Project HALO (High Altitude Lafayette Observatory)
A Community Engagement Project at Purdue University

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Executive Summary

Project HALO was an outreach and engagement project completed in the summer of 2019 by Purdue University's School of Aeronautics and Astronautics. Under the guidance of an aero/astro Ph.D. student, ten high school juniors and seniors from schools in the Lafayette/West Lafayette area designed, built, launched, and recovered a high-altitude balloon over the course of six weeks from mid-June to late July.

This endeavour was motivated by two things: (1) a desire to provide interested students an opportunity to pursue an ambitious, real-world engineering challenge and (2) to commemorate the 50th anniversary of the Apollo 11 moon landing. The construction of a high-altitude balloon payload was chosen as a project appropriate for both the student participants and the resources available in Purdue's School of Aeronautics and Astronautics. Construction of such a payload requires the design of mechanical, electrical, and computer systems, as well as successful integration of all of these systems; the reward is a clear and tangible result with the ability to inspire students. The balloon also offers a compelling vehicle for engaging the broader community as the concept is simple to understand but still impressive in scope for a typical layperson.

Students participating in Project HALO were recruited from local schools, with team members coming from Harrison, McCutcheon, and West Lafayette High Schools. The team met twice a week at Purdue University, utilizing the design and fabrication spaces typically used by undergraduate students for their senior design projects. Students broke into teams to design the instrumentation, communication, and recovery systems, as well as build the payload structure and program the flight computer. Students also ran simulations to predict the flight path and landing location of the payload. Funding from the Purdue University School of Aeronautics and Astronautics and the Indiana Space Grant Consortium (INSGC) supported the costs of the balloon, helium tank, and the flight hardware and other supplies required to construct and launch the payload.

The Project HALO payload was launched on July 27th, 2019; it completed a flight of approximately 2.8 hours, reaching an estimated peak altitude of approximately 30,000 meters. It was recovered by parachute approximately 20 km south of the launch point by an unaffiliated citizen near Romney, IN. Data on atmospheric pressure and carbon dioxide concentrations were collected and video footage recorded for the first 24,000 meters of the flight before failure of the payload's power systems.

Students involved in the project described their experiences very favorably, with many reporting a sharpened interest in pursuing science and engineering careers. Through pre- and post-project surveys, all students reported an increase in their understanding of the engineering design process, the distinctions between engineers and scientists, and their abilities to lead teams solving technical problems.

1 Overview

Project HALO was a collaborative community engagement project undertaken at Purdue University in conjunction with three local high schools. Over the course of six weeks, the high school students used Purdue facilities and resources to construct and launch a high-altitude balloon payload.

The motivation for this project was threefold: to engage students in the community with an interest in STEM careers with a meaningful, real-world engineering challenge; to bring together members of the community who would not ordinarily have the chance to work together; and to commemorate the 50^{th} anniversary of the Apollo 11 landing.

2 Team

Students for Project HALO were recruited by contacting science teachers at four high schools in the Greater Lafayette area - West Lafayette, Harrison, McCutcheon, and Jefferson high schools. Unfortunately, no teachers at Jefferson High School returned emails, but a diverse team of ten students was formed from students at the remaining schools. The ten students who were nominated by their teachers were a mix of rising seniors and juniors with an interest in pursuing degrees in STEM fields.

Due in large part to the funding allocation process being delayed by the 2018-2019 government shutdown, the recruitment process was somewhat rushed by the impending end of the school year. Nonetheless, by mid June, the team was assembled; the students met approximately twice a week for six weeks to plan, design, and build the high altitude balloon payload.

3 Payload Summary

The payload consisted of sensors to measure atmospheric quantities (temperature, pressure, and CO_2 concentration) as well as video and still cameras and a radio-based GPS position reporting system.

The launch train consisted of a single foam payload structure with a 58-inch recovery parachute suspended from a 1200 g Kaymont high-altitude balloon. The payload was designed using a Raspberry Pi computer equipped with sensors to measure ambient temperature, pressure, and carbon dioxide concentration, along with three-axis acceleration. The primary objective of the Project HALO payload was to measure atmospheric profiles of temperature and carbon dioxide concentration.

Structure

The payload structure was built primarily from sheets of 2" extruded polystyrene (XPS) foam, cut to fit into a rectangular prism using a CNC hot wire cutter. An internal structure for mounting mission-critical components was assembled from 3 mm hobby-grade plywood components cut with a CNC laser cutter.

Rough calculations of conductive heat transfer through the foam walls were performed assuming basic Fourier conduction with the conjugate heat transfer problem solved in the time domain for the duration of a nominal flight length. These calculations suggested that for a sufficiently small internal volume, the heat produced by the flight computer would likely be sufficient to ensure adequate temperature (approximately 0 C or greater) within the payload enclosure to allow the electronics to function throughout the flight (see Figure 1).

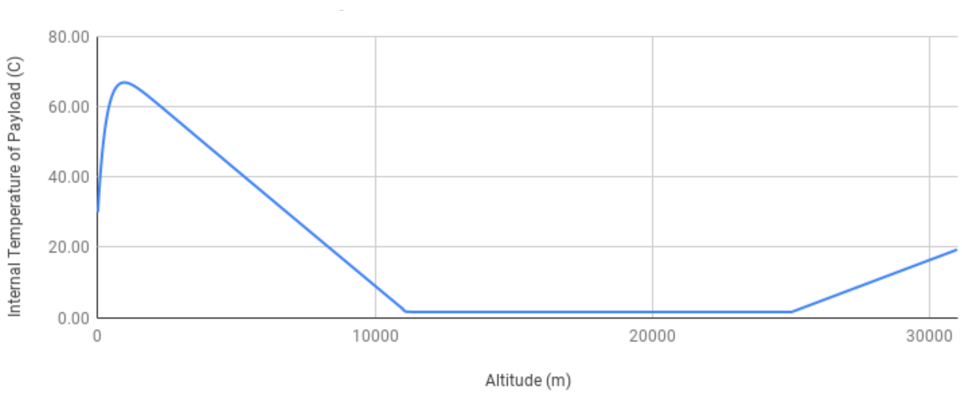


Figure 1: Predicted payload bay temperature

Flight Computer

The core of the payload was a Raspberry Pi 3B+ running a collection of Python 3 scripts for sensor reading and data logging as well as transmitting tracking data. The flight computer (and its associated sensors) were powered by a 10000 mAh lithium ion battery which was estimated to provide several hours of power.

Instrumentation

The HALO team decided to equip the payload with sensors to measure ambient temperature, pressure, and carbon dioxide concentration, along with a three-axis accelerometer and still and video cameras. These sensors (shown in Table 1) were chosen to provide a useful assortment of atmospheric measurements throughout the balloon's flight.

Sensor	Description	Purpose
Accelerometer	Adafruit Triple-Axis Accelerometer	Characterizing payload motion
Pressure sensor	Adafruit MPRLS Ported Pressure Sensor	Measuring ambient pressure for altitude calculations
Temperature sensor	Waterproof DS18B20 Digital temperature sensor	Measuring ambient temperature profile
Carbon dioxide sensor	MH-Z14A NDIR Infrared Carbon Dioxide Sensor Module	Measuring atmospheric carbon dioxide levels
Video camera	GoPro Hero 3+	Recording footage of the launch, flight, and recovery
Still camera	Raspberry Pi Camera	Recording still images of the flight
GPS receiver	Adafruit GPS breakout	Obtaining location for tracking purposes

Table 1: Sensor suite for the Project HALO payload

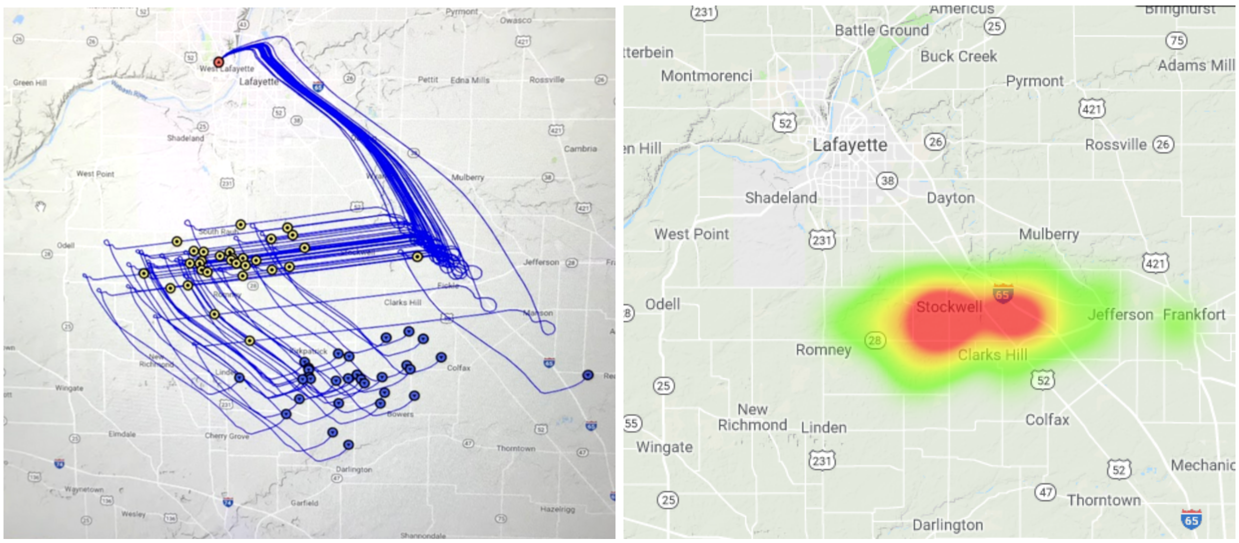
Tracking

To aid in recovery of the balloon payload, a simple Automatic Packet Reporting System (APRS) tracking system was implemented. This consisted of a GPS receiver connected to the flight computer, which was in turn used as a radio signal generator to create APRS packets, which were transmitted as audio signals using a Dire Wolf "software soundcard". These signals were transmitted using a quarter-wave ground plane antenna, to be received by the network of web-linked amateur repeater stations.

4 Flight Summary

4.1 Preparation

The HALO payload was equipped with a 58-inch ripstop nylon parachute for recovery and launched using a 1200 g Kaymont high-altitude balloon. A series of flight predictions was made using the University of Southampton's ASTRA High Altitude Balloon Flight Planner [1], showing a likely landing site approximately 25 km southeast of the launch site on Purdue's campus. Estimated flight time was approximately 2 hours.



(a) Family of predicted flight paths

(b) Predicted landing zones

Figure 2: In-flight images from the downward-facing camera

4.2 Launch

Following successful inflation of the balloon and assembly of the payload, launch occurred at 0940 on Saturday, July 27th, 2019. Difficulties in securing the parachute lines to the payload led to an unsteady ascent, with the payload visibly spinning around its vertical axis. Otherwise, the launch was smooth and the balloon drifted immediately to the east.

4.3 Recovery

Signal contact with the payload (via the APRS tracking network) was lost shortly after launch, so the exact flight path of the mission remains unknown. However, the payload descended by parachute into a field near Romney, IN, where it was recovered by a passerby and reported back to the launch team. Estimated time of landing was approximately 1225. Upon recovery, the payload appeared to be in excellent shape, with no external or internal damage except for the antenna radials, which were destroyed upon landing. Notably, the camera and computer were both powered down, presumably due to discharged batteries.

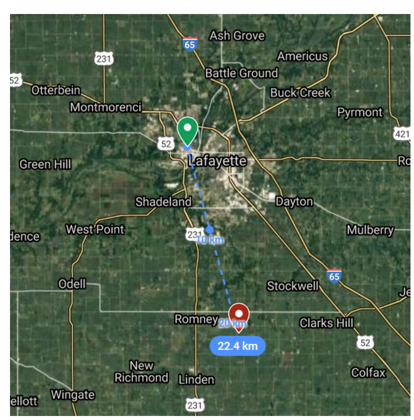


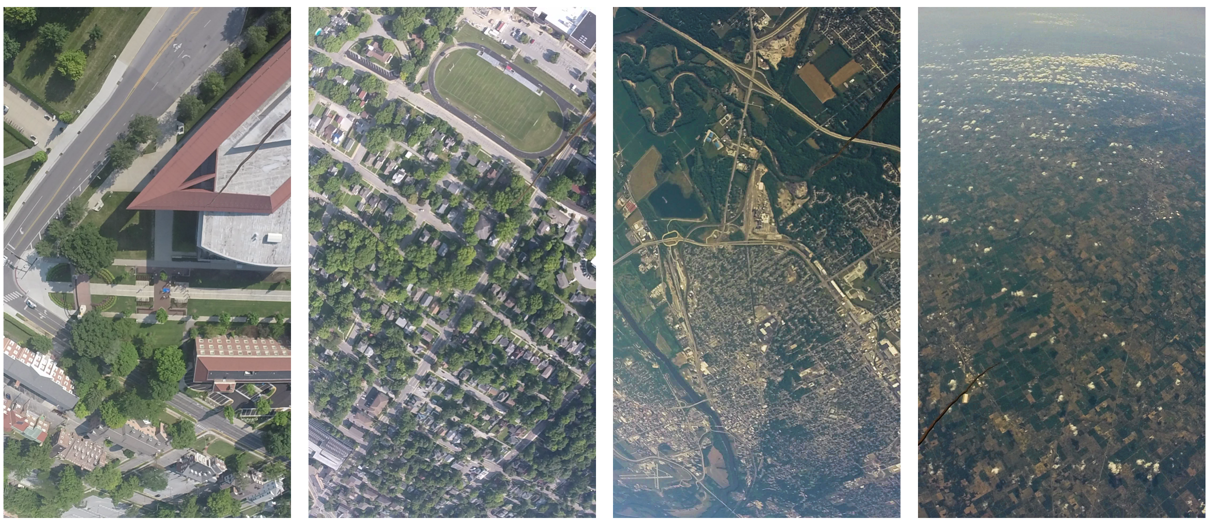
Figure 3: Launch and landing locations for the Project HALO payload

5 Data Analysis

Data were collected up to a pressure altitude of 23,966 m at two-minute intervals. However, the payload did not record any data during its descent - the final recorded measurements were written at 1.8 hours after launch, or just shy of an hour before the payload was recovered. This, combined with the fully-discharged state of the batteries at the end of the flight suggest that the batteries discharged prematurely, likely due to lower-than-expected temperatures within the payload enclosure. In addition, an unidentified instrumentation error prevented the temperature sensor from recording data during the flight.

5.1 Images

The GoPro camera mounted on the vehicle underside recorded video throughout the flight (until battery failure); still images taken from this footage are included below in Figure 4. The images provide a representative notion of the payload's flight path, which started on Purdue's campus, drifted over West Lafayette and Lafayette, and proceeded predominantly south.



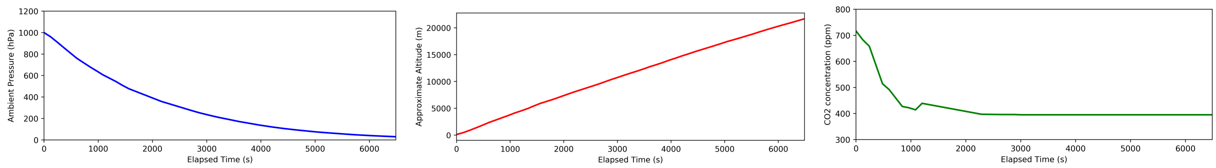
(a) (b) (c) (d)

Figure 4: In-flight images from the downward-facing camera

Figure 4(a) shows the launch site outside of Armstrong Hall on Purdue's Engineering Mall; Figure 4(b) shows West Lafayette Junior/Senior High School; Figure 4(c) shows the edge of Lafayette; and Figure 4(d) shows a view from an estimated altitude of 24,000 m.

5.2 Atmospheric Measurements

Data from the Project HALO payload are shown in Figure 5 as functions of mission elapsed time. Based on the recorded ambient pressure, the pressure altitude of the payload was calculated throughout the recorded portion of the flight using a standard atmospheric model - this altitude history shows that the payload rose at a consistent rate of 2.1 m/s until the flight computer died. Measurements of atmospheric carbon dioxide concentration (recorded in parts per million) show a significant peak near the ground.



(a) Ambient Pressure Measurements

(b) Estimated Flight Altitude

(c) Carbon Dioxide Concentration Measurements

Figure 5: Flight data from the Project HALO payload

Comparison of the carbon dioxide concentration measurements shows approximate agreement with expected values. Figure 6 shows the measured values plotted with respect to ambient pressure; in addition to the data recorded by the HALO payload, profiles generated by (1) the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS), a space-based instrument, and (2) the TM5 atmospheric chemistry model are provided. These comparison data are taken from a paper by Foucher at al. [2]; they cover the approximate latitude of the HALO flight and were recorded in July 2008. Agreement is strong above 300 hPa, corresponding to a pressure altitude of approximately 9150 m. Below this altitude, the HALO payload appeared to record a drastically higher concentration of carbon dioxide, perhaps as a result of its launch from a semi-urban area (for example, the launch point was on Purdue's campus, only a few meters away from a major road intersection). A few unexplained data dropouts in the carbon dioxide measurements (or example, between 600 and 300 hPa in Figure 6) make it difficult to track the decrease in measured carbon dioxide concentration with increasing altitude.

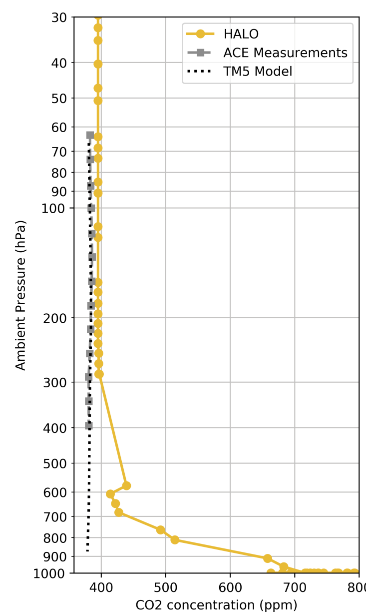


Figure 6: Comparison of CO_2 measurements to experimental and modeled data

6 Student Evaluation

Students were surveyed before the project began and after it ended to get a sense of how their experiences shaped their perceptions of engineering, science, and the technical design process. Due to the small sample sizes, the results of these surveys do not achieve statistical significance but they are presented below nonetheless as a semi-quantitative metric for the educational value of the program.

The first portion of the pre- and post-project surveys asked the students to choose five words from a list of 16 adjectives (in random order) which they felt best described engineering. The frequency with which each word was selected was calculated from both the pre- and post-project surveys; the difference in word incidence was calculated and is shown in Figure 7.

Students' responses indicated the largest increases in the incidence of the words "Inspirational" and "Methodical" and the largest decreases in the incidence of the words "Scientific" and "Mathematical". Overall, this heuristic supports observations that over the course of the project, students developed a more nuanced view of the engineering design process - they began to see engineering as an endeavour in which worthwhile goals are achieved through collaboration and carefully-reasoned choices rather than just an abstract concept shrouded in difficult mathematics and science.

The second portion of the surveys asked students to rate their own perceptions of their own abilities and interest. Noting again that the results are not statistically significant, they are nonetheless interesting - students consistently rated themselves higher in their understanding of the engineering design process and their confidence in their technical leadership abilities. These results are tabulated in Figure 8.

Word Incidence Changes	
Inspirational	78%
Logical	19%
Methodical	78%
Multidisciplinary	33%
Collaborative	19%
Mathematical	-56%
Creative	-22%
Demanding	-11%
Difficult	-56%
Scientific	-70%

Figure 7: Changes in students' descriptors of engineering pre- and post-project

On a scale of 1-5, please rate your feelings on the following statements.											
I have a clear understanding of the engineering design process											
20%	2.875	3	3	3	2	3	4	4	1		
	3.444	4	5	2	3	2	4	3	4	4	
I have a good understanding of the differences between scientists and engineers and the ways in which they work together.											
9%	3.375	3	4	3	3	2	5	5	2		
	3.667	4	5	3	2	3	4	3	5	4	
I feel capable of leading a team to accomplish a complex technical objective.											
16%	3.250	4	3	3	2	3	5	5	1		
	3.778	5	4	3	1	3	3	5	5	5	
I am interested in potentially pursuing a career in engineering.											
11%	3.500	2	4	5	1	4	5	5	2		
	3.889	3	5	5	1	4	5	3	5	4	
I am interested in potentially pursuing a career in science.											
1%	4.625	5	5	4	5	5	5	5	3		
	4.667	5	5	4	4	5	5	5	5	4	

Figure 8: Students' self-evaluation from pre- and post-project surveys

7 Conclusions

7.1 Payload Engineering

Overall, the Project HALO team was able to design, build, and launch a successful high altitude balloon payload. The team was able to partially meet their primary goal of collecting data on the atmospheric temperature and carbon dioxide concentration profiles of the atmosphere. The payload reached a verified altitude of 24,000 m, likely peaking at closer to 30,000 m based on flight simulations, though failure of the onboard flight computer makes this impossible to prove.

Several important lessons were learned from the mishaps experienced during the launch and recovery of the Project HALO payload. Perhaps the most important concern for future payloads is the necessity of redundant tracking systems; the APRS system installed on the 2019 payload failed after launch and effectively left the team flying blind, so to speak. The installation of a secondary tracking system would make payload recovery much simpler and location data would add extra value to the in-flight measurements. Another important issue is maintaining adequate temperature within the payload bay. As mentioned above, the predicted internal temperature would have allowed the payload electronics to function adequately throughout the flight; however, the flight data suggest that the temperature dropped precipitously and caused premature failure of the electronics. Future payloads would need to incorporate better insulation and a small heating element; a temperature sensor within the enclosure could also provide a useful validation of the heat transfer model used to predict internal temperature. The last major lesson learned from the Project HALO payload was the importance of minimizing spin of the launch train. A combination of slightly haphazard parachute rigging and the essentially cubic shape of the payload both contributed to high-rate spins which decreased the quality of onboard video and placed higher strain on the internal components of the payload.

7.2 Project Management

Project HALO also satisfied its goal of enabling curious high school students to pursue a real-world engineering project and inspiring them to accomplish a difficult design challenge. Participants in the program reported a worthwhile and beneficial experience which favourably affected their views of engineering and STEM professions while helping them to develop leadership and teamwork skills.

The most critical improvements to the management of the program would likely be schedule-based; this project suffered slightly from a timeframe which was compressed by a variety of factors (government shutdown, desire to celebrate the Apollo 11 anniversary, students' summer schedules and the academic calendar, etc.). In addition to a more careful schedule, a more rigorous approach to teaching the design process to future participants and more time for testing the payload systems would be hugely beneficial.

Notwithstanding these minor issues, Project HALO was overall a successful engagement/outreach program which accomplished its goals of pursuing an engineering challenge through partnership between Purdue University and the surrounding community.

Acknowledgements

The author would like to thank several individuals and organizations who made this project possible, namely Chell Nyquist, Philip Baldwin, the Indiana Space Grant Consortium, and Purdue University School of Aeronautics and Astronautics.

References

[1] C. Paulson and A. Sóbester, "Parameterization and geometric optimization of balloon launched sensorcraft for atmospheric research missions," in *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, p. 944, 2013.

[2] P. Foucher, A. Chédin, R. Armante, C. Boone, C. Crevoisier, and P. Bernath, "Carbon dioxide atmospheric vertical profiles retrieved from space observation using ace-fts solar occultation instrument," 2011.

A Budget Summary

Item	Qty.	Description	Unit Cost	Tax	Shipping	Purchase Total
Raspberry Pi	1	Flight computer	37.52	0.00	0.00	37.52
Raspberry Pi Camera	1	Sensor package	24.98	2.59	0.00	39.56
Breadboard	1	Sensor wiring	11.99			
Pressure Sensor	1	Sensor package	14.99	3.01	10.15	46.05
Accelerometer	1	Sensor package	7.95			
Temperature Sensor	1	Sensor package	9.95			
CO2 Sensor	1	Sensor package	40.00	2.59	0.00	42.59
GoPro (used)	1	Sensor package	60.67	0.00	0.00	60.67
Parachute	1	Recovery system	32.50	0.00	8.50	41.00
Balloon	1	Launch system	75.00	0.00	10.00	85.00
10000 mAh battery	1	Payload power	24.99	4.49	0.00	52.55
Audio cable (3.5 mm jack)	1	Antenna cable	6.08			
3 mm craft plywood	1	Structure material	16.99			
Female coaxial plug	1	Antenna base/plug	7.99	2.70	0.00	41.39
Solid copper wire (12 ga)	1	Antenna material	10.35			
USB to TTL converter	1	Sensor package	12.76			
Coaxial cable (male)	1	Antenna cable	7.59			
USB to TTL converter	1	Sensor package	12.76	3.92	0.00	59.91
Header pins	1	Sensor wiring	5.79			
Adafruit GPS breakout	1	Sensor package	37.44			
Eye bolts	1	Parachute mounting points	8.41	1.03	6.31	15.75
Spray paint	1	Payload enclosure paint	5.99	1.11	0.00	17.03
Barbed hose fitting	1	Inflation hardware	3.99			
Hose clamp	1	Inflation hardware	1.79			
Nylon bolt	4	Payload assembly	0.65			
Nylon nut	1	Payload assembly	0.40			
Nylon bolt	1	Payload assembly	0.35			
Wood screws	8	Payload assembly	0.10			
Mini USB Cable	1	Camera charging cable	4.79	1.18	0.00	17.96
MicroSD card	1	Flight camera	11.99			
Helium Tank Rental	1	Launch system	88.10	0.00	0.00	88.10
					TOTAL	**645.08**

Table 2: List of expenses for Project HALO (2019)