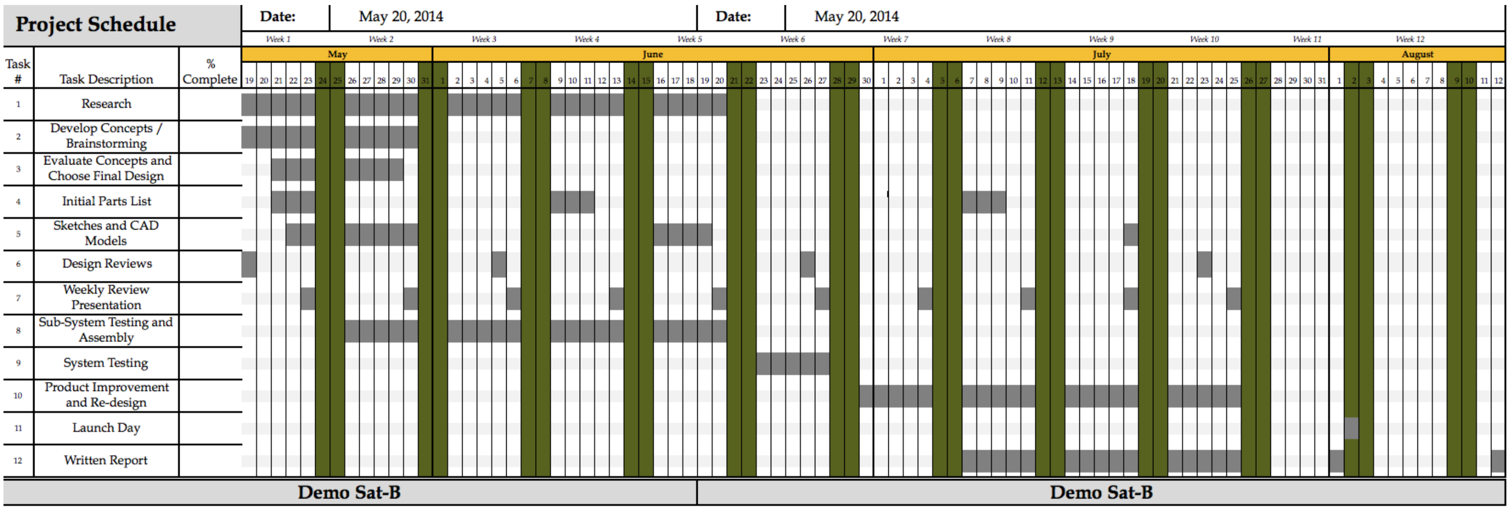


Figure 4.1: Project Schedule

A list with a Gantt chart, Table 4.1, was also created for individual tasks during the project and each task assigned to a specific group member. This kept the group organized and made sure each member had something to work on. If there was a question regarding the project, other group members knew who to talk to. Hours and days were also assigned to each task to have a critical path of when items should be completed. By working together on all important aspects of the project each member had an input and did not feel left out or unknowledgeable about the section. Every day there were updates about progress made the previous day and where to proceed that day. Group dynamics made this summer a successful one, keeping everyone informed on each step provided learning experiences for all.

Table 4.1: Group Tasks

Official Tasks	Responsible
Brainstorm/Project Definition	Group
Project Plan	Kristen
Research	Group
Specifications	Group
CAD	Kristen/Ryan/Zach
Structure	Ryan/ Kristen
Heater	Zach
Data Storage	Jeff
Altimeter	Jeff
Power	Jeff/ Zach
CO_2 Sensor	Jeff
GPS	Ryan
Soldering Components	Jeff
Troubleshooting Components	Jeff/Zach
Detailed Subsystem	Zach
Bill of Materials	Ryan
Schedule Tests/ Supplies	Kristen/Zach
Testing	Group
Weekly Presentations	Group
Presentation complier	Kristen
Final Report	Group

5.0 Budget

For this project there was a budget of $1,000 and a weight limit of 1500 grams. The budget included all testing equipment as well as components for the payload. The budget was sufficient for the project and allotted enough money to purchase sensors multiple times when the payload ran into electrical difficulties. In addition, weight was allocated to ensure the payload did not exceed the limit. This constraint was important to make sure the payload would launch. The final payload weighed in at 1417 grams, the payload was under the requirements by 83g. Below is the bill of materials needed to recreate a payload weighing approximately 1417 grams and costing about $428.

Table 5.1: Payload BOM

Item	Function	Quantity	Distributor	Cost
Compact/OEM bellows vacuum/pressure pump	Air Pump	1	Cole-Parmer	35.17
On/Off switch	Turn payload On/Off	1		Donated
Adafruit Ultimate GPS	Read Location	1	Adafruit	39.99
Altimeter Module	Measure altitude/pressure	1	Parallax	29.99
MicroSD card breakout board+	SD card recorder	1	Adafruit	14.99
MicroSD card 8gb	Data storage	1	Adafruit	12.99
.6 micron oil filter	filter out water and particles	1	Mcmaster carr	18.33
K-30 10,000ppm CO2 Sensor	Sense CO2	1	CO2 Meter	85
Tygon Tubing	Air flow	3 feet	Mcmaster carr	10.1
ZIPPY Flightmax 4000mAh 3S1P 20C (USA Warehouse)	Battery	2	HobbyKing	44.99
Nylon T-Connectors 10 Pairs	Power Connectors	1	HobbyKing	4.99
Mini DC/DC Step-Down (Buck) Converter - 5V @ 1A output	Regulator	1	Adafruit	14.99
LiPo Battery Charger	Charge Battery	1	sparkfun	29.99
Solder		1	RadioShack	2.99
Soldering Board		1	Mountain State Elec.	2.45
Arduino MEGA		1	newegg	19.99
Stickers		1	Wal Mart	2.5
5 Watt 10 Ohm Resistor	Heating Element	5	Mountain State Elec.	6
PVC Pipe	Heating Structure	1	Home Depot	3.99
PVC End Cap		2	Home Depot	4.5
Epoxy	Glue	1	Home Depot	3.99
Insulating Foam	Structure	1 2'x8'x2" Sheet	Home Depot	12
Press Disconnect Tubing Fitting	Connections	2	Motion & Flow Products	5
Foam Adhesive	Glue	2	Home Depot	6.99
Caulk Gun	Distribute Adhesive	1	Home Depot	5
Threaded String Rod	Attach to String	1	Home Depot	3.13
Nuts	Keep rod in place	2	Home Depot	2.3
Outer Plastic Washer	Seal Structure	2	Fort Collins Plastics	
Polycarbonate Sheet	Board For Components	1	Fort Collins Plastics	6
			Total	428.33

The total amount spent was $999.06 leaving $0.94 remaining. The project was not particularly expensive and we expected to spend less than our overall budget, but some components malfunctioned and replacements were required. Below is the full parts list, Table 5.2. This list includes expenses due to test setup and component replacement as well as optimization of the payload.

Table 5.2: Full Parts List

Item	Function	Quantity	Distributor	Cost
Compact/OEM bellows vacuum/pressure pump	Air Pump	1	Cole-Parmer	35.17
On/Off switch	Turn payload On/Off	1		Donated
Adafruit Ultimate GPS	Read Location	1	Adafruit	72.42
Altimeter Module	Measure altitude/pressure	3	Parallax	96.93
Tenergy TB6-1 LiPo/NiMH Battery Pack Balance Charger	Battery Charger	1	Allbatteries	
MicroSD card breakout board+	SD card recorder	1	Adafruit	
MicroSD card 8gb	Data storage	1	Adafruit	
Temp Sensor	Sense Interior Temp	5	Adafruit	58.45
.6 micron oil filter	filter out water and particles	1	Mcmaster carr	18.33
K-30 10,000ppm CO2 Sensor	Sense CO2	2	CO2 Meter	186.2
12 Volt Lithium Ion Battery	Power	1		Donated
K30, K33 Sensor Tube Cap Adapter	Allow airflow into sensor	1	CO2 Meter	37.1
PVC Tubing	Air flow	1	Mcmaster carr	10.1
TB6612FNG Dual Motor Driver Carrier	Power pump and heater	2	pololu.com	8.9
Arduino UNO R3 Development Board Microcontroller + USB Cable	Microcontroller	2	newegg	11.29
MicroSD card breakout board+	SD card recorder	1	Adafruit	22.66
Micro SD Card	Data Logger	1	Wal Mart	7.54
ZIPPY Flightmax 4000mAh 3S1P 20C (USA Warehouse)	Battery	2	HobbyKing	
Nylon T-Connectors 10 Pairs (20pc) (US Warehouse)	Battery Connectors	1	HobbyKing	55.15
Mini DC/DC Step-Down (Buck) Converter - 5V @ 1A output	Regulator	3	Adafruit	
GPS Antenna	GPS Sensing	1	Adafruit	
Antenna Adapter Cable	GPS Sensing	1	Adafruit	77.09
LiPo Battery Charger	Charge Battery	1	sparkfun	42.9
Arduino MEGA		1	RadioShack	
Solder		1	RadioShack	70.51
Soldering Board		1	Mountain State Elec.	2.45
Arduino MEGA		1	newegg	19.99
SD Card and stickers		1	Wal Mart	12.72
5 Watt 10 Ohm Resistor	Heating Element	8	Mountain State Elec.	9.3
PVC Pipe	Heating Structure	1	Home Depot	
PVC End Cap		2	Home Depot	
Epoxy	Glue	1	Home Depot	34.44

Insulating Foam	Structure	1 2'x8'x2" Sheet	Home Depot	
Press Disconnect Tubing Fitting	Connections	2	Motion & Flow Products	5
Foam Adhesive	Glue	2	Home Depot	3.13
Caulk Gun	Distribute Adhesive	1	Home Depot	
Threaded String Rod	Attach to String	1	Home Depot	
Nuts	Keep rod in place	2	Home Depot	
Outer Plastic Washer	Seal Structure	2	Fort Collins Plastics	6.00
Clear Acrylic tube	For Ultrasonic tests	1	Fort Collins Plastics	
Acrylic Sheet	Board For Components	1	Fort Collins Plastics	
Liquid Nitrogen	Cool Payload	25 Liters	CSU Chemistry Stockroom	47.11
Liquid Nitrogen deware	Container for LN2	1		donated
45 QT Styrofoam cooler	Container		kmart	15.79
Plastic funnel	Help pour LN2	1	kmart	1.89
Duct Tape	Tighten lid	1		donated
Leather gloves & googles				donated
Thermocouples		6		donated

6.0 Test Plans/ Test Results

6.1 Structural Testing

In order to test the structural integrity of the payload, four tests were performed: a whip test to simulate flight conditions, a shake test to simulate jerk while on the flight string, a drop test to simulate landing impact, and a stair pitch test to simulate post-landing roll.

The whip test, figure 6.2, was conducted by attaching the payload to the flight string and swinging it wildly above the head in a circular motion as fast as possible. There were no failures as a result of this test.

The shake test took place by violently shaking the payload, holding only the flight string, and jerking it around. As a result, the zip ties securing the battery broke. To fix this issue, larger and stronger zip ties were used instead.

The drop test, figure 6.2, involved the payload being dropped multiple times from a height of 18 feet onto a concrete surface. As a result, the plastic battery holder broke, figure 6.1, a small portion of the exterior corner of the payload housing chipped off, and the components board slipped out of its groove. To fix the battery holder issue, a set screw wrapped in tubing was used in place of the plastic battery holder. The corners of the payload were sanded to a rounded finish to prevent further chipping, and the exterior of the payload was wrapped tightly in aluminum foil.

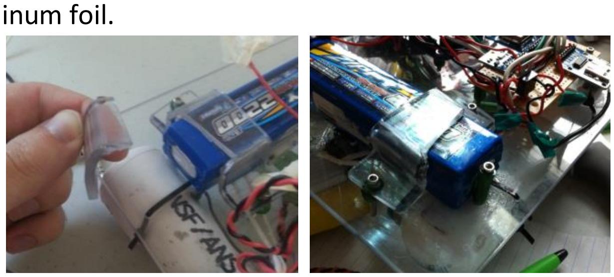


Figure 6.2 – Battery holder damage and fix

The stair pitch test, figure 6.2, was performed by kicking the payload down a flight of 22 metal stairs. Again, the components board slipped out of its groove. To prevent this a new groove was carved which is much tighter than the original one. An additional groove was also carved into the bottom section of the payload to help keep it in place.

Figure 6.1 – From left to right: Whip test, drop test, stair test

6.2 Functional System Testing

System testing was done on the component level before integrating it all together. For the heater test, cold air was drawn into the heater (figure 6.3). Cold Air was generated by inserting the intake into a cup of ice. Neither test provided conclusive results as it was difficult to maintain a cold air intake for a long duration; however the exit air temperature never fell out of the specified range of 0°C to 50°C. The amperage draw was monitored for both the pump and heater throughout the tests, and no abnormalities occurred. Additionally, to ensure that it would not burn up or melt, the heater itself was run independent of other components for a few hours. The heater did not melt or malfunction.

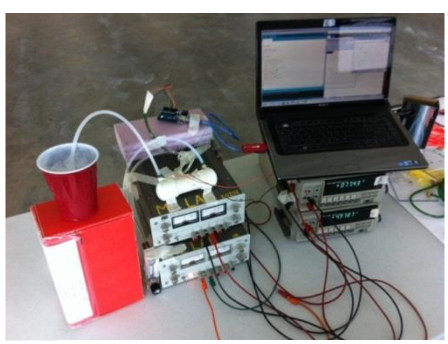


Figure 6.3 – Heater Testing

Next, the filter and CO2 sensor were then attached to the heater and pump, and a flow meter was added to the system to ensure proper flow rates (figure 6.4). The entire CO2 sensing subsystem was run for just over two hours. The test showed positive results, with the CO2 sensor measuring CO2 values that were expected in ambient indoor conditions, thus showing that our system could operate for a long duration and should not negatively affect the CO2 readings.

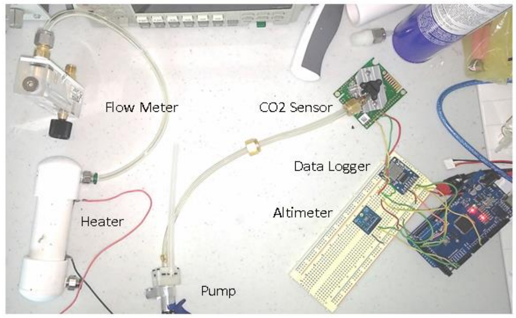


Figure 6.4 – CO2 system testing

To test the GPS module, it was wired up to the microcontroller and brought outside to acquire a signal. The module was moved throughout the Powerhouse Energy Campus, and the coordinates recorded were cross-referenced on Google maps. The coordinates lined up correctly to within 3 meters. Next, the GPS module altitude reading was recorded at ground level, and then the module was brought to the fourth floor of a building. The module detected a 14-meter difference, which was correct.

The altimeter was tested by comparing the pressure it recorded with the published pressure reading of Fort Collins on the NOAA website. Although the reading was within the specifications listed for the sensor, it was not as accurate as we would like it to be. The primary goal is to use the GPS module to detect altitude, cross reference the corresponding pressure through published data, and use the altimeter as a backup in case the GPS module does not acquire a signal or failed.

The SD data logger consistently logged data throughout system testing, showing that our SD data logger was operating correctly. Since our payload will run continuously until it is retrieved or until the battery runs out, a concern was that the SD card would have issues if the battery power became low or ran out. To test this, the entire system was run until the battery ran out of power. The SD card logged data without any issues.

Throughout testing, as more components were integrated together, the code required to run all of these integrated components exceeded the available memory of the Arduino UNO microcontroller. Because of this, the microcontroller was upgraded to an Arduino MEGA, which has almost ten times as much memory capacity.

6.3 Cooler Testing

To ensure that the payload functioned as desired at the cold temperatures likely to be experienced at high altitudes, cooler tests were performed. The coldest temperature that the payload should experience during its flight is -80°C. To simulate this cold environment, the payload was placed in a cooler and liquid nitrogen was added periodically through a small hole in the top to keep the temperature around -80°C for over an hour (figure 6.5).

Figure 6.5 – Pouring LN2

The external air temperature of the initial cooler test fell well below -80°C, reaching as low as -120°C, and was run for duration of 90 minutes. This test resulted in a battery failure, SD data logger failure, and significant frosting and condensation (figure 6.6) of the interior of the payload. Additionally, the CO_2 system air intake or air stream temperature dipped well below the minimum threshold of 0°C.

Figure 6.6 – Frost on the board

The second cooler test was modified to run at a warmer temperature than the first, and saw an external temperature of -80°C for duration of 60 minutes. For this test, a warm-up period of 15 minutes was also established for the payload, as the previous test did not have a warm-up time. The entire exterior of the payload was wrapped in aluminum foil to better insulate it, and the heater chamber was also wrapped in aluminum foil to insulate it as well. After this test, there was much less condensation than the previous test, and the battery had roughly 65% power left. The CO2 system air stream remained above 0°C and the electronics survived the test, however, the SD data logger failed to record data again. The culprit was suspected to be an SD card and logger falling below their operating ranges.

A specific heater, providing 1.25W of power, was added to the SD data logger area and the test was re-run. The external temperature was heavily monitored to ensure that it stayed around the desired -80° for the entire test. The test spanned just over an hour, and proved successful. The air stream temperature did not fall below 0°C, the battery had 75% power remaining, and the SD card logged data. The built in temperature sensor of the altimeter showed that the internal temperature did not drop below 16°C. Figure 6.7 shows the CO2 system air stream and external temperatures of the final cooler test. The breaks seen in the external temperature line are when the thermocouple was disconnected from the data logger to monitor the temperature live. Every time liquid nitrogen was added to the cooler, the external temperature rose abruptly before dropping again. (The Leidenfrost effect)

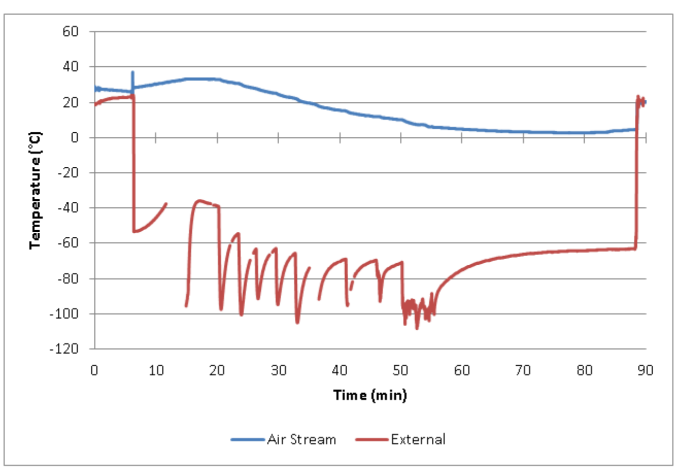


Figure 6.7 - Cooler Testing Temperatures

In addition to determining whether the electronics would survive the cooler test, there was also concern as to whether or not the adhesive used to bond the foam layers together would stand up to the extreme cold temperatures. Two pieces of foam bonded with the foam board adhesive used on our payload were left in the cooler during the final test. Once removed, the pieces were pried apart, only to have the foam tear instead of the bonded joint. From this test, it was determined that the adhesive will be suited for the extreme low temperatures.

6.4 Vacuum Testing

Prior to performing a vacuum test on the entire payload, the pump was first analyzed separately to see if it could perform up to our expectations. Since the primary objective is to measure CO2 levels in the troposphere, and the CO2 sensor requires a minimum flow rate of 0.2 liters per minute, the pump must output a flow of at least 0.2 liters per minute up to 43,000 feet (13,106 meters).

To analyze the pump flow versus pressure, the pump was connected to flow meters and placed inside of a vacuum chamber. Since the flow meters were also in the vacuum chamber, the recorded flow rates had to be corrected to account for the pressure change. The results of the corrected values can be seen in Figure 6.8. The flow rate of the bellows pump appeared to be linearly dependent with pressure.

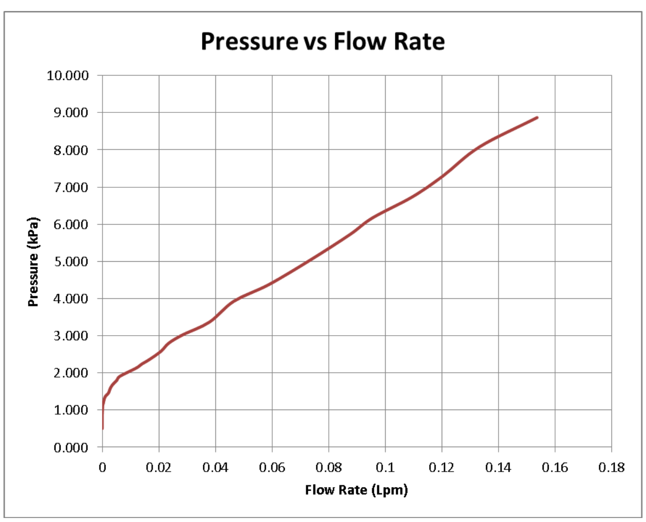


Figure 6.8 – Pressure vs flow rate for pump testing

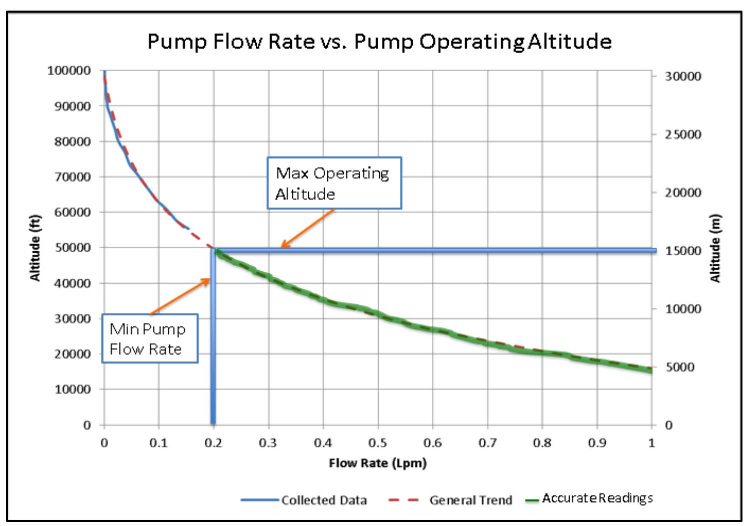


Figure 6.9 – Altitudes within acceptable pump flow rates

Figure 6.9 shows the flow rate as a function of altitude if a linear trend with pressure was assumed. Because the pump will be able to produce of flow of 0.2 liters per minute above 43,000 feet (13,106 meters), this validates that our pump will be able to perform up to our expectations. Readings up to 50,000 feet (15,240 meters) should be accurate based on this test. However flow rates above this altitude will be less than the required 0.2 liters per minute, and therefore any readings above this elevation are not guaranteed to be accurate.

To test that the payload would survive the extremely low pressures seen at high altitudes, it was placed inside of a vacuum chamber and the pressure was pumped down to 0.01 atm. Two tests were run; one at ambient temperatures, and one with a large block of aluminum cooled to -80° that the payload was set on, and then the entire system was wrapped in aluminum foil (figure 6.10). The purpose of the second test was to simulate a low pressure, low temperature environment, similar to what the payload will experience during its flight. Once pumped down to the appropriate pressure (about 3-5 minutes of pumping-down), a manual vent was opened to slowly allow the pressure to increase back to atmospheric conditions. The original test lasted roughly 35 minutes, while the cooled test lasted about 42 minutes.

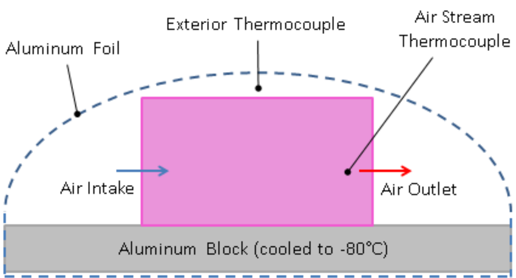


Figure 6.10 – Cooled vacuum test setup

Figure 6.11 – Vacuum chamber

Figure 6.12 shows the recorded temperatures of the external temperature as well as the air stream temperature for both tests, where zero time indicates the start of the vacuum chamber pump-down. The ambient temperature test was accidentally pumped down much too far which is why there is a large temperature drop at the start of that test. As can be seen in Figure 6.12, the cooled test produced temperatures cooler than that of the ambient temperature test, although they were not as low as expected.

The ambient temperature test showed that our air stream temperature actually exceeded our upper limit of 50°C. The cooled test did not produce air stream temperatures above that limit, and is closer to the conditions that should be expected on the flight. The data logger logged data throughout both tests. However the CO_2 sensor data did not record correctly. The corrected CO_2 readings were expected to stay fairly constant while the recorded readings were expected to decline as pressure decreased. As can be seen in figure 6.13, the CO_2 readings did not behave as expected, and were very sporadic. For a long duration during the test, the CO_2 sensor gave the same reading it does when it does not have power. Since the CO_2 sensor runs off of the 5V regulator, the 5V regulator was suspected to be the cause. Additionally, the internals felt very hot, and further testing proved that the 5V regulator does not operate at high temperatures. Concerns of overheating were established. A switching 5V regulator is much more efficient than a linear regulator and was installed to correct the issue. In addition, to compensate for the overheating concern, an internal temperature sensor was experimented with to turn the heater off in case of extremely high temperatures. Electrical issues that occurred soon after vacuum testing hindered the addition of a temp sensor, and it was never added. Instead, another resistor was added in series to lower the power of the board heater from 2.5W to 1.25W.

Aside from faulty CO_2 readings, due to an overheating 5V regulator, the vacuum chamber tests were a success. The payload logged all other data accurately and performed as intended. None of the components broke and the entire system was reusable.

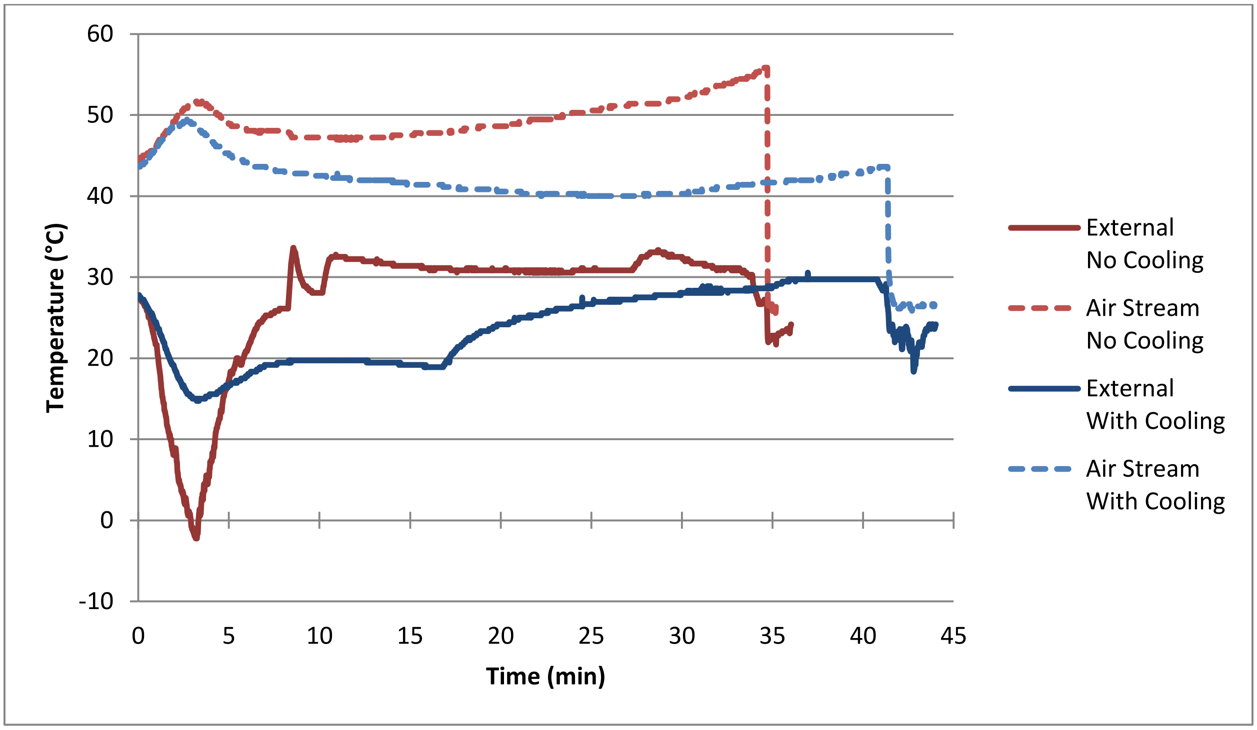


Figure 6.12 – Vacuum chamber testing temperatures

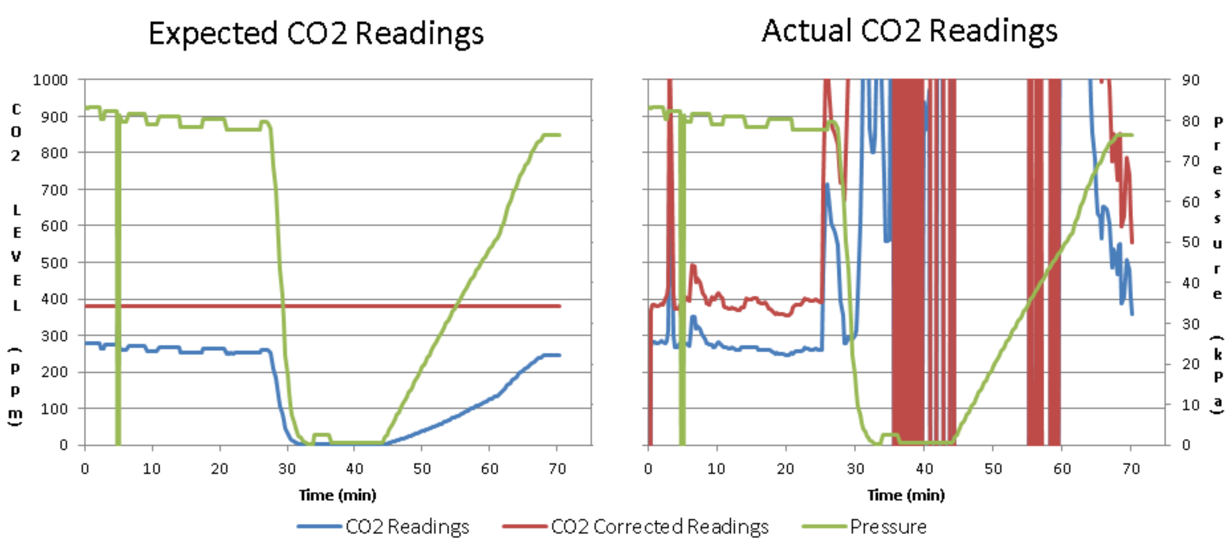


Figure 6.13 – Expected CO2 readings versus actual CO2 readings

6.5 CO_2 Testing

The K-30 CO_2 sensor was tested and calibrated to ensure accuracy of the sensor. Modifications to the air flow were made to improve sensitivity and response time. A zero-point for the sensor was set using a tank of pure nitrogen (N_2) and shorting the 0ppm calibration jumpers on the sensor as specified by the manufacturer. When set to 0, the Arduino read approximately -1.5ppm CO_2. This is because the Ardunino was not sensing exactly 1 volt but ~ .99 volts. The sensor does not need to be span calibrated because is follows Beer's law and came calibrated at 400 and 0 ppm. Resetting the zero point insures greater accuracy.

The next test was to see the response time, accuracy and sensitivity of the sensor. Three different tests were conducted. All of the tests utilized a pure nitrogen tank and a CO_2/Nitrogen mix (391.4 ppm CO_2). The two tanks had their air streams go through a flow meter and mixed together at a controlled rate. The test was run with 391.4ppm CO_2 going into the payload at the start and then concentration was decreased in steps of ~3ppm every two minutes. The first test used two dial flow meters. A mass flow controller was used for tests two and three on the nitrogen tank. Test one and two used the stock sensor setup and test three used the modified sensor. Below is a block diagram to explain the test (figure 6.14).

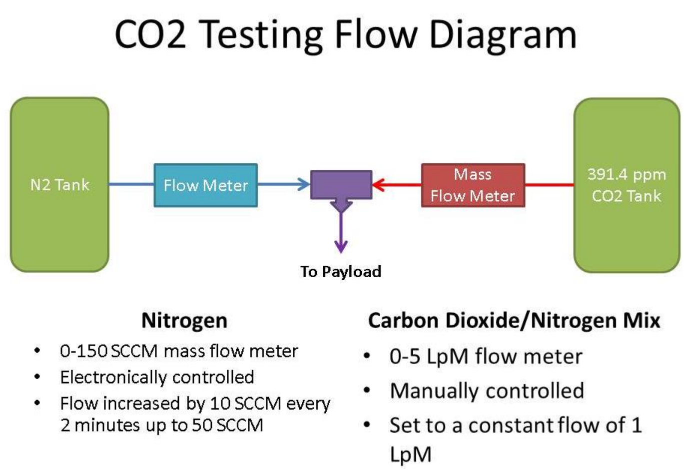


Figure 6.14: CO2 Test Set Up

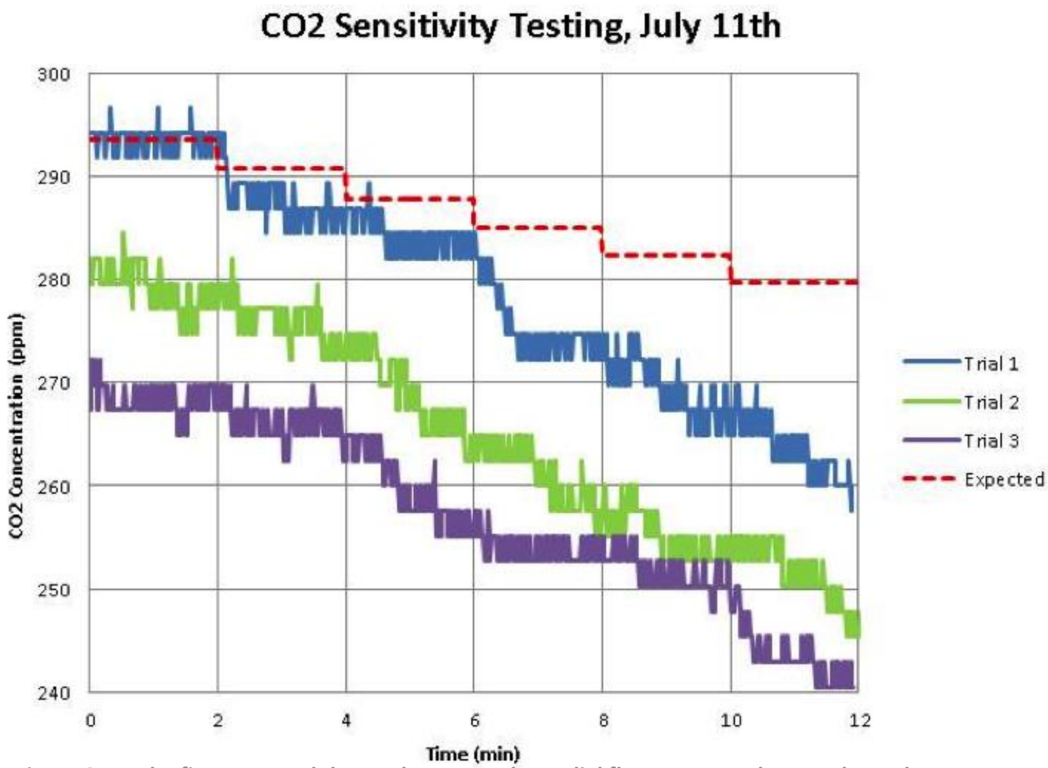


Figure 6.15: The first test used the stock setup and two dial flow meters. The test showed a gradual saturation of the system by the nitrogen tank.

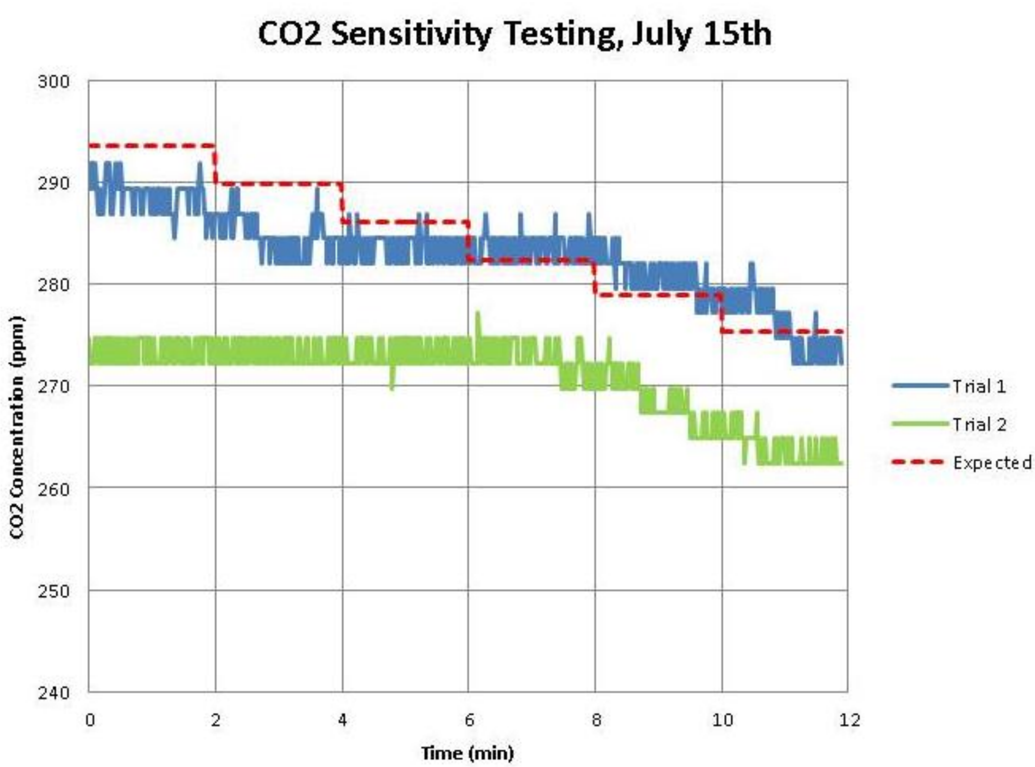


Figure 6.16: The second test consisted of only two trials and used the mass flow meter on the nitrogen tank, which is much more accurate than the dial flow meters.

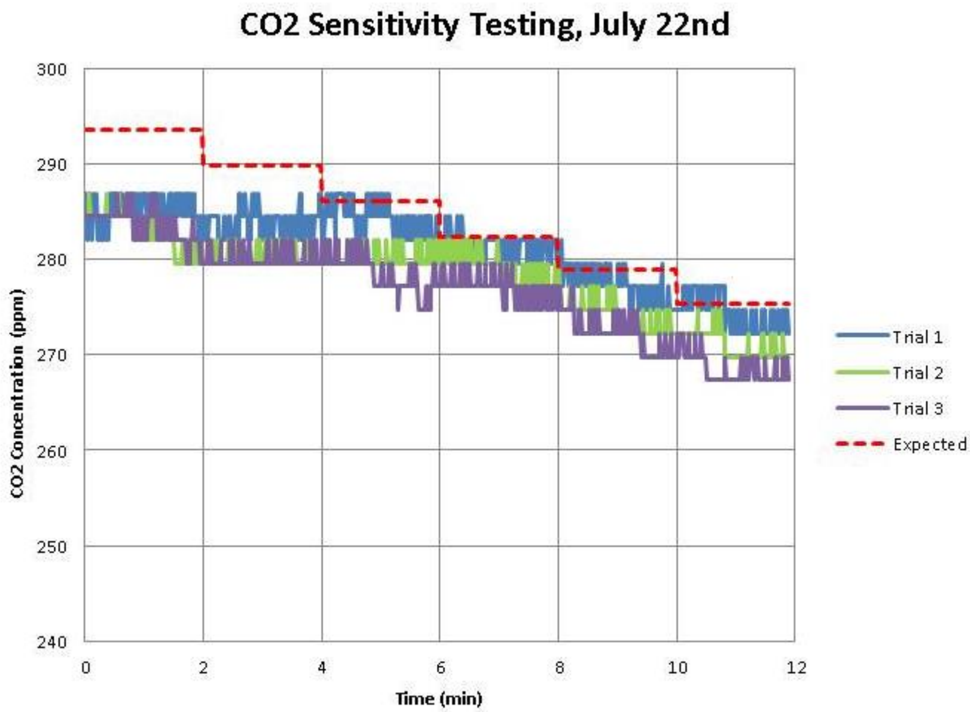


Figure 6.17: The third test used the modified sensor air intake and no stock filter along with the mass flow meter. This test showed the most consistency and slightly better response times.

Conclusions

Each of the three tests (figures 6.15-6.17) had better results than the previous test. The addition of the mass flow controller in the second and third test gave better confidence in the accuracy of our readings. The third test showed the increased consistency gained when modifying the sensor and no signs of a decrease in accuracy. The setup from the third test is exactly the same as the setup used in the launch. This setup was able to achieve a sensitivity of about ±3.5ppm and an accuracy of ± 10ppm and a response time of about 12 seconds.

7.0 Expected Results

The main goal of the project is to measure CO2 in the atmosphere up to 45,000 ft. CO_2 readings are expected to maintain around 390 ppm. On the ascent through the troposphere, there is an expected deviation of 10-15 ppm.

In addition, the known values of CO_2 are expected to change depending on the time of day. This is due to the mixing effect. This effect changes daily and seasonally.

During the flight we hope to encounter a plume of CO_2 which will spike the readings drastically. If we can read the plume, we can approximately determine the location of the source of the plume. This will be done using GPS to track wind speed and direction. In the surrounding areas of the launch site, there are multiple sources of CO_2 that may create detectable plumes of CO_2. The launch location is near a major high way and oil wells, figure 7.1, which both emit CO_2.

The pump can create an acceptable flow until about 50,000 feet. Before the payload reaches 50,000 feet it may run into trouble because the recorded CO_2 concentration will be within the rate accuracy of the sensor with zero. At about 45,000 feet, the sensor could be reading as low as 20ppm before correction. This could cause inaccurate readings due to the sensor reading below zero. 45,000 feet should be high enough for the payload to have already seen potential plumes and get a good sense of the vertical profile (figure of CO_2. 7.11)

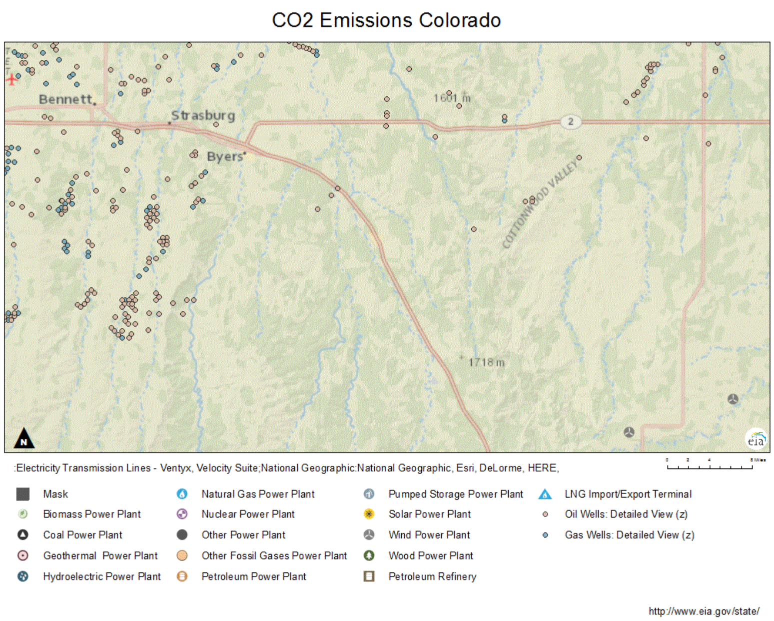


Figure 7.1 CO2 sources shown. Mostly oil and gas wells.

Source: www.eia.gov

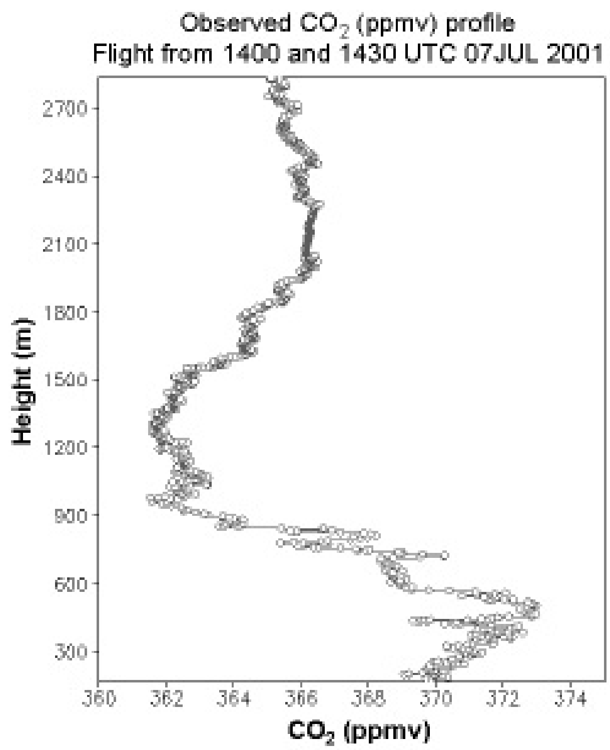
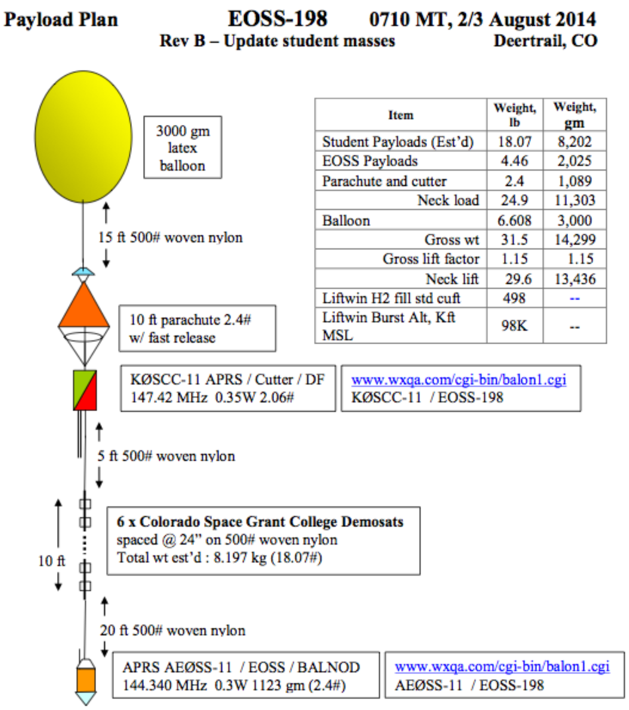


Figure 7.11 Vertical profile of CO_2
Source: CLAIRE-LBA

8.0 Launch and Recovery

8.1 Launch

After completing the payloads design and testing, it was ready for launch. Launch day was August 2, 2014 at 7:10 a.m. The weather was clear with a high of 81°F and a low of 48°F. The Edge of Space Science (EOSS) organization provided a plan to launch and recover a 3000 g latex balloon. The balloon is expected to ascend at a rate of 1329 fpm. On the decent a 10 foot diameter parachute is released shortly after the peak altitude and fall a rate of approximately 950 feet per minute. A diagram of the balloon set up is seen below. The balloon connects a woven nylon cord to the parachute, GPS tracker and six of the Colorado Space Grant College Demostat payloads.



Item	Weight, lb	Weight, gm
Student Payloads (Est'd)	18.07	8,202
EOSS Payloads	4.46	2,025
Parachute and cutter	2.4	1,089
Neck load	24.9	11,303
Balloon	6.608	3,000
Gross wt	31.5	14,299
Gross lift factor	1.15	1.15
Neck lift	29.6	13,436
Liftwin H2 fill std cuft	498	--
Liftwin Burst Alt, Kft MSL	98K	--

Figure 8.1 Launch Details Source www.eoss.com

The EOSS organization provided a team of 16 employees to help with tracking, recovering and flight coordination. Each participating team received a walkie-talkie, a map and a GPS antenna for the vehicle and balloon to map live on a computer. This allows each car to track the balloon individually and communicate between cars to observe the balloon location, figure 8.2. The live tracking made the recovery easy and exciting to see the shifts in the wind.

Figure 8.2: Caravan of Cars

At the launch, we had our entire team present; four students and an advisor. Jeff volunteered to hold the payload and release it when the balloon started to rise after the countdown. After the release the team kept visual contact on the balloon and started to track the ascent on the laptop. Our group followed the balloon in a car with the help of GPS and watched it land onto a field.

The balloon landed approximately 0.75 miles away from the closest road in a field full of cacti and yucca plants. The payload was orientated on its side and landed on a small cactus, figure 8.3. There was no external damage to the payload and the device was still running. After documenting the landing position, the payload was switched to the OFF position.

Figure 8.3: Landing Site Pictures

The results of the balloon track follow a similar pattern to the predictions posted by EOSS, figure 8.4. The balloon headed east towards Limon and veared closer to the highway. It seems like there was a large unanticipated wind gust at the higher altitudes which made the balloon cross the high way and burst on the opposite side that predicted, figure 8.5

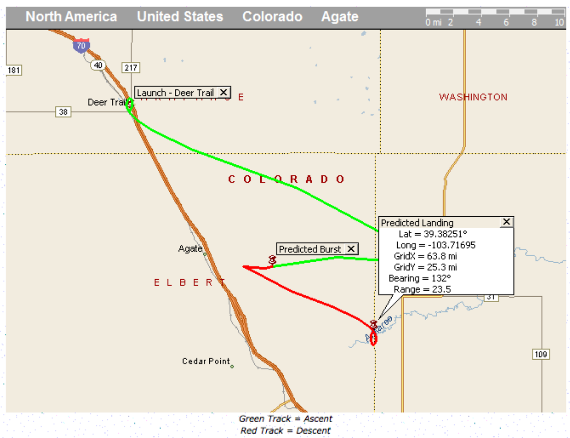


Figure 8.4: Predicted Balloon Trajectory

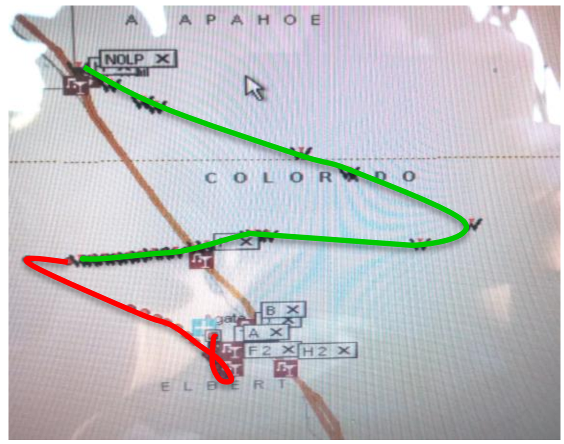


Figure 8.5: Actual Balloon Trajectory

Data recovery was easy for our device. Once the payload was detached from the flight string and the other devices, the wing nuts were unscrewed to open up the payload cap. Inside, the board comes completely out of the payload and and the SD card is ejected from the data logger. The SD card is directly inserted into a computer and the data collected for the entire balloon ride is transferred and uploaded into Excell, figure 8.6. The SD card collected pressure which was adjusted to altitude and CO_2 readings which were adjusted for pressure compensation. The readings are then graphed and displayed for analysis and conclusions for the report.

Figure 8.6: Data Analysis at landing site

9.0 Results, Analysis and Conclusions

9.1 Results

After retrieving the payload, there were multiple successes of the project. The primary mission of recording and tracking CO_2 in the atmosphere was achieved.

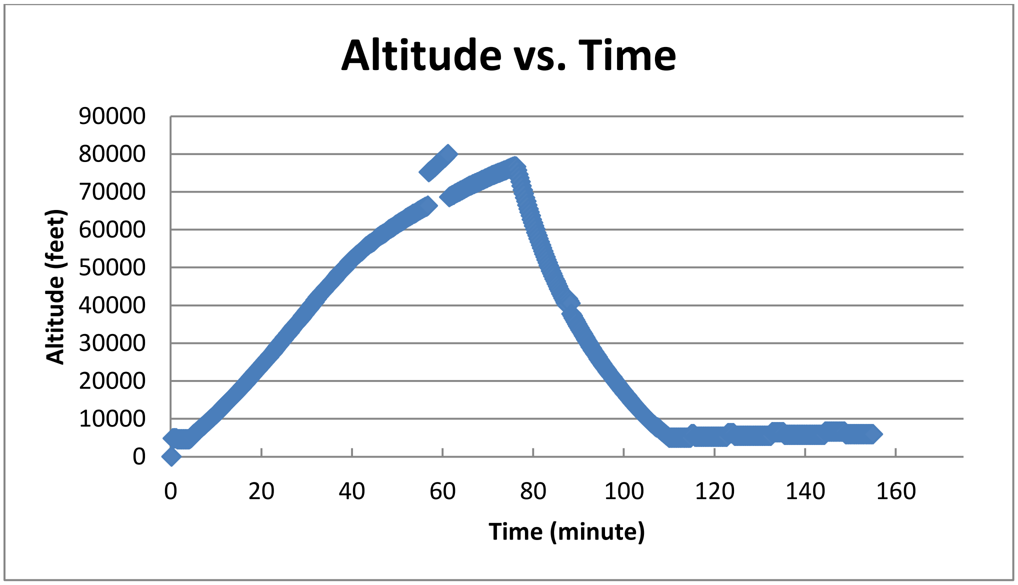


Figure 9.1: Flight Altitude

The graph above, figure 9.1, displays the entire flight was under two hours. The descent was about twice as fast as the ascent. The max altitude of 80,000 feet does not match with the 90,000 feet as reported by EOSS. After around 110 minutes, the payload landed and continued to run until retrieval. Also an error appeared to have occurred around 60 minutes.

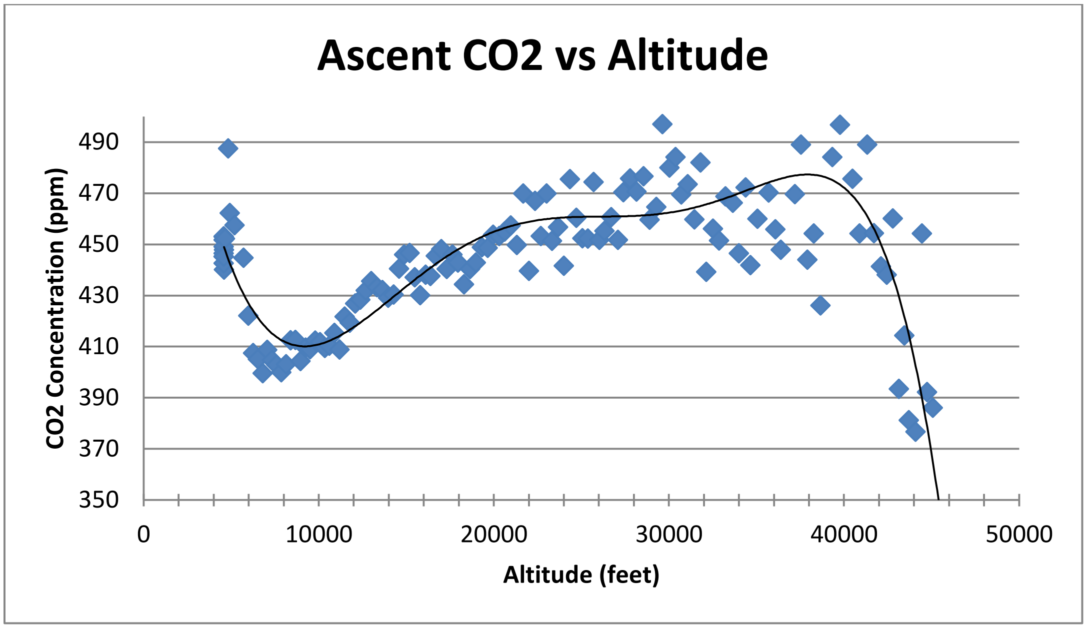


Figure 9.2: Ascent readings of CO_2

Figure 9.2 illustrates the CO_2 concentration vs altitude on the ascent. The graph is cutoff early because the pressure is too low beyond 40,000 feet to get reliable readings. The CO_2 concentration started higher than the baseline, but nearly all of the beginning readings above 410 ppm are taken at ground level. Then, the concentration was around 400ppm from about 6000 feet to 12000 feet. The CO_2 concentration continued to rise and may have started to level off around 20,000 feet, but not enough data points are present to be sure.

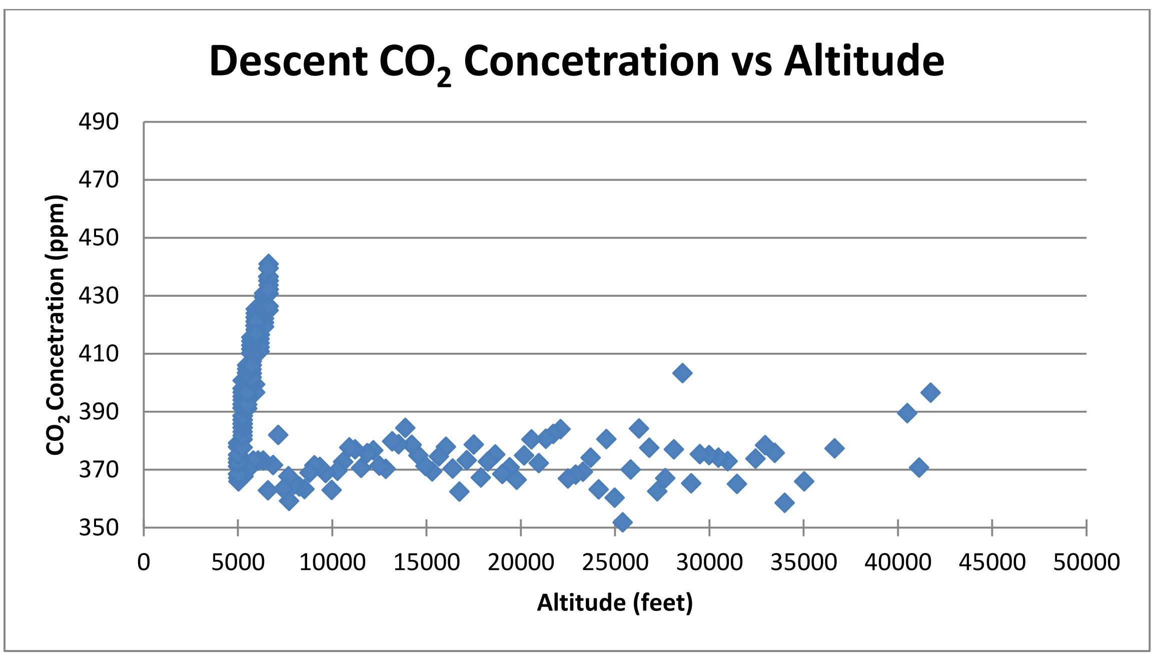


Figure 9.3: Decent Readings of CO_2

Figure 9.3 shows the CO_2 concentration during the descent of the balloon. Readings were taken every 15 seconds for approximately 35 minutes for the decent. Around 5,000 feet or ground level, communication between the Arduino and the altimeter caused some errors because the altitude was constant. Overall, the average is much closer to 380ppm and much smoother than the ascent.

9.2 Analysis:

Overall the data retrieved from the payload was positive. The best result is noted on the descent. The descent displays a nice vertical profile of the amount of CO_2 in the atmosphere over a small region. The balloon stays around the same location between 40,000 feet and ground level which makes the readings close to the same position. Figure 9.4 displays the vertical profile of CO_2 concentrations up to 40,000 ft. As the payload increased in altitude the readings of CO_2 are within the 15 ppm changes expected for the beginning of August during morning hours. The readings seem a bit low in comparison to ground readings in Fort Collins, but the payload was found in an area with few CO_2 sources. It is possible that CO_2 concentrations vary depending on surroundings, and this reading is outside of the ±10ppm accuracy of the sensor when compared to a 400ppm baseline. It should also be noted that this data was taken at about 8:30 AM when CO_2 readings are typically lower than the baseline. On the descent, there are no noticeable plumes of CO_2.

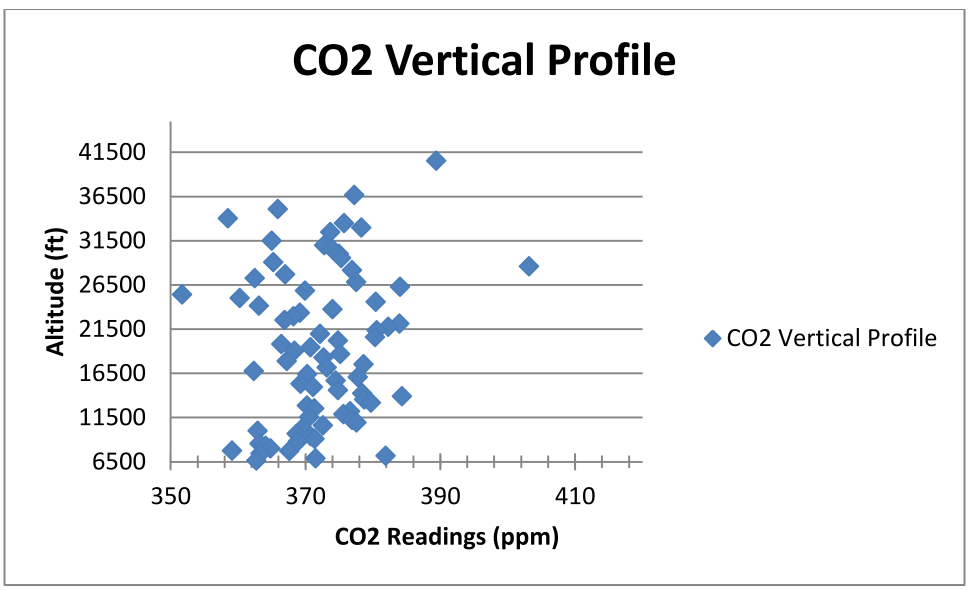


Figure 9.4: Descent Vertical Profile

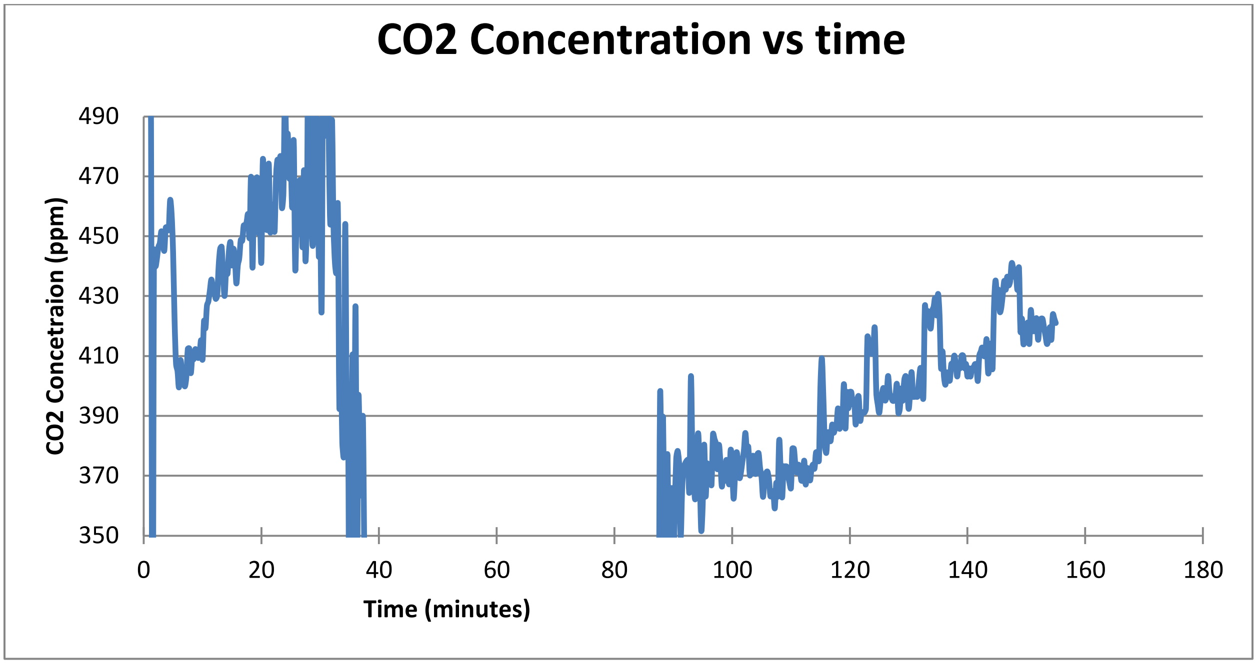


Figure 9.5: CO_2 Concentrations over time

Figure 9.5 shows the CO_2 concentration measured during the entire flight with respect to time. The large gap of missing data in the middle is due to the payload being above our max height measuring threshold of about 40,000 feet. The beginning outliers occur mostly before the payload has left the ground. The ending CO_2 concentration jumps are due to the pressure compensation and errors in the altimeter that occur when sitting at ground level for a long period of time.

9.3 Causes for CO_2 concentration difference between ascent and descent:

On the way up, the CO_2 concentration rose from 400ppm at ground level to ~475ppm at 40,000 feet. This is interesting and not something that was expected. This rate at which the CO2 was raising was approximately linear from ground level until about 20,000 feet. At 20,000feet, a lower sloped increase occurred until 40,000 feet when the readings started becoming unreliable. Because the rate of climb was linear from the ground until about 55,000 feet, the pressure compensation should not be to blame for this change. Below, a few possible causes for this rise will be shown.

Payload Malfunction:

A possible reason that the CO_2 readings were different on the ascent and descent could be that the air was not heated properly on the ascent, but was heated correctly on the descent. This can occur because of the less than five minute warm-up time that the payload got on the ground. This was caused because the team assumed it would take longer for the launch to start and due to inexperience with the launch in general. When air colder than the CO_2 sensor's minimum operating temperature enters the sensor, the concentration of CO_2 will appear higher due to the ideal gas law. The highest reading is taken at the Tropopause or about 32,000 feet which is the coldest part of the atmosphere. Then, the readings start to taper off. At this point, the heater is hot enough that it is properly heating the air entering the CO_2 sensor.

CO_2 emissions plume:

Figure 9.6 shows a map of the flight path on top of the map of CO_2 sources in Colorado. The green line shows ascent of the balloon and the red line shows descent of the balloon. The first purple dot is approximately where the balloon passed 40,000 feet and CO_2 readings could no longer be made by the payload. The second purple dot is where the payload passed below 40,000 feet and readings can again be made by the sensor. The yellow lines are an estimate of the edges of the CO_2 emissions from the three oil wells to the Northwest given the wind direction below 42,000 feet. This wind direction was derived by the payloads heading and then the switching of heading around 42,000 feet.

As shown in Figure 9.6, the balloon ascended in a zone that could have contained CO_2 emission plumes from local oil wells. The balloon did not descend in a zone that would be prone to an increased CO_2 concentration. One possible explanation for the increase in CO_2 is that the balloon traveled through a CO_2 plume coming from local oils wells on the ascent, but did not travel through this plume on the descent.

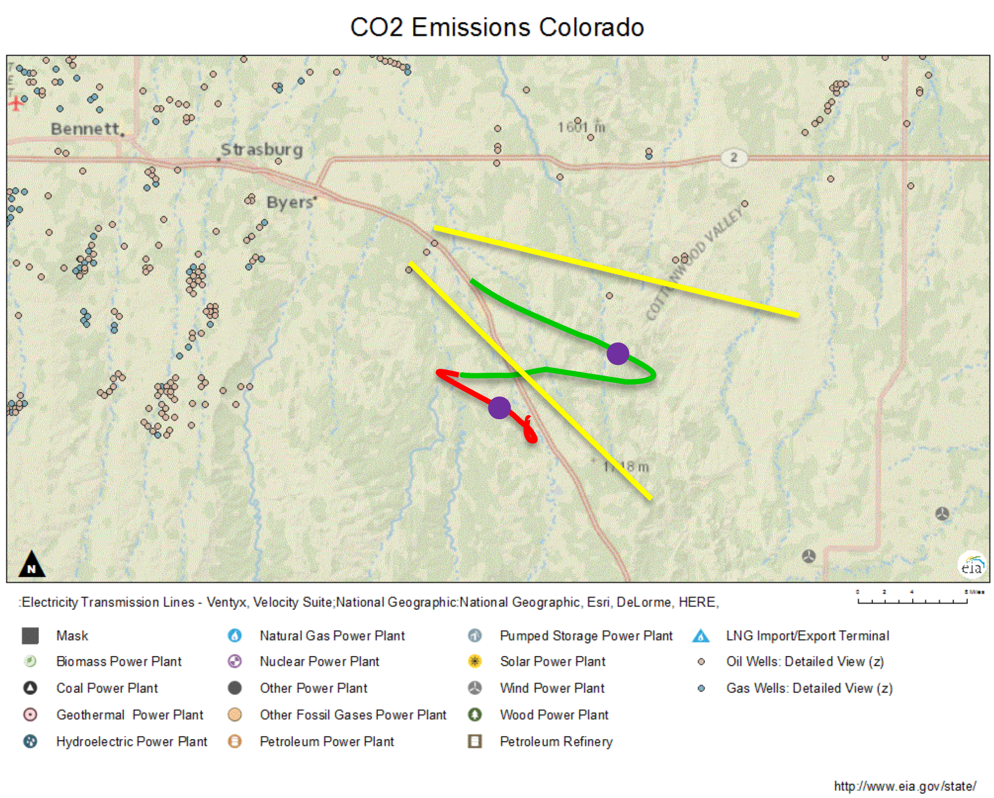


Figure 9.6 Oil Emissions of CO2 with Flight Projected
Source: www.eia.gov

10.0 Ready for Flight

Overall, the payload performed very well. The flight was successful and there were no issues with components breaking. Much of this was thanks to extensive testing. Therefore, if another flight were to occur, the payload would be ready to fly again as is. All that would be need is some simple prep work such as charging the batteries and clearing the SD card and installing it. Launching the payload again could be quite beneficial to a more finite conclusion about results. CO2 vertical profiles are quite dependent on the time of day, month, and weather conditions. A second launch could help show the reason for the deviation between ascent and descent as well as give an idea how the vertical profile of CO_2 changes throughout the year.

There are a few additions that could be made to the payload if it were to fly again. One addition would be adding a working GPS. Unfortunately the GPS sensor broke just before launch and there was not time or budget to replace it. The GPS was part of the payload's secondary goal so it was not necessary for CO_2 measurements, but it would have been nice to have the chance to have better position mapping. Temperature sensors, both inside and outside, would also be included to have a better understanding of how the payload performed overall and if there was any time when it was close to either freezing or overheating. These additions, while not completely necessary the payload's overall goal, could provide data that further stimulates understanding in how the payload performed. Also, a longer warm-up time of about 15 minutes could be used to eliminate the possibility of the internal temperatures skewing results.

11.0 Lessons Learned

The Space Grant Internship provided multiple learning experiences throughout the summer. One of the largest lessons is in regards to the electronics. For all of us, it was our first time programming with an Arduino. A whole programming language was learned and mastered. Our group found that everything would be working incredibly well then suddenly adding one more component can fry the whole system. Electronics are bound to burn out or be improperly wired. Although this is frustrating and ate away at our budget, there was a lot learned in the electronics. The motto for the summer was "If it ain't broke don't fix it". This motto should have been followed towards the end of the project when time was limited. If the payload works fine, adding extra luxuries at the end may cost the functionality of the payload. In addition, when ordering parts it is a good idea to order two or three of every component. One thing might go wrong and rather than waiting a week for the part to come in, you already have it. This would is our lesson learned and hope future teams take replacements into account when thinking about future projects with a strict time schedule.

12.0 Message to Next Year

Overall, the Space Grant program was a great experience. Our group worked 8-hour days for 10 weeks. By the end of the summer, the project was a success. One message of advice is not to be afraid to choose a project which no one in the group has any knowledge about. This is all a part of the experience and by the end of the project the group will have in depth knowledge about the topic. This summer the group learned about atmospheric science and environmental issues that are arising in today's society. This was really an eye opening experience into a possible career field.

In addition, the project has multiple design considerations at high altitudes. The atmosphere is not the same as it is on Earth so testing is the most important thing to do before launch. Everything thing might work perfectly on Earth but suddenly doesn't preform adequately at higher elevations. To make sure testing goes smoothly, plan for two weeks of testing and an additional two weeks to tweak the design or order additional parts. One must account time for design, research and shipping times. A good strategy is to order parts sooner rather than later so there is something to work on the first few weeks of the project. This helps accomplish the final manufacturing of the payload by week 6 and start testing on time. This summer we followed this schedule and as it turns out, the extra time at the end was greatly appreciated

13.0 Benefits to NASA and Scientific Community

This payload was designed to be a simple, lightweight device that will measure gas in the atmosphere. There are multiple applications to the scientific community where the sensor can be implemented. These include but are not limited to: using a similar design to sense other gasses, putting the device on a remote controlled aircraft to detect CO2 in hard to reach locations and taking data at a remote or hostile location. The most applicable application is to determine emissions from power plants or oil wells. Reduction of CO_2 is needed for life to be stable and healthy in the future and figuring out what places should cut back on emissions is the best place to start.

Acknowledgements

We would like to recognize all the individuals who helped assist in this summer's project. Your time and knowledge was greatly appreciated.

- Laurie McHale, Graduate Student at Colorado State University
- Dr. Azer Yalin, Associate Professor at Colorado State University
- Dr. John Williams, Associate Professor at Colorado State University
- Burnadette Garcia, Associate Director of Colorado Space Grant
- Ray Hicks, Owner of CO2meter.com
- Colorado State Powerhouse Energy Campus

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