PROFILING AND QUANTIFYING PARTICULATE MATTER AND OZONE THROUGHOUT AN ATMOSPHERIC COLUMN

AEROSOLUTION

Colorado State University

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ABSTRACT

NASA allotted grants to a motely of universities throughout Colorado to encourage undergraduates to conduct research experiments where teams must build a payload which then gets launched into near space on a weather balloon.

AEROSOLUTION is a team from Colorado State University participating in the Colorado Space Grant Consortium, who decided to fabricate a reusable and lightweight air quality monitoring instrument. The payload was dual designed to collect particulate matter on Teflon membrane filters which are then analyzed in a gravimetric machine, an optical transmissometer, and x-ray fluorescence machine; and the payload also includes a sensor which reads the concentration of ozone throughout the atmosphere – up to 30km.

The data was checked for accuracy by comparing it to information collected by the Colorado Air Pollution Monitoring Control Division. A malfunction occurred during launch where only one filter was exposed, however the data collected for ozone throughout the atmospheric column depicted a similar behavior to the predicted lineation in the hypothesis. If the payload were to be fixed, it could potentially be manufactured and distributed to regions struggling to establish air quality standards.
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1 Mission Overview

1.1 Problem Statement
Atmospheric aerosols are particulates that are suspended throughout the atmosphere which originate from natural and anthropogenic sources [12]. In the troposphere, these particulates act as a “seed” for water vapor to condense around and form clouds, which can affect the weather. Furthermore, in the stratosphere, particulates can travel long distances, polluting and contaminating the air for years. Human health is at risk of increased respiratory and cardiovascular problems, especially the more sensitive groups, as the sources for aerosols continue to grow with the increasing human population. Having a better understanding of the aerosol concentration throughout the atmosphere can aid in developing strategies to mitigate further introduction of aerosols into the atmosphere.

Particulate matter (PM) is categorized by diameter: those that are less than 2.5µm ($PM_{2.5}$) are fine grit and those that are less than 10µm ($PM_{10}$) are coarse grit. When PM circulates through the atmosphere to the lower troposphere, it can easily be inhaled and threaten public health [1]. Difficulty breathing, coughing, aggravated asthma, and a decrease in lung functionality are all symptoms of exposure to $PM_{10}$; while irregular heartbeats, heart attacks, and premature death for those with heart diseases are potential effects of $PM_{2.5}$ exposure since these particulates are miniscule enough to enter the bloodstream [1].

![Figure 1. Sizes and composition of particulate matter [11]](image-url)
Weather can be modified by aerosols due to their capability of suppressing precipitation. When aerosols are present, the water droplets that form clouds become more numerous and smaller since the moisture in the air is divided amongst more particulates. The smaller sized droplets aren’t heavy enough to precipitate. Clean air however, results in clouds comprised of a small number of large droplets, which lead to rain and snow. Aerosols also have a significant impact on climate due to their ability to absorb and scatter ultra-violet (UV) radiation. Essentially, with a high concentration of translucent particles in the troposphere and stratosphere, water condenses around them so that the clouds are modified to contain a larger number of droplets than usual. A larger number of droplets contained within clouds causes additional scattering of UV radiation and reduces the amount of light that passes through the troposphere. This ultimately causes net cooling of the Earth’s surface and is known as the Cloud Albedo Effect [12]. Hence, aerosols can alter the natural distribution of heat on Earth’s surface, which could pose difficulties for atmospheric scientists to make predictions on climate change.

Ground-level ozone is a gaseous pollutant that also poses hazards to public health, especially in $NO_2$ from motor vehicle exhaust and volatile organic compounds (VOC) from oil and gas combustion react in sunlight [14]. Due to unnatural heat distribution caused by aerosols, Colorado has endured higher temperatures over the last 30 years. This increased temperature prompts the NO and VOC pollutants to incubate in the heat leading to an increase in ground-level ozone concentration. Due to the increased ozone generation, counties like Arapahoe, Larimer, and Denver have been in violation of the EPA standards established by the Clean Air Act since it was signed into law. In 2017, Denver was ranked as the 11th most ozone-polluted area in America. Colorado now has until July 2018 to lower ozone to 70 ppb from +80ppb to alleviate health implications [5].

Local weather, climate, the environment, and public health can be negatively impacted due to high concentrations of aerosols and ozone. Therefore, it’s important to frequently monitor the air quality throughout the atmosphere to determine if stricter standards need to be established and if current standards are being met.

**1.2 Mission Statement**

While there are plenty of ground-based instruments that can measure the PM in the lower troposphere, there aren’t many cost-effective observational systems that can measure the concentration of aerosols up the atmospheric column. The ability to measure the vertical profiles of air pollutants would help to create more precise and updated atmospheric models, which is important because authorities can devise strategies to assuage air pollution and reassess standards. There are satellites, like CALIPSO, with the ability to measure aerosol layers with respect to altitude; however, satellites can only collect data during the day [12]. Aircraft are also utilized to measure PM but they are expensive to operate and cannot ascend to 30 km like a weather balloon. Therefore, the payload constructed by AEROSOLUTIONS will be mounted onto a low cost high-altitude balloon carrying multiple payloads. The balloon will be inflated using helium and will have a total ascend time of approximately 75 minutes.
AEROSOLUTION’s objective was to conceive a lightweight and reusable air quality monitoring instrument that can detect and quantify aerosols and ozone throughout the atmosphere. It was dual designed:

1. The payload attached to the high-altitude balloon was designed to expose eight 37mm Teflon membrane filters to the atmosphere at different altitudes based off the onboard altimeter readings. Each filter would be exposed in altitude steps of 3.44 km up to approximately 27.5 km. The samples would then be taken back to the CSU Aerosols Lab, so the concentration and composition could be analyzed in gravimetric, optical transmissometer, and X-Ray Fluorescence (XRF) measurement equipment.

2. An ozone sensor with a resolution of ±1ppb was inserted inside the payload to monitor ozone concentration as a function of altitude. The sensor data was recorded to an SD card via $I^2C$ communication.

The data collected from the payload was then compared to the data from the Colorado Air Pollution Control Division to check for accuracy. If the instrument fared well, then it could be manufactured and distributed to developing countries or heavily populated regions in the United States as a user-friendly device, which would be launched at a low cost and high frequency to better document the local air pollution and to aid in monitoring the effectiveness of pollution control measures.

1.3 Hypothesis
Particulate matter (specifically $PM_{10}$) and ground-level ozone are most prevalent in Colorado out of the six common criteria pollutants as defined by the Environmental Protection Agency (EPA) and listed in Colorado’s 2016 Air Quality Data Report from the Air Pollution Control Division [1]. The high levels are a result of the many motor vehicles active on the roads, biomass cooking and heating fires, Colorado’s many booming industries, and forest fires – all of which release particulates and contribute to increased levels of ozone.

The simplest aerosol sampling technique involves prolonged airflow through a filter membrane that captures particulate matter with a diameter of 10µm or less, also known as $PM_{10}$. A pump can be utilized to improve the airflow through the filter, increasing the amount of particulate matter collected. Due to the balloon payloads weight constraints and the mass of the other flight hardware, the pump was restricted to a mass of <100 g. A miniature diaphragm pump weighing 80 g and capable of 6.7 liters per minute depending on atmospheric properties was selected. To determine if the pump was adequate for aerosol sampling, an estimate of aerosol concentration as a function of altitude was made. The atmospheric pressure, temperature, and air density from ground level to 30 kilometers was determined using Equations 1-6 shown in Appendix A[3]. Their respective graphs are shown in Appendix B. At ground level the average expected value of $PM_{10}$ in the area was 42 [µg/m^3] with a standard deviation of 22 [µg/m^3][10]. Due to the decrease in air density with increasing altitude, the mass of air flowing through the filters also decreased as shown in Figure 2. Therefore, given the expected ground level $PM_{10}$ averages from Colorado’s Air Quality Data and the decrease in air mass flowing through the filters it was expected that the first three exposed filters would collect 6.5 µg ± 3 µg of $PM_{10}$. These values could have varied depending on the exact location, time of day, weather conditions, and other factors, such as wild fires.
However, these expected concentrations of $PM_{10}$ were adequate for analysis using the gravimetric and the X-Ray fluorescence machine in the Aerosol’s Lab at Colorado State University.

![Graph](image)

Figure 2. Mass of air decreases with altitude due to decrease in air density

Ground level ozone predictions were based on two major field campaigns conducted jointly in July/August of 2014. These were the Front Range Air Pollution and Photochemistry Experiment (FRAPPÉ) and Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ), which were both conducted in the Northern Colorado Front Range Metropolitan Area (NFRMA). These studies conducted ozone vertical observations using P-3 aircraft flight paths, ozone sonde launches, and ground-based observations [14].

AEROSOLUTION used the ozone measurements from FRAPPÉ and DISCOVER-AQ and scaled the vertical profile based on the ground level measurement to best represent the expected ozone concentrations in the Deer Trail area [10]. It was expected that the ground level ozone concentration in Deer Trail would be approximately 55 ppb and increase to 70 ppb within the first 5 km. From there the concentration was predicted to decrease before reaching the stratosphere where the concentration will largely increase due to the ozone layer. These values were subject to change as the sources for ozone depended on pollution from urban sources, power plants, large industrial sources, agricultural activities, and oil and gas extraction [14].

Based off the Air Quality Index (AQI) – a standard for categorizing the extent of pollution concentration in the air – the hypothesis categorizes Colorado in “Good” for particulate matter but “Unhealthy for Sensitive Groups” for ozone shown in Table 1 below.
Table 1. Air quality index as approved by the EPA [2]

<table>
<thead>
<tr>
<th>Air Quality Index Levels of Health Concern</th>
<th>Numerical Value</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>0 - 50</td>
<td>Air quality is considered satisfactory</td>
</tr>
<tr>
<td>Moderate</td>
<td>51 - 100</td>
<td>Air quality is acceptable; however, some pollutants may be a moderate health concern for a small portion of the population</td>
</tr>
<tr>
<td>Unhealthy for Sensitive Groups</td>
<td>101 - 150</td>
<td>Members of sensitive groups may experience health effects</td>
</tr>
<tr>
<td>Unhealthy</td>
<td>151 - 200</td>
<td>Everyone may begin to experience health effects</td>
</tr>
<tr>
<td>Very Unhealthy</td>
<td>201 - 300</td>
<td>Health warnings of emergency conditions</td>
</tr>
<tr>
<td>Hazardous</td>
<td>301 - 500</td>
<td>Health alert: everyone may experience more serious health effects</td>
</tr>
</tbody>
</table>

2 DESIGN

2.1 DESIGN OVERVIEW
The objective of the air quality monitoring instrument was to create a reusable device that measures the concentration of aerosols and ozone throughout the atmosphere and then can export the data collected to create vertical profiles of the pollutants. This is important because it enacts a new method of monitoring atmospheric pollutants which is not only affordable but can also be used frequently. This was achieved by creating a rotary mechanism that exposes filters at different elevations to collect \( PM_{10} \) while also measuring the concentration of ozone with a sensor. Therefore, two important design aspects for the payload include a lightweight compartment and rotary mechanism.

2.2 COMPUTER-AIDED DRAWING (CAD) MODELS

2.2.1 Payload Compartment
The payload is comprised of nine foam board components adhered to make a 361mm x 276mm x 200mm trapezoidal prism. The payload configuration reduces the overall volume of foam, which minimized the weight and reduced high stress concentrations in the joints, as they aren’t perpendicular. It also passed all structural tests when using aluminum tape to secure the compartment together and fared very well during the environmental tests due to the well-insulated foam board. Furthermore, this design included an ON/OFF toggle switch on the outer surface with a green LED. When the switch was flipped up the Arduino Mega initialized, powering the LED to
signal that the instrument was being powered and the code was running. Finally, the design proved to be the most cost effective given the parameters and ultimate goal.

2.2.2 Rotary Mechanism
Figure 4 illustrates an exploded view of the final iteration of the rotary mechanism that was utilized to house eight filters for individual exposure, as well as one control filter. Multiple design iterations were required to finalize a mechanism that was light weight and performed well. 3-D manufacturing proved to be ideal for this iterative design process since it allowed the group to quickly re-print any changes, maintain accurate dimensions, and minimize weight.
2.3 **Requirements and Limitations**
While the DemoSat-B Program allows for a lot of ingenuity and creativity on the topic and project teams would like to research, there are a few strict design parameters which must be abided by: weight, financial budget, and incorporation of the flight tube. The payload may not exceed 1kg and the total purchases must be less than the $1,000 allotted budget. Other factors to take into consideration while designing were that it must be electrically self-contained, withstand up to 15g’s of shock, must be able to endure a pressure drop from 101kPa to 1kPa, and nothing may drop from the payload. The required flight tube was to be constructed of 3/8” inner diameter Polyethylene tubing and secured on both sides of the payload using wire and washers.

2.4 **Wiring Diagram**
The wiring diagram shows the final orientation of all components, where all the connections are made with quick-clip connectors. The entire system was modular to make for easy replacements.
To reach the final product, AEROSOLUTION divided the work of the project into three primary aspects: design and modeling, programming, and circuitry. While the team members shared responsibilities and ideas for each part - Mr. Julian Aguilar took the lead in modeling, Ms. Susan Ossareh focused on programming, and Mr. Michael Sartini oversaw the wiring and soldering. All the efforts were combined so each part could be integrated into the air quality monitoring instrument where all testing was conducted as a group.

**Figure 6. Gantt Chart**


## 4 Budget

Table 2. Bill of materials for AEROSOLUTION

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Product Assembly</th>
<th>Name</th>
<th>Description</th>
<th>Qty</th>
<th>Lead Time</th>
<th>Manufacturer</th>
<th>Distributor</th>
<th>Mass (g)</th>
<th>Unit Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13-V Battery</td>
<td>Lithium Ion Polymer Battery</td>
<td>- 3.7V 2500mAh</td>
<td>3</td>
<td>1 week</td>
<td>Aeadraft</td>
<td>Aeadraft</td>
<td>46.5</td>
<td>$14.95</td>
<td>$67.22</td>
</tr>
<tr>
<td>2</td>
<td>5-V Battery</td>
<td>Ultra Life 9V</td>
<td></td>
<td>2</td>
<td>-</td>
<td>Utouchide</td>
<td>Batteries Plus Bulbs</td>
<td>8</td>
<td>$7.99</td>
<td>$63.92</td>
</tr>
<tr>
<td>3</td>
<td>Altimeter</td>
<td>Altimeter Module MS5807</td>
<td></td>
<td>1</td>
<td>2 weeks</td>
<td>Parallax</td>
<td>Robot Shop</td>
<td>10</td>
<td>$2.99</td>
<td>$29.90</td>
</tr>
<tr>
<td>4</td>
<td>Battery Assembly</td>
<td>Foam Insulated Container</td>
<td></td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>5</td>
<td>Carbon Monoxide Sensor</td>
<td>CO (Carbon Monoxide) Gas Sensor</td>
<td></td>
<td>1</td>
<td>N/A</td>
<td>Parallax</td>
<td>Parallax</td>
<td>10</td>
<td>$5.99</td>
<td>$59.90</td>
</tr>
<tr>
<td>6</td>
<td>Contact Adhesive</td>
<td>Adhere foam parts together</td>
<td></td>
<td>1</td>
<td>1 day</td>
<td>-</td>
<td>Home Depot</td>
<td>-</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>7</td>
<td>Filter</td>
<td>3/4 in. Geometric Filters</td>
<td></td>
<td>8</td>
<td>-</td>
<td>In-Stock CNS AeroLab</td>
<td>SKC</td>
<td>5</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>8</td>
<td>Flag</td>
<td>Sticker for payload</td>
<td></td>
<td>1</td>
<td>1 day</td>
<td>-</td>
<td>Ace</td>
<td>-</td>
<td>$3.59</td>
<td>$3.59</td>
</tr>
<tr>
<td>9</td>
<td>Gas Sensor Board</td>
<td>Gas Sensor Board</td>
<td></td>
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<td>N/A</td>
<td>Parallax</td>
<td>Parallax</td>
<td>10</td>
<td>$24.99</td>
<td>$249.90</td>
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<tr>
<td>10</td>
<td>Heater</td>
<td>Electric Heating Pad</td>
<td></td>
<td>3</td>
<td>1 week</td>
<td>Aeadraft</td>
<td>ACE</td>
<td>10.12</td>
<td>$4.99</td>
<td>$49.90</td>
</tr>
<tr>
<td>11</td>
<td>Hot Glue Gun</td>
<td>Hot Glue Gun</td>
<td></td>
<td>1</td>
<td>1 day</td>
<td>Ace</td>
<td>Ace</td>
<td>5.99</td>
<td>$5.99</td>
<td>$5.99</td>
</tr>
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<td>12</td>
<td>Hot Glue Gun Sticks</td>
<td>Glue Sticks</td>
<td></td>
<td>1</td>
<td>1 day</td>
<td>Ace</td>
<td>Ace</td>
<td>8</td>
<td>$7.99</td>
<td>$79.90</td>
</tr>
<tr>
<td>13</td>
<td>Lipo Battery charger</td>
<td>Micro Lipo w/ Micro USB Jack - USB LiIon/LiPoly charger</td>
<td></td>
<td>1</td>
<td>2 day</td>
<td>Aeadraft</td>
<td>Aeadraft</td>
<td>-</td>
<td>$6.95</td>
<td>$69.50</td>
</tr>
<tr>
<td>14</td>
<td>Lipo Battery charger</td>
<td>Micro Lipo w/ USB Type B - LiIon/LiPoly charger</td>
<td></td>
<td>1</td>
<td>1 day</td>
<td>Sparkfun</td>
<td>Ace</td>
<td>-</td>
<td>$7.99</td>
<td>$79.90</td>
</tr>
<tr>
<td>15</td>
<td>Male battery connector</td>
<td>JST Male Battery Connectors</td>
<td></td>
<td>1</td>
<td>2 weeks</td>
<td>Amazon</td>
<td>Amazon</td>
<td>12</td>
<td>$12.10</td>
<td>$121.00</td>
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<td>16</td>
<td>Microcontroller Kit</td>
<td>2560 Arduino Mega</td>
<td></td>
<td>1</td>
<td>3 weeks</td>
<td>Arduino</td>
<td>Arduino</td>
<td>37</td>
<td>$10.99</td>
<td>$109.90</td>
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<td>17</td>
<td>Noodle</td>
<td>Noodle for rotary mechanisms</td>
<td></td>
<td>3</td>
<td>-</td>
<td>AEROSOLUTION AEROSOLUTION</td>
<td>10</td>
<td>$0.00</td>
<td>$0.00</td>
<td></td>
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<tr>
<td>18</td>
<td>Outer Sensor</td>
<td>MQ131 Ozone Gas Sensor 12-bit</td>
<td></td>
<td>1</td>
<td>3-5 days</td>
<td>Control Everything</td>
<td>National Control Devices</td>
<td>10</td>
<td>$42.95</td>
<td>$429.50</td>
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<td>Payload Containter</td>
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<td>N/A</td>
<td>N/A</td>
<td>105</td>
<td>$0.00</td>
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<td>20</td>
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<td>3D filament, PLA - BLACK for rotary Mechanism</td>
<td></td>
<td>1</td>
<td>4-5 day</td>
<td>Dazzle Light</td>
<td>Amazon</td>
<td>-</td>
<td>$14.90</td>
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<td>21</td>
<td>Pcb Board</td>
<td>Pcb Proto Half-Sized Breadboard PCB</td>
<td></td>
<td>2</td>
<td>2 day</td>
<td>Aeadraft</td>
<td>Aeadraft</td>
<td>12</td>
<td>$4.30</td>
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<td>Pump</td>
<td>T2-04 Miniature Diaphragm Pump</td>
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<td>Relay Board</td>
<td>Relays used to supply external power to heaters and pumps</td>
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<td>2-3 days</td>
<td>Panasonic</td>
<td>MSE</td>
<td>15</td>
<td>$4.00</td>
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<td>Rotary Mechanism</td>
<td>Filter Rotary Mechanism</td>
<td></td>
<td>1</td>
<td>-</td>
<td>AEROSOLUTION AEROSOLUTION</td>
<td>185.5</td>
<td>-</td>
<td>-</td>
<td></td>
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<tr>
<td>25</td>
<td>SD Card Reader</td>
<td>Sandisk Ultra 32GB Micro SDHC UHS-I Card with Adapter</td>
<td></td>
<td>1</td>
<td>1 week</td>
<td>Sandisk</td>
<td>Amazon</td>
<td>0.5</td>
<td>$12.10</td>
<td>$12.10</td>
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<tr>
<td>26</td>
<td>Servo</td>
<td>Feedback 360 Degree - High Speed Continuous Rotation Servo</td>
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<td>1</td>
<td>2 day</td>
<td>Aeadraft</td>
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<td>40</td>
<td>$10.95</td>
<td>$438.00</td>
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<td>Switch</td>
<td>SPST Toggle Switch</td>
<td></td>
<td>1</td>
<td>1 day</td>
<td>MSE</td>
<td>MSE</td>
<td>15</td>
<td>$4.00</td>
<td>$60.00</td>
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<td>Tape</td>
<td>Aluminum Tape</td>
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<td>1 day</td>
<td>Nishua</td>
<td>Home Depot</td>
<td>30</td>
<td>$7.88</td>
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<td>Test Batteries</td>
<td>5PCS Temperature Sensors TMP010 Precision Linear Analog Output For Arduino Raspberry Pi</td>
<td></td>
<td>1</td>
<td>2 days</td>
<td>KYOKYE</td>
<td>Amazon</td>
<td>2</td>
<td>$0.99</td>
<td>$1.98</td>
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<td>30</td>
<td>Test Batteries</td>
<td>Energizer E522 Max 9V Alkaline battery Exp 11/22 or later</td>
<td></td>
<td>1</td>
<td>4-5 day</td>
<td>Energizer</td>
<td>Amazon</td>
<td>-</td>
<td>$8.99</td>
<td>$89.90</td>
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<td>31</td>
<td>Toshiba</td>
<td>Toshiba 1/2 in. O.D. x 3/8 in. I.D. x 25-8. Polyethylene Tubing</td>
<td></td>
<td>1</td>
<td>1 day</td>
<td>Everbilt</td>
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<td>Voltage Regulator</td>
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<td>2 day</td>
<td>Digikei</td>
<td>Digikei</td>
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<tr>
<td>33</td>
<td>Wires</td>
<td>20 AWG Solid Core Wire</td>
<td></td>
<td>1</td>
<td>2-3 days</td>
<td>Sparkmax</td>
<td>Sparkmax</td>
<td>40</td>
<td>$10.95</td>
<td>$438.00</td>
</tr>
</tbody>
</table>

**Total:** $1738.90

## 5 Test Plans and Results

### 5.1 Structural Testing

#### 5.1.1 Drop Test

To prepare for launch, there were a motley of tests conducted to check the integrity of the payload’s structure. The project should be able to withstand large impact, centripetal forces, and rapid chaotic motion. These were simulated in the Drop Test, Whip Test, Stair Test, and Jostling Test, to observe possible deformation, breaks, and stress. Numerous trials of the Drop Test were conducted with the various tape options to determine the optimization of strength versus weight. It was concluded that aluminum tape would minimize weight while yielding the strongest structural rigidity required to withstand the expected forces exerted on the payload during the flight.
5.1.2 Whip Test
Whip Testing simulates centripetal forces acting upon the payload during launch. A mock payload was built to weigh 1kg and then strung up on paracord; it was whipped around steadily for a minute and then chaotically for another minute. AEROSOLUTION conducted the whip test on July 2\textsuperscript{nd} and concluded that at max weight parameters the payload remained on the flight string for the entire duration of the test without showing signs of stress in the material. The test supported the new payload design with the joints only being connected by aluminum tape and the walls at a 70° angle with respect to the base.

5.1.3 Stair Test
To test the payload’s resilience to chaotic motion and impact a Stair Test was performed on July 2\textsuperscript{nd} where the team built a 1kg mock payload and tossed it down a staircase. The stair test was successful, resulting in no structural damage and the washers and flight tube remained secure. It could be determined, based off the evidence from testing, that the structure was sturdy enough to withstand impact.
5.1.4 String Up Test
The string up test was performed to observe how well the flight tube and washers were integrated to the payload. A 1kg payload was mocked up with the flight tube and string running through the center and 2 paper clips securing it in place. A team member stood at the top of the stairs and dropped the structure while holding the flight string. Chaotic motion was induced as the payload jostled around, however it remained on the flight string due to the knot tied at the bottom. One of the paperclips failed causing the flight tube to slip out of place and resulted in a design change to use a thicker gauge wire instead of a paper clip.
5.2 ENVIRONMENTAL TESTING

5.2.1 Cold Test
The team conducted two cold tests to determine the payloads ability to withstand the temperature change in the expected conditions at 100,000 feet. The conditions were mimicked by placing the payload inside a cooler with dry ice for two hours, which is known as the “cooler test”. Certain components like the pump specified an operating temperature above freezing. Therefore, temperature sensors were secured to the components of interest which allowed the team to monitor the temperature and control when the heaters would initialize. These critical components include the pump, ozone sensor, servo motor and microcontroller. The lowest temperature recorded inside of the payload was 6 °C. This indicated that the cooler test was sufficient to determine the behavior of the payload when atmospheric temperature could reach -30 °C or lower. The test concluded that the payload was well insulated and didn’t require the heaters to be powered for a very long duration, which in turn increases the operating time of the batteries. It also assured the team that all the components were able to continue to function at low temperatures, especially the servo motor which commanded the rotary filter mechanism. In Figure 11, proper indexing due to the servo was demonstrated during the experiment, signifying that the heaters prevented the rotary mechanism from warping, which would have resulted in failure.

![Servo Angle vs Time](image1)

Figure 11. Servo Angle versus time in the cold test

5.3 FUNCTIONAL TESTING

5.3.1 Flat Sat Test
AEROSOLUTION performed multiple functional tests with the payload prior to the scheduled launch on July 28, 2018. These Flat-Sat tests were performed to develop a better understanding of how the electrical components and software would function individually and when integrated
together. The Arduino IDE software program was used to write the code that would be uploaded into the Arduino Mega microcontroller. Separate code was written for the ozone sensor, altimeter, temperature sensors, servo, microSD card reader/writer, and relays for the pump and heaters. The final Flat-Sat tests with all components integrated together was performed in the two weeks prior to the launch. These tests proved to be successful and therefore all the components were more permanently connected using solder or using quick release pin connections.

### 5.3.2 Ozone Sensor Colocation Test

The ozone sensor purchased needed to be calibrated before the flight. After conducting a phone interview with Mr. Greg Harshfield from the Colorado Air Pollution Control Division, he suggested AEROSOLUTION should “conduct a colocation experiment with the ozone sensor and a Fort Collins ground-based monitoring system” [6]. On July 12, 2018 the ozone sensor was placed next to an ozone analyzer inlet next to the CSU campus for two hours, then the data collected was compared minute-by-minute. The results showed that the purchased sensor was consistently reading about 50 ppb above the data from the ground station, signifying a DC offset. The code was altered to adjust for the offset.

![Figure 12. Comparison of ozone concentration readings over 2 hours](image)

### 6 Launch and Recovery

On July 28 the team’s payload successfully launched in Deer Trail Colorado (Figure 13) at 6:36 A.M. The flight string carried a total of nine payloads to a max elevation of 100,274 ft [7]. The flight ran for two hours and two minutes and landed at 8:38 A.M. (Figure 14). A 1.2-mile hike to recover the payloads began once access to private property was granted. The filter mechanism was found to be in the closed position and the batteries were completely drained since the LED light indicating power was not on.
7 DATA AND ANALYSIS

7.1 RESULTS
The post launch process was to bring the payload back to the Powerhouse where the SD card was read and the filters were measured. The results from the SD card weren’t as expected. Essentially the data showed that the instrument seemed to have completely restarted right as the high-altitude balloon launched. Then the altimeter module MS5607 read up to 0.071 km before suddenly reading the elevation to be at 0 km. It repeated this anomaly of reaching 0.071 km and then returning to zero, 12 times over the course of 24 minutes before abruptly reading zero for the rest of the flight.
Due to the sensor not correctly reading the altitude, it was only able to trigger the servo motor to index to the first filter, as the next altitude step wasn’t until 3.44km. Give the 3:1 gear ratio, the servo position was at 120° for the filter 1. Therefore, only the first filter was exposed and kept that status for the entire ascent.

![Angle of Servo vs Elevation](image)

**Figure 15.** The servo motor indexed to the first filter at 120 degrees and remained exposed for the duration of the flight due to issue with altimeter

All the filters were measured in the gravimetric and SootScan optical transmissometer, while just the first filter which had been exposed was measured in the XRF machine. A gravimetric machine weighs the filter prior to being loaded by particulates and then immediately after being exposed for the experiment to determine the mass of $PM_{10}$ that had been collected on the filter. If the mass value exceeds 51µg, then it’s within the limit of quantification, which means it is rated at moderate or above on the AQI (see Table 1); however, that’s not often seen in Colorado, especially in less urban areas such as Deer Trail [8].

![3D printed filter cassette](image)

**Figure 16.** The 3D printed filter cassette which houses a control filter as well as eight exposed filters
Table 3. Mass of particulate matter measured by the gravimetric machine

<table>
<thead>
<tr>
<th>Filter</th>
<th>Particulate Matter Mass (µg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>4.7</td>
</tr>
<tr>
<td>1</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>10.3</td>
</tr>
<tr>
<td>3</td>
<td>22.7</td>
</tr>
<tr>
<td>4</td>
<td>13.3</td>
</tr>
<tr>
<td>5</td>
<td>11.7</td>
</tr>
<tr>
<td>6</td>
<td>17.0</td>
</tr>
<tr>
<td>7</td>
<td>11.7</td>
</tr>
<tr>
<td>8</td>
<td>9.3</td>
</tr>
</tbody>
</table>

The SootScan detects the mass of black carbon (BC) - a type of aerosol - on the filters using ultraviolet and infrared absorption. The machine measures the absorption of light due to the BC and calculates the attenuation using Equation 13 from Appendix A. That then can be used to solve for the mass of BC using Equation 12 from Appendix A.

Table 4. Mass of black carbon measured by the SootScan optical transmissometer

<table>
<thead>
<tr>
<th>Filter</th>
<th>Black Carbon Mass (µg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>

Ozone concentration was collected over the entirety of the ascent, however, without altimeter data it was difficult to create a vertical profile of the pollutant. AEROSOLUTION normalized UVVDU’s GPS data to determine the velocity of the balloon. The data was then multiplied by each time step, yielding estimated altitudes. A vertical profile was plotted, showing the max ground-level ozone concentration in the troposphere occurred at 10km and reached 130ppb.
Upon further inspection of the payload it was noted that there was an issue with the wiring for the ON/OFF switch. The switch uses two leads that were connected directly to the power supply. The ground wire for the switch had been spliced and soldered to another wire so it could reach the proto board; however, it was noted after launch that the connection was partly broken due to fatigue. Therefore, upon any large acceleration or change in speed the circuit would disconnect and restart the Arduino. This would explain why the instrument reset when the balloon launched. Despite the wire damage, the rest of the circuitry inside the payload remained unharmed, further supporting the reusability of the payload.

7.2 ANALYSIS
After observing the issue with the altimeter, the manufacturer was contacted to help troubleshoot whether the sensor was faulty or if there were hardware and/or software complications. According to Parallax, Inc. there were a few possibilities to explain the irregular altitude readings. To wire and code the module there are two choices for interfaces to use: inter-integrated circuit communication ($I^2C$) or SPI, the sensor’s default interface was $I^2C$. Parallax stated that while both interfaces can be used, SPI is more user-friendly since $I^2C$ can lead to very complicated coding. Therefore, it’s possible the code that was imported into the Arduino didn’t have a good enough bit resolution or could have been written differently to account for the complexity. However, to use the SPI interface, an SDI port would be needed and the only port on the board was occupied by the SD card reader, which was essential for collecting data. To combat the fluke then, the code can be revised with the assistance of the manufacturer to solidify the $I^2C$ interface and increase the bit resolution, or AEROSOLUTION could purchase the same GPS module (Ublox NEO-6M) as UVVDU because it worked for them during the launch.
After retrieving the data on the Teflon membrane filters from the machines in the Aerosols Lab, the results suggest the design allowed for contamination. This was observed because only the first filter was exposed through the nozzle during the flight, so it should have been the only one to collect particulate matter. While it did collect the most out of all the filters – weighing at 28µg – some of the other filters collected quite a lot as well, in particular, filter 3 weighed 22.7µg. Due to contamination, the team was prompted to revise the design. The nozzle could have an O-ring to create an air tight seal between itself and the lip of the filter opening. To prevent issues with friction between PLA and rubber, vacuum seal lubricant could be applied to the ring. Colorado Air Pollution Control Division collected 17µg of PM$_{10}$ during the launch hours at the Adams County monitoring site (the closest site to Deer Trail). It was difficult to determine the accuracy of the device because the first filter was over exposed to the atmosphere. However, the measurements indicate there were aerosols present, although not enough to exceed 51 on the AQI, which supports part of the hypothesis.

Another item to note was the amount of black carbon present on each filter. The mass of each was about 1µg, with exception of the second and eighth filters, which weighed 2µg. In comparison to the overall weight of particulate matter on each filter, it can be surmised that in Deer Trail, CO there isn’t much black carbon, but there are aerosols present. Therefore, the aerosols were likely comprised of translucent particles like salts such as sulfate and nitrate. According to Figure 1, the sources could have been more anthropogenic, which suggests that the populace should be wary of the chemicals being released into the air and which specific sources could be producing air pollutants.

The predicted lineation of ozone through the atmospheric column was supported by the data collected. As observed in Figure 17, the sensor detected higher ozone emissions within the upper level of the troposphere and then rapidly decreased. When the payload reached the stratosphere the concentration increased dramatically, implying it reached the ozone layer. The hypothesized peak value for ground level ozone was 70 ppb; while the Colorado Air Pollution Control Division measured 57ppb for ground-level ozone in Aurora East (the closest site to Deer Trail that measured ozone). While the hypothesis was nearly accurate to the CAPCD, the actual experimental data differed from the given data by +73ppb. It’s possible that the discrepancy is due to the different locations (Aurora East versus Deer Trail) or maybe needing to have recalibrated the sensor. With the motely of factors to take into consideration, it was difficult to determine the accuracy of the measurements from the ozone sensor.

8 CONCLUDING REMARKS

The NASA Colorado Space Grant is a rigorous internship that pushes teams to become more knowledgeable and inquisitive. Extreme attention to detail when it came to design was paramount to the fabrication and testing of the project. Even so, the results came out unexpectedly due to a malfunction with the $I^2C$ interface for the altimeter, contamination, and faulty connection in the ground wire for the switch. If a relaunch were to occur, AEROSOLUTION would have to redesign and reconfigure some aspects of the project but it would more likely undergo a successful launch in terms of functioning as designed. The data collected would have to undergo further analysis in
the Aerosols Lab to determine the speciation of the particulates and the accuracy of $PM_{10}$. Overall, it was a demanding project that pushed each member to hone their problem-solving skills and pursue a goal under difficult constraints, resulting in an intriguing and innovative research project.

9 MESSAGE FOR FUTURE TEAMS

This is a valuable growing experience for engineering students - relish the opportunity to tackle the challenges ahead! Also, be prepared to go through many iterations of the overall objective and design chosen for the payload, as there will be a lot of factors that instigate changes and redirect the initial plan. Furthermore, it’s highly suggested to take meeting minutes every day. This helps keep the team focused on what has been accomplished and which items need to be taken care of from there and is also a great way to communicate with coworkers. Good luck!

10 ACKNOWLEDGMENTS

AEROSOLUTION had a great deal of support from a number of people, and if it had not been for their resources and information, the project wouldn’t have been as successful. First, thank you to Dr. Azer Yalin, supervisor, and Mr. Adam Friss, advisor, for the guidance and advice as well as providing the team with access to the Laser Lab, which had a motely of materials and tools that were crucial to completing the project. Also, many thanks to Mr. Christian L’Orange who contributed by giving AEROSOLUTION twelve free Teflon membrane filters, trained two of the members on the optical transmissometer, and took the time to measure the filters in the gravimetric and XRF machines. Finally, Greg Harshfield from the Gaseous Pollutants Unit at the Colorado Air Pollution Control Division was a huge help by driving from Denver to Fort Collins to assist in an ozone colocation test to calibrate the ozone sensor. Finally, the team would like to recognize UVVDU, the other CSU team, who offered their data to be extrapolated after the launch.
11 BIBLIOGRAPHY


12 APPENDIX

12.1 APPENDIX A: CALCULATIONS

Pressure and Density Calculations

For \( h < 11,000 \)

\[
T = 15.04 - 0.00649 \times h \quad \text{Equation 1}
\]

\[
P = 101.29 \times \left[ \frac{T + 273.1}{288.08} \right]^{5.256} \quad \text{Equation 2}
\]

For \( 11,000 < h < 25,000 \)

\[
T = -56.46 \quad \text{Equation 3}
\]

\[
P = 22.65 \times e^{1.73 - 0.000157 \times h} \quad \text{Equation 4}
\]

For \( h > 25,000 \)

\[
T = -131.21 + 0.00299 \times h \quad \text{Equation 5}
\]

\[
P = 2.488 \times \left[ \frac{T + 273.1}{216.6} \right]^{-1.388} \quad \text{Equation 6}
\]

Where:

\( T \equiv \text{Temperature (}^\circ\text{C)} \)

\( P \equiv \text{Pressure (kPa)} \)

\( h \equiv \text{height (m)} \)

Bernoulli’s Equation:

\[
P_i + \frac{\rho_i v_i^2}{2} + \rho_i \times g_i \times h_i = P_o + \frac{\rho_o v_o^2}{2} + \rho_o \times g_o \times h_o \quad \text{Equation 7}
\]

Solve for \( v_o \):

\[
v_o = \sqrt{\frac{2(P_i - P_o)}{\rho} + v_i^2} \quad \text{Equation 8}
\]

Where:

\( P \equiv \text{Pressure (kPa)} \)

\( \rho \equiv \text{Density} \left( \frac{kg}{m^3} \right) \)

\( v \equiv \text{Velocity} \left( \frac{m}{s} \right) \)

\( g \equiv \text{Gravity} \left( \frac{m}{s^2} \right) \)
\( h \equiv \text{Height (m)} \)

**Volumetric Flow Rate:**

\[
\dot{V} = v_o \cdot A
\]

Equation 9

Where:

\[
\dot{V} \equiv \text{Volumetric Flow Rate} \left( \frac{m^3}{s} \right)
\]

\[
v \equiv \text{Velocity} \left( \frac{m}{s} \right)
\]

**Area of Circle:**

\[
A = \pi \cdot r^2
\]

Equation 10

Where:

\[
A \equiv \text{Area} \left( m^2 \right)
\]

**Mass Flow Rate:**

\[
\dot{m} = \rho \cdot \dot{V}
\]

Equation 11

Where:

\[
\dot{m} \equiv \text{Mass Flow Rate} \left( \frac{kg}{s} \right)
\]

**Calculating Black Carbon using SootScan Transmissometer:**

\[
BC = \frac{Atn}{\sigma}
\]

Equation 12

\[
Atn = 100 \cdot \log \left( \frac{s}{S} \right)
\]

Equation 13

\[
\sigma = 12.4
\]

Equation 14

Where:

\[
BC \equiv \text{Black Carbon} \left( \frac{\mu g}{m^2} \right)
\]

\[Atn \equiv \text{Attenuation} \]

\[S \equiv \text{Signal} \]

\[B \equiv \text{Blank} \]

\[\sigma \equiv \text{Constant} \]
12.2 APPENDIX B: GRAPHS

Figure 18. Atmospheric temperature versus altitude

Figure 19. Atmospheric pressure versus altitude

Figure 20. Atmospheric air density versus altitude