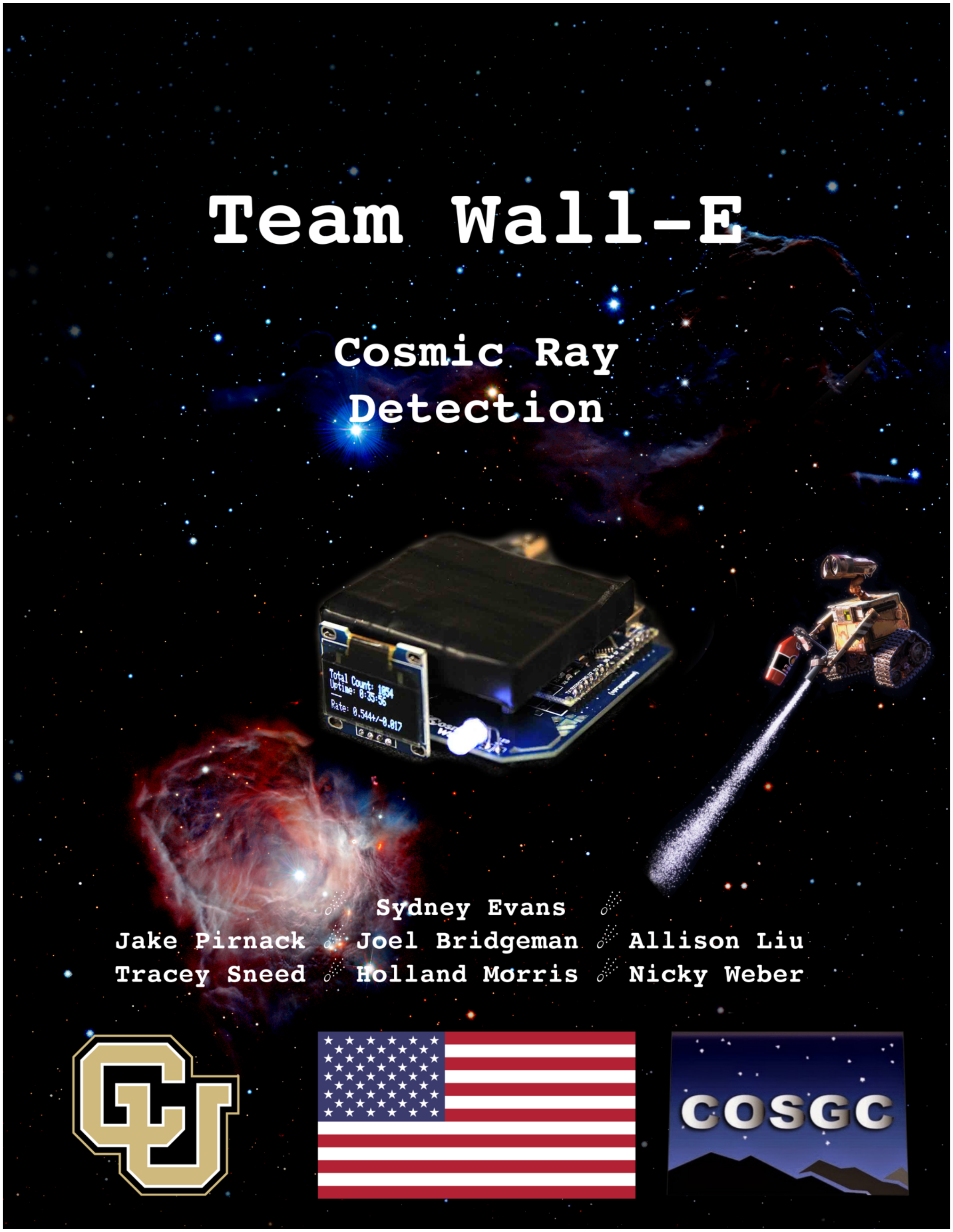
Team Wall-E
Cosmic Ray Detection
Sydney Evans
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COSGC

Enterprise

Revision Log

Revision	Description	Date
A/B	Conceptual and Preliminary Design Review	10/18/18
C	Critical Design Review	11/08/18
D	Analysis and Final Report (First Draft)	12/08/18
D	Analysis and Final Report (Final Draft)	12/16/18

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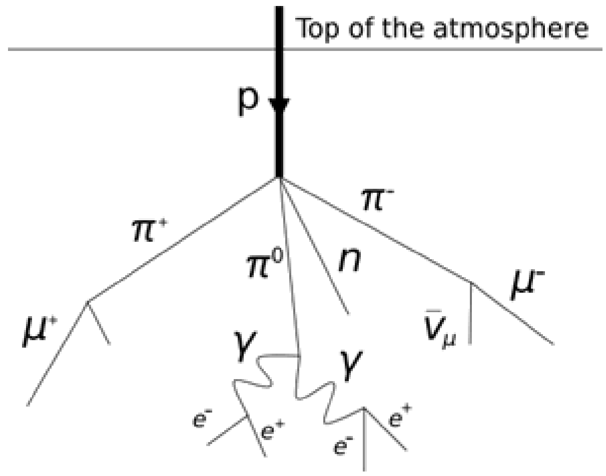
1.0 Mission Overview and Statement

1.1 Mission Statement

Team Wall-E's *Enterprise* Mission, executed in cooperation with the Colorado Space Grant Consortium through the Gateway to Space class at the University of Colorado Boulder, shall design, build, and launch a BalloonSat to an altitude 30 kilometers. The team shall collect data on atmospheric temperature, pressure, and humidity, as well as use a CosmicWatch detector[1] to measure muon count as a function of altitude.

1.2 Mission Overview



Cosmic rays—high-energy atomic nuclei originating from deep space—travel at nearly the speed of light and are impossible to measure directly from inside the atmosphere.[2] When cosmic rays enter the atmosphere of the Earth, they interact with air molecules and decay into unstable, negatively charged particles, including muons (Figure 1.1). Radiation detectors, such as the CosmicWatch created by Spencer Axani, measure the byproducts of these cosmic interactions.

The CosmicWatch detector prevents low energy radiation (such as alpha and beta particles) from triggering the sensor, while allowing higher energy charged particles such as muons to pass through. When muons travel through the plastic scintillator, they interact with the material and create a flash of light, which is detected by a photomultiplier. The photomultiplier converts the flashes of light into a voltage change that is picked up and stored by an Arduino Nano microcontroller. An additional Arduino Uno will collect data from Project *Enterprise's* altitude, temperature, pressure, and humidity sensors. The team expects to detect a positive correlation between altitude and muon count until a peak point, after which muon count begins to decrease[3]. More muons exist at higher altitudes because the muons have not had a chance to decay from their initial source point high in the atmosphere. However, due to the thinning of the atmosphere, those initial collisions not occur as often as the altitude increases. Thus, muon count is expected to decrease after a particular altitude.

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[1] http://cosmicwatch.lns.mit.edu/detector
[2] "A Detector Thirty Times the Size of Paris." Pierre Auger Observatory, Pierre Auger Collaboration, www.auger.org/index.php/cosmic-rays/detection.
[3] Fukuyama, Tama, et al. "Flux of Muons at Different Altitudes." Poster: Flux of Muons at Different Altitudes, 25 May 2011, www.i2u2.org/elab/cosmic/posters/display.jsp?name=poster_fluxofmuons.data.

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During flight, Project *Enterprise* and its payload will experience varying, extreme conditions as it travels through the atmosphere. Because functioning electronics are essential for data collection and because silicone radiation detectors are influenced by temperature, the internal temperature of the payload shall be regulated by a heater inside the BalloonSat. External temperature, pressure, and humidity shall change drastically. Team Wall-E shall compare the muon flux data collected against these external conditions. From this, the ideal external conditions for muon detection—and hence, its application to imaging—could be inferred.

1.3 Mission Application – Muon Imaging

Muons are particularly interesting particles to examine due to the combination of a few properties. They have a longer average lifetime compared to other unstable particles (such as mesons), as well as having substantially more mass compared to other particles; they have about 200 times more mass than electrons ($m_{\mu} \approx 207\ m_e$). Due to these properties, muons have a significantly higher probability of making it to the surface of the Earth and further into the crust. This allows for scientists to apply the technique of muon imaging.

Muon imaging, also known as muon topography or muography, has been utilized in projects such as measuring long-term volcano activity using scintillator-based scopes. This is possible because muons loose energy as they pass through material, therefore by comparing the how far the muons penetrate different areas of the mountain (magma absorbs less energy from muons than the denser surrounding rock, therefore the muon can travel farther in magma), we can generate an almost 3-D map of the interior. Some results have yielded evidence of a temporal correlation between muon counts in different regions of a volcano and magma movement recorded near the surface of the volcano. The study implied that continuous monitoring of active volcanoes with muon detection instruments may improve our understanding of their structure and even provide a warning system for local populations of a risk of eruption[4].

Muon topography can also be used as a technique for detecting shielded nuclear contraband. This is because when muons pass through materials with different densities, they deflect specific amounts. This means that physicists can place detectors on various sides of the target and measure the deflection angles of the particles in order to image and identify the internal componenets.

A primary issue that these teams face, however, includes potentially hostile environmental conditions the muon detector needs to function in. These detectors need to be resilient to changes in pressure, temperature, humidity, and vibration. As these conditions change, muon detection may be affected. Team Wall-E hopes to determine the viability of using a low-cost, portable muon detector (CosmicWatch) to analyze muon count with respect to altitude and these other conditions, which will be experienced by Project *Enterprise* during its flight on a weather balloon. It is known that temperature variations can induce changes in detection efficiency[4], therefore in an effort to control some variables, Team Wall-E will manage the internal temperature of the BalloonSat via a heating system to ensure the electronics function properly throughout the whole flight and changes in muon count are considered unrelated to external temperature variations. Team Wall-E hopes to determine an optimal altitude for muon generation and learn about muon energy levels, potentially providing such information to groups interested in applying the findings to the science of muon imaging.

2.0 Requirements Flow Down

Team Wall-E will abide by the Level 0 requirements outlined below. These requirements have been derived from Team Wall-E's mission statement and the Fall 2018 Request for Proposal developed by the Colorado Space Grant Consortium and the University of Colorado Department of Aerospace Engineering. These requirements form the foundation of Project *Enterprise* and are critical to its success.

Level 0 Requirements

Number	Requirement	Origin
0.1	The BalloonSat shall reach an altitude of 30km above the surface of the Earth.	Mission Statement
0.2	The BalloonSat shall collect data on atmospheric temperature (internal and external), pressure, and humidity.	Mission Statement
0.3	The BalloonSat shall measure muon count as a function of height in the atmosphere using a CosmicWatch Detector.	Mission Statement
0.4	The BalloonSat shall be ready for launch on November 10, 2018.	RFP
0.5	Project *Enterprise* shall meet all ASEN 1400 requirements outlined in the Fall 2018 RFP.	RFP

Team Wall-E will abide by the Level 1 requirements outlined below. These requirements have been derived from the Level 0 requirements and build on the foundational mission requirements. They are essential for the success of Project *Enterprise*.

Level 1 Requirements

Number	Requirement	Origin
1.1	The BalloonSat shall be insulated and heated to ensure hardware will function properly in near space conditions.	Requirement 0.1
1.2	The BalloonSat shall store data collected from the atmospheric accelerometer, temperature, pressure, and humidity sensors on a microSD card.	Requirement 0.2

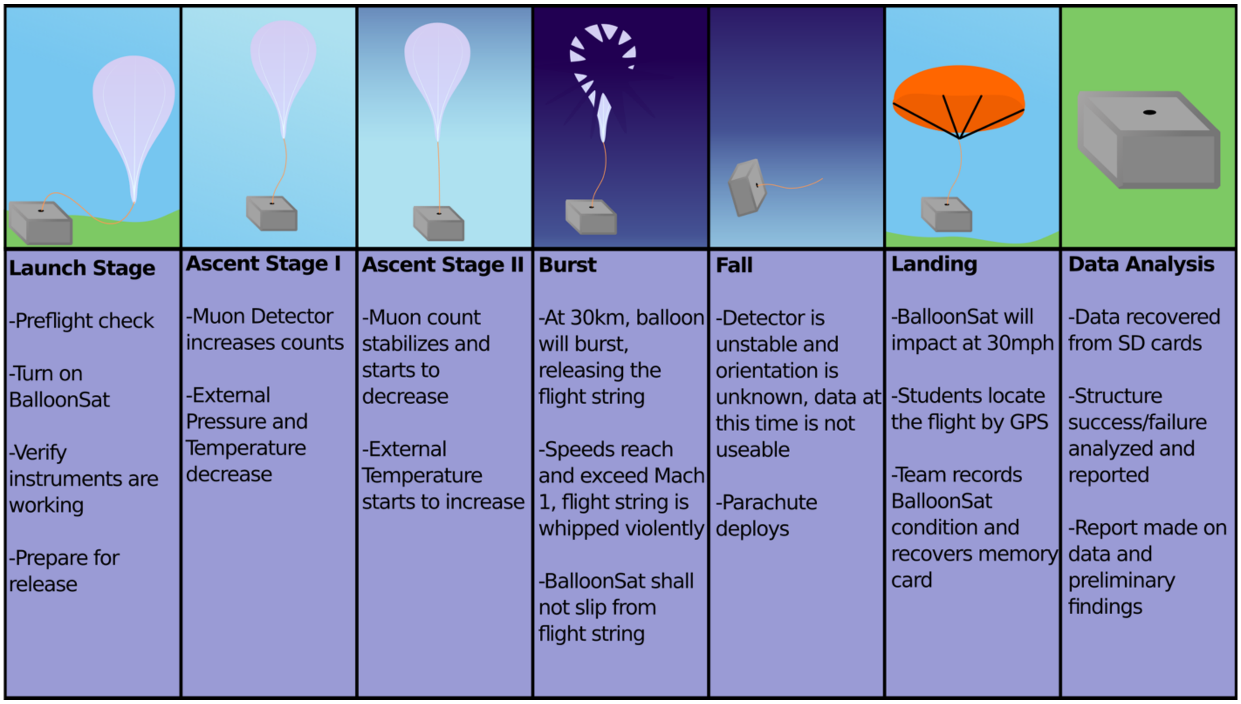
[4] Procureur, Sebastien. "Muon Imaging: Principles, Technologies and Applications." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 878, 11 Jan. 2018, pp. 169–179. Science Direct, University Libraries, www.sciencedirect.com/science/article/pii/S0168900217308495

1.3	The CosmicWatch Detector shall detect and record muon count at various altitudes throughout the flight.	Requirement 0.3
1.4	All systems and sensors shall be individually tested in a controlled environment to ensure function during flight.	Requirement 0.4
1.5	The BalloonSat shall not exceed 800g.	Requirement 0.5
1.6	The BalloonSat shall be constructed of foam core and have indicators on the outside to confirm payload is active.	Requirement 0.5
1.7	The BalloonSat shall record flight video using a GoPro Hero4.	Requirement 0.5

3.0 Design

3.1 Concept of Operations

The BalloonSat will be tested by the team and vetted by the instructor before launch. At launch, all systems will be powered on. During the ascent, data will be collected by all sensors, recorded by the Arduino microcontrollers, and stored on microSD cards. At the same time, the GoPro camera will be recording video. The balloon shall carry the satellites to an altitude of 30 kilometers before the balloon fails and bursts. After burst, the BalloonSat will whip violently around the string. This event will be recorded by the two-axis accelerometer inside the BalloonSat. The muon detector makes its measurements based on the area of the scintillator, and the violent unpredictable change in attitude at this time is expected to render the data recorded by the detector nonsensical. Once the BalloonSat experiments have landed, the team will locate the flight string by the GPS attached. The switches will be turned off, SD cards will be removed and the data recovered. A preliminary analysis of the data along with graphs will be completed shortly after.



3.2 General Mission Requirements Summary

These requirements are found in the RFP document provided by Professor Chris Kohler. The first table shows the mission requirement number and how Team Wall-E shall meet the requirement, as well as any limitations experienced in meeting the requirement. The second table displays a summary of where more information about Team Wall-E's compliance can be found in the design document.

Req. #	Team Wall-E's Compliance
1	Team Wall-E built and flew a CosmicWatch muon detector.
2	Team Wall-E built and flew the balloon shield from the Arduino Deep Dive session to collect flight data.
3	Project *Enterprise* shall be turned in on 12/13/18 working and ready to fly again.
4	Team Wall-E included the plastic flight tube in the design and construction of Project *Enterprise* and secured it to the box with washers, hot glue, and paper clips as depicted in Appendix A of the RFP compliance form.
5	Project *Enterprise* included a heater which kept the internal temperature above -8℃, which is above the required -10℃.
6	Project *Enterprise* weighed 688g at check-in.
7	Team Wall-E acquired ascent and descent rates of the flight string with the accelerometer included in the Arduino Uno system on Project *Enterprise*.
8	Design included and Arduino Uno and OpenLog microSD card shield as provided.
9	Design included an external temperature sensor, which extended 2.5 cm beyond the exterior of the box.

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10	Team Wall-E flew a GoPro Hero4 camera on Project *Enterprise* that captured stills of the entire flight.
11	Team Wall-E built a CosmicWatch muon detector, which included an Arduino Nano, to gather and command data, which was then stored on a separate microSD card in an OpenLog shield.
12	Project *Enterprise* was built from foam core.
13	Parts list and budget includes spare parts.
14	Project Enterprise has contact information written on the outside, along with a US flag, which was provided during check in.
15	Proposal, design, and other documentation units are in metric.
16	All members of Team Wall-E were there for launch on 11/10/18. Five team members participated in recovery.
17	No one was hurt during the project.
18	All hardware shall be returned to the Gateway to Space program in working order on 12/13/18.
19	All parts were ordered and paid by Chris Koehler's CU Visa. Team Wall-E maintained detailed budgets on all purchases and no reimbursements were needed.
20	No reimbursements were needed.
21	Team Wall-E had fun and worked diligently with no complaining about the amount of work required.
22	There were no live components of Project Enterprise.
23	DD Rev D shall be turned in 12/16/18 before 1pm. Team video was turned in on 12/08/18 during the Design Expo.
24	Project Enterprise included visual indicators (LED's) on the outside of the box to indicate that the payload was active and running. They worked successfully.
25	Team Wall-E developed electrical circuits with switches to activate all hardware from outside the BalloonSat before launch. They worked successfully.
26	All switches and LED indicators were protected with a foam core cover in the form of a flap in the box.
27	Team Wall-E used 9V batteries to power Project Enterprise.

Topic	Req. #	Location in DD
Design includes all given components	1, 2, 4, 5, 7, 8, 9, 10, 11, 12, 14, 24, 25, 26, 27	3.3, 3.4, 3.5, 3.6
Weight and budget limit	6, 13, 19, 20	5.0
Testing Results	4, 5, 7, 17,	6.0
Schedule	16, 23	4.1
Post-Launch	3, 7, 18	6.2, 3.1

3.3 Structural Design

Team Wall-E's box design is 20 cm x 20 cm x 10 cm built from black foam core. The lid and bottom of the BalloonSat include a hole with a diameter of 19.05 mm to allow for attachment to the meteorological balloon flight string, with a plastic tube 42.49 mm in length and a thickness of 1.49 mm protecting the edges and interior from the flight string. It is attached to the BalloonSat according to the description in the RFP. Included in this design are: one Arduino Uno, one balloon shield with all integrated sensors, one Cosmic Watch detector (includes an Arduino Nano), one heater, one GoPro, three switches, and four lithium 9V batteries.

The four walls of the BalloonSat shall be attached to the foam base plate. On the foam base plate, the Arduino Uno (including the given sensors and OpenLog microSD card and shield), the four lithium 9V batteries, GoPro, CosmicWatch detector and heater will be placed. On the back wall of the BalloonSat, three protected switches that control the electronic functions of the spacecraft will sit adjacent to the CosmicWatch. These will be used to turn on the internal components prior to launch. LED indicators will be placed by the switches to confirm that the payload is active and running. On the opposing wall, a 3.5 cm x 3.5 cm open window is present to allow for video capture by the GoPro. The BalloonSat will have Team Wall-E's contact information written on the outside of the foam core, along with a US flag.

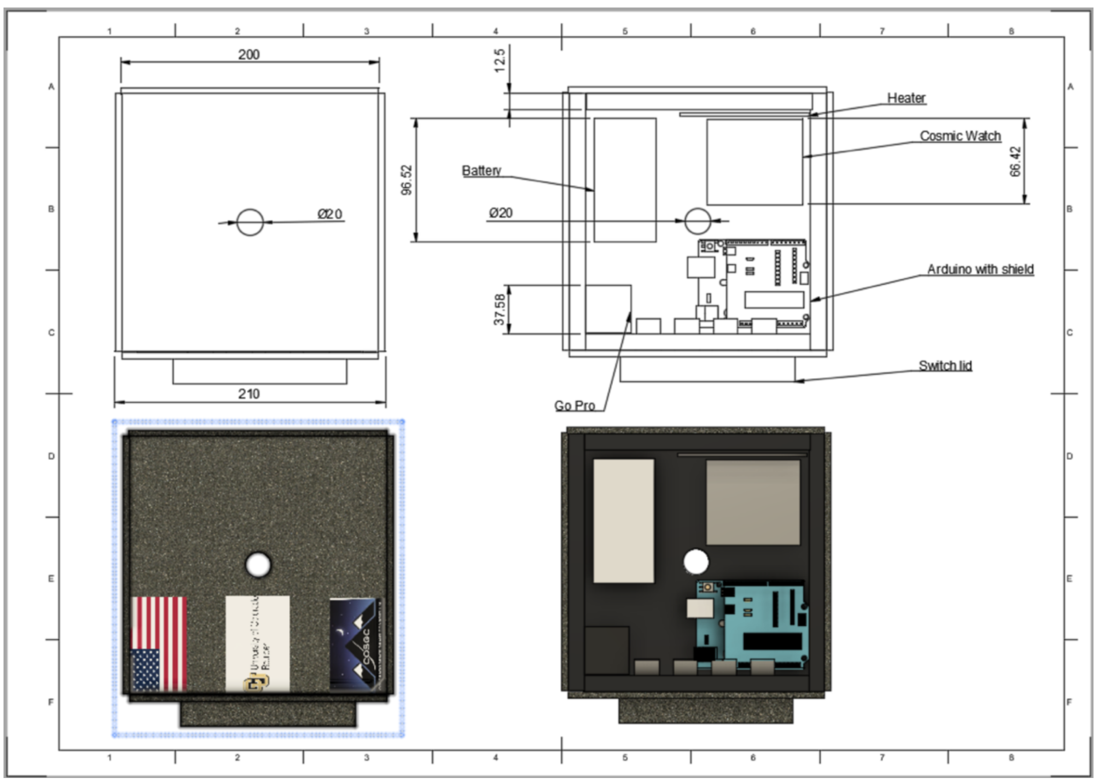
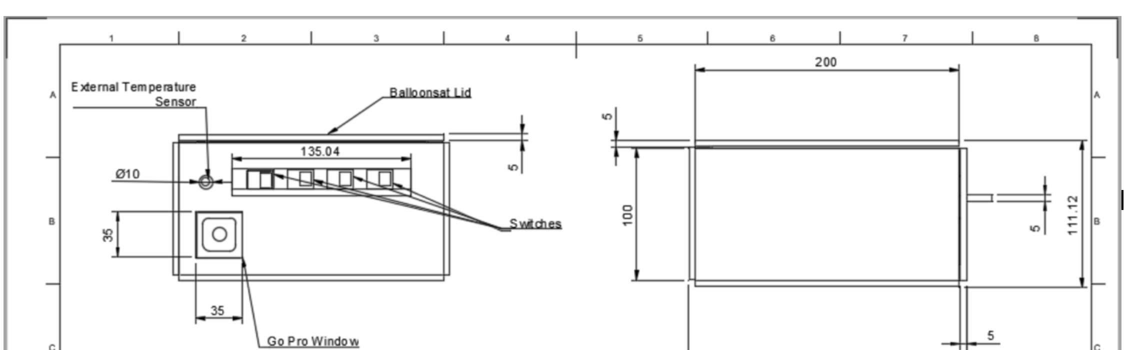


Figure 3.31 Top view CAD drawing of Project Enterprise.



3.4 Hardware

Project *Enterprise* shall utilize a collection of sensors and circuit boards, which shall be powered by a lithium 9V battery. Extra care shall be taken to ensure internal wiring is sound. The hardware provided by the Gateway to Space program at the University of Colorado Boulder includes an Arduino Uno circuit board, internal and external temperature sensors, a humidity sensor, a pressure sensor, a three-axis accelerometer, a GoPro Hero 4, switches, LED's, and other various manufacturing materials from the Project Depot located in the ITLL building. Team Wall-E shall acquire a heater and the hardware necessary for building a Cosmic Watch detector from Sparkfun, Amazon, Digikey and Ebay. See Section 5.0 for a full table of materials ordered, along with the supplier and cost.

3.4.1 Arduino Uno

The Arduino Uno shall control the pressure sensor, humidity sensor, internal and external temperature sensors, and the accelerometer. It is coded to collect a data sample from each of these sensors every 0.5 second. These samples are compiled in sequential order and saved on to a micro SD card that is attached to the Arduino Uno. The Arduino unit is powered by the lithhium 9V battery and shall be turned on prior to launch using an external switch.

3.4.2 Pressure Sensor

The pressure sensor shall be controlled by the Arduino Uno and shall measure pressure every 0.5 seconds with respect to altitude during flight. The data that is collected during flight shall be stored on the micro SD card that attached to the Arduino Uno.

3.4.3 Humidity Sensor

The humidity sensor shall measure the humidity inside of the BalloonSat every 0.5 seconds during the flight. The data that is collected during flight shall be stored on the micro SD card that is attached to the Arduino Uno.

3.4.4 Temperature Sensors

The internal and external temperature sensors shall be controlled by the Arduino Uno and shall measure the temperature inside and outside of the BalloonSat respectively every 0.5 seconds during flight. The external temperature sensor will extend 2.5 cm beyond the exterior of the BalloonSat. The data that is collected during flight will be stored on the micro SD card that is attached to the Arduino Uno.

3.4.5 Accelerometer

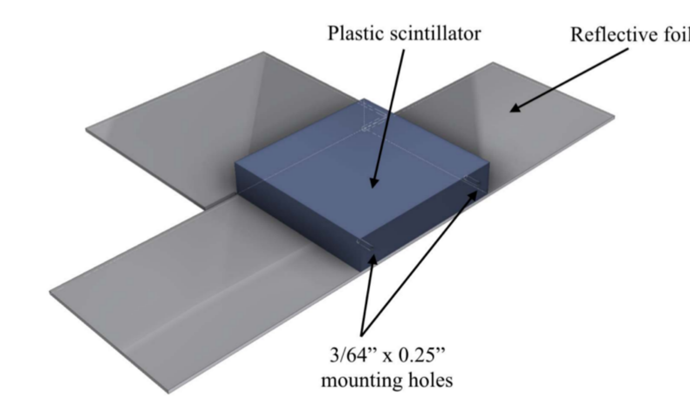
The accelerometer shall measure the motion of the BalloonSat through its flight. To do this it shall measure the acceleration of the BalloonSat in the x-direction (horizontally) and z-direction (vertically) every 0.5 seconds during the flight. It shall be controlled by the Arduino Uno and data from the sensor shall be stored on the micro SD card that is attached to the Arduino Uno.

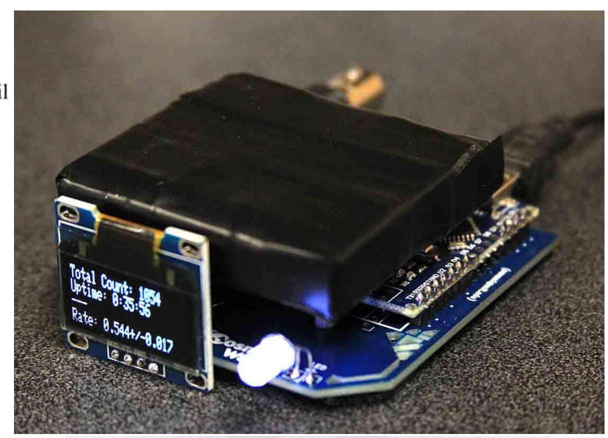
3.4.6 GoPro Hero 4

The GoPro Hero 4 shall take video through the duration of the flight. The video shall be stored on an internal SD. The GoPro shall be powered by its own internal battery throughout flight.

3.5 Cosmic Watch Function and Design

The focus for the scientific data collection shall be on detecting muons. A CosmicWatch detector shall be built to detect and record muon count at various altitudes throughout the BalloonSat's flight. The dimensions of the completed detector are approximately 65 mm x 100 mm x 38 mm and weighs 76g,[5] which can be seen in Figure 3.23. Team Wall-E was going to build an aluminum case for the CosmicWatch, however due to time and weight constraints, the team decided that this would not be feasible. To further protect against light leakage, a problem that could invalidate all collected data, Team Wall-E shall construct a case for the detector prior to launch out of foam core, vacuum foil and electrical tape. When muons travel through the CosmicWatch, they pass through a 5 cm x 5 cm x 1cm plastic scintillator (Figure 3.21) and emit a flash of light. This flash is detected by a silicon photomultiplier (SiPM) attached to the bottom of the plastic scintillator and a signal is created by the SiPM. This signal is sent to a custom designed circuit board which changes the signal into a something that a microcontroller, in this case an Arduino Nano, can read. The microcontroller stores the number of flashes recorded at the various altitudes throughout the flight in a microSD card. Figure 3.22[6] shows the plastic scintillator attached to an Arduino Nano. Figure 3.21 also shows an optional OLED screen which will not be utilized during flight.

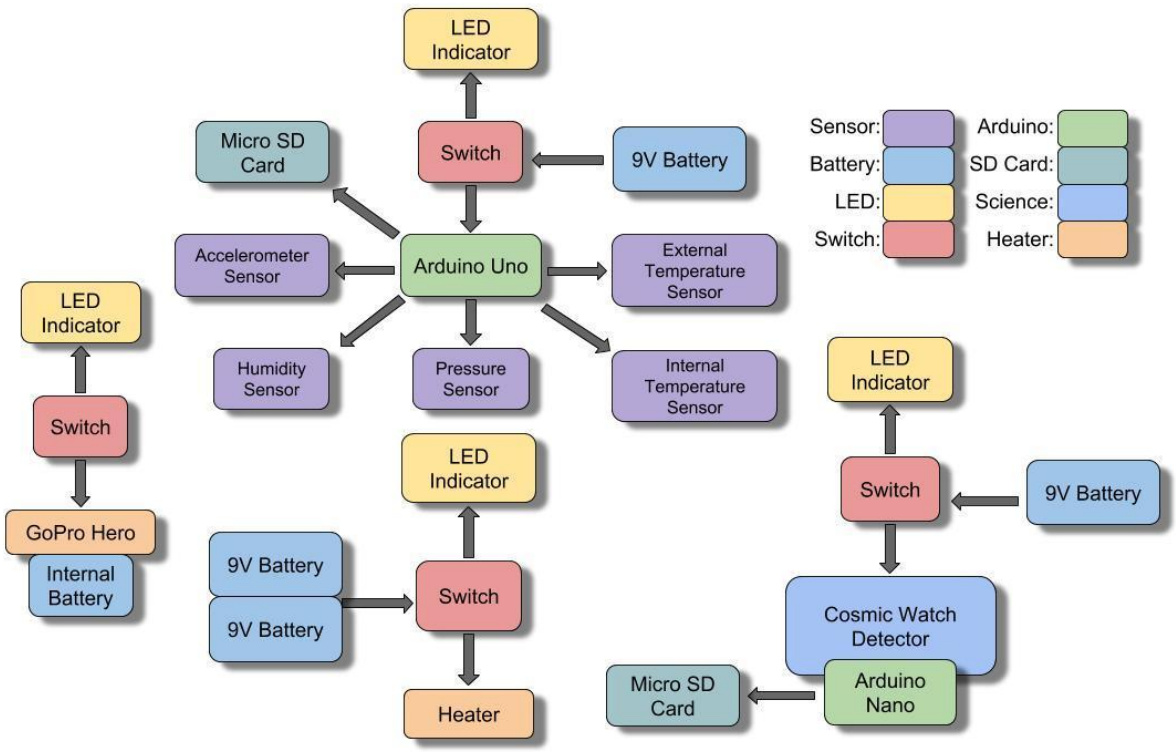




[5] Axani, Spencer N, et al. The CosmicWatch Desktop Muon Detector: a Self-Contained, Pocket Sized Particle Detector. 2018, The CosmicWatch Desktop Muon Detector: a Self-Contained, Pocket Sized Particle Detector, arxiv.org/pdf/1801.03029.pdf.
[6] Figures 3.21 and 3.22 are from the Cosmic Watch website. http://cosmicwatch.lns.mit.edu/detector

3.6 Functional Block Diagram

Team Wall-E's first Arduino Uno will control the given sensors including the accelerometer, humidity, pressure, and temperature sensors. Team Wall-E is supplementing their second Arduino Uno with an Arduino Nano to be used in the Cosmic Watch detector. This is because the Arduino Nano is smaller, and therefore can fit inside the detector better. The data from both Arduino units will be logged on SD cards (see Section 2.6). Four lithium nine-volt batteries will power both Arduino units and the heating system.



4.0 Management Overview

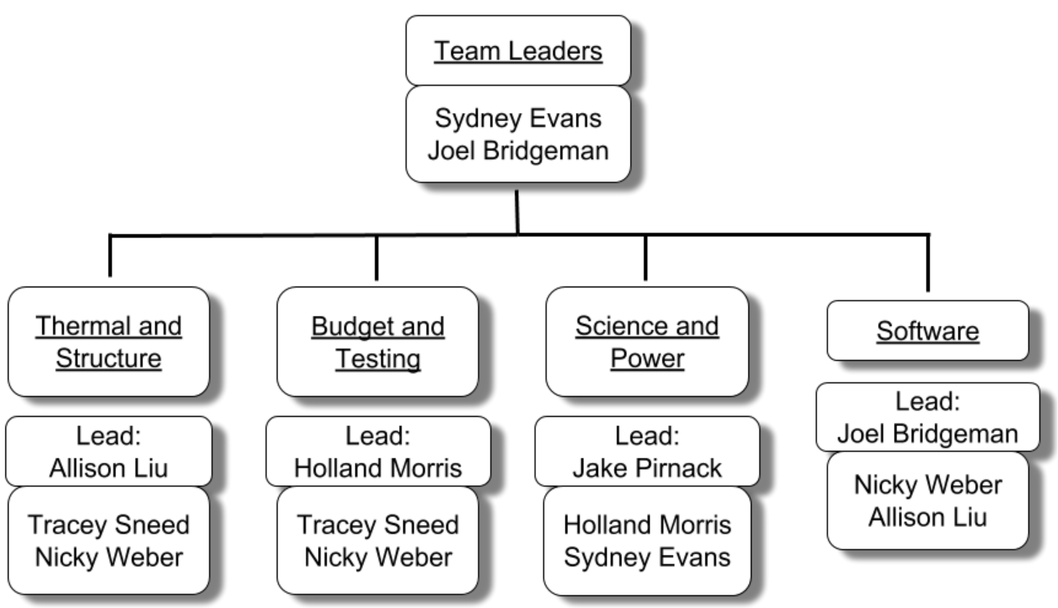
4.1 Schedule

Below is a schedule for Project *Enterprise*. Listed are important dates by which Team Wall-E shall have completed milestones for the project. The team will also meet regularly on Fridays from 3:00pm to 5:00pm in an ITLL study room, and Sundays from 9:00am to 12:00pm in the Kittredge Central classroom. Sub-teams will determine if additional meeting time is deemed necessary for the upcoming week and arrangements will be made appropriately.

Date	Milestone	Date	Milestone		
09/27	Obtain Authority to Proceed	11/08	DD Rev C Complete		
	Turn In Hardware Order Form	11/09	Final Weigh In		
	Design Complete	11/10	LAUNCH!		
09/30	Ardunio Uno Electronics Complete	11/13	Quick Look Post Launch Presentation Complete		
10/05	HW08: Systems Engineering Exercise Complete	11/15	Quick Look Post Launch Presentation		
	Foam Core Structure Built	11/26	Community Service Activity Complete		
10/07	Begin DD Rev A/B		Work on 1st Draft DD Rev D		
10/12	PDR Presentation Complete		Work on Final Presentation		
	Structural Testing Complete		Begin Team Video		
	Arduino Nano Electronics Complete	11/29	HW09 Due		
10/14	Sensor Electrical Testing Complete	12/02	1st Draft DD Rev D Complete		
10/16	PDR Presentation		Team Video Complete		
10/17	DD Rev A/B Complete		Community Service Presentation Complete		
10/30	Cosmic Watch PCB Boards Complete	12/07	Final Presentation Complete		
11/01	Mission Simmulation Test	12/08	ITLL Design Expo		
10/31	Cosmic Watch Built	12/09	Work on Final DD Rev D		
11/01	Mission Simmulation Test #2	12/12	HW10		
11/02	LRR Presentation Complete	12/14	Final DD Rev D Complete		
11/06	LRR Presentation	12/16	Community Service Presentation		
11/9	Experiment Testing Complete	Key:	Testing	Design Document	
11/9	BalloonSat Complete		Presentations	HW	Completed

4.2 Team Management

Responsibility for Project *Enterprise* has been broken up into subgroups based on major components of the project. The leads on each subgroup have experience and confidence in their category, and team members were assigned subgroups in a way to maximize learning and skill acquisition in those who have less experience and confidence.



4.3 Team Member Contact Information

Holland Morris: homr7619@colorado.edu

Allison Liu: allison.liu@colorado.edu

Sydney Evans: sydney.evans@colorado.edu

Joel Bridgeman: jobr3181@colorado.edu

Jake Pirnack: japi8981@colorado.edu

Nicky Weber: niwe6634@colorado.edu

Tracey Sneed: trsn6222@colorado.edu

5.0 Budget Overview

Team Wall-E's budget is managed by Holland Morris. The team will contribute thoughts and advice regarding purchases, but Holland will keep the budget in check for the duration of the project. Team Wall-E has spent $210 of the $200 budget which has been approved by Chris Koehler. Team Wall-E is planning to spend about $100 more out of pocket for batteries, dry ice, and other expenditures not covered by COSGC. The budget accounts for spares of circuit pieces that are small, fragile, and inexpensive in case a part malfunctions, breaks, or needs to be replaced for any other reason. All purchases up to this point have gone through a request and approval process with Chris Koehler and have been purchased via Chris Koehler's CU Visa Card. Receipts have been returned to Chris Koehler. Initially, the team did not expect to exceed 800g and current weigh-ins read 668g.

Materials	Count	Weight	Source	Part Number	Cost
Arduino With Sensors	1	65g	COSGC		NA
SD Cards	2	2g	COSGC		NA
GoPro Hero 4 With USB	1	91g	COSGC		NA
Box with Foam Core, Insulation, Tube, and Paper Clip	NA	262g	COSGC		NA
LED's	~10	~1g	COSGC		NA
Wiring and Resistors	-	30g	COSGC		NA
Heating pad	1	3g	Spark Fun	COM - 11288 ROHS	$4.00
49.9 Ohm Resistor	3	-	Digikey	311-49.9CRCT-ND	$0.46

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499 Ohm Resistor	1	-	Digikey	311-499CRCT-N	$0.30
1K resistor	3	-	Digikey	311-1.00KCRCT-ND	$0.46
10k resistor	2	-	Digikey	311-10.0KCRCT-ND	$0.46
100k resistor	2	-	Digikey	311-100KCRCT-ND	$0.30
226k resistor	1	-	Digikey	311-226KCRCT-ND	$0.33
5pF capacitor	1	-	Digikey	1276-2552-1-ND	$0.94
22pF capacitor	1	-	Digikey	399-1113-1-ND	$0.72
10nF capacitor	1	-	Digikey	311-1136-1-ND	$1.23
0.1uF capacitor	1	-	Digikey	399-1170-1-ND	$0.57
0.47uF capacitor	1	-	Digikey	399-8100-1-ND	$0.48
1uF capacitor	1	-	Digikey	587-1308-1-ND	$1.08
10uF capacitor	1	-	Digikey	490-1718-1-ND	$1.56
47uH inductor	1	-	Digikey	490-4063-1-ND	$1.68
Schottky diode	2	-	Digikey	MBR0540CT-ND	$1.71
4 pin header	1	-	Digikey	S5440-ND	$1.89
6-pin connector	1	-	Digikey	WM17457-ND	$0.46
6-pin header	1	-	Digikey	1212-1229-ND	$1.48
Reset button	1	-	Digikey	P12215S-ND	$0.30
BNC header	1	-	Digikey	WM5514-ND	$0.46
Standoff for SiPM PCB	2	-	Project Depot		NA
Standoff screws Main side	4	-	Project Depot		NA
Plastic scintillator screws	4	-	Project Depot		NA
DC-DC Booster	1	-	Digikey	1738-1144-ND	$3.00
Op-Amp	1	-	Digikey	LT1807IS8#TRPBFCT-ND	$10.00
Barrell Jack	1	-	Digikey	WM5514-ND	$1.00
Arduino Nano	1	-	Digikey	1050-1001-ND	$20.00
Dry Ice	1	-	King Soopers		NA
Tin Foil	1	-	Project depot		NA
Black electrical tape	1	-	Project Depot		NA
SiPM	1	-	Sensl.com		$60.00
Plastic scintillator	1	-	Ebay	BC408-505010	$30.00
Vaseline	<1mL	-	Walgreens		$2.00
Main PCB + SiPM PCB	1	-	Created in ITLL		$15.00
9V Batteries	4	180g	King Soopers		NA
Cosmic Watch (weight)	NA	68g	NA		NA

Buffer		50g			$20.00
Shipping		NA	NA		$48.00
Total	-	668g	-		~$210.19

6.0 Testing

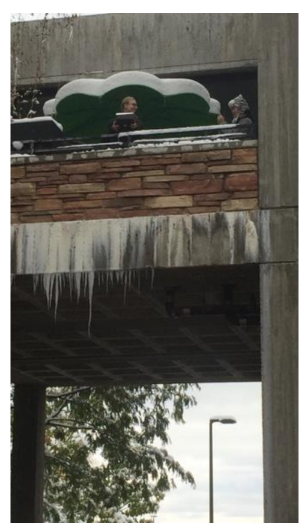
6.1 Health and Safety

The safety of all members of Team Wall-E is paramount over the course of the semester. The Cosmic Watch detects muons that pose no known threat to humans. Thus, Team Wall-E expects there to be no danger in testing the detector without protection. Team Wall-E anticipates the main dangers of Project *Enterprise* to occur during stress testing, particularly the freeze test and the structure tests. For the freeze test, one team member— equipped with thermal protection—shall handle the dry ice and payload during the test. During structural testing, only one team member shall conduct the drop, whip, and stair tests at a time; the rest of the team shall maintain a safe distance. Other potential dangers include knives when cutting foam board and hot glue used during construction. To mediate these threats, Team Wall-E will be aware of the situation, and a limited number of team members shall interact with these dangers at a time. Safety glasses and skin protection and other personal protective equipment shall be worn when necessary.

6.2 Structural Testing

Due to the extreme conditions experienced by the BalloonSat during flight, Project *Enterprise* shall undergo vigorous pre-launch testing to ensure its structural integrity and functionality at the time of launch. After completing the tests, Team Wall-E shall make any changes necessary to accommodate for weaknesses and failures presented during the testing phase. These changes shall be completed before launch. When recovered after landing, Team Wall-E shall make any necessary fixes to the BalloonSat and shall turn it in to Professor Chris Kohler in “ready-to-fly” condition.

6.2.1 Drop Test

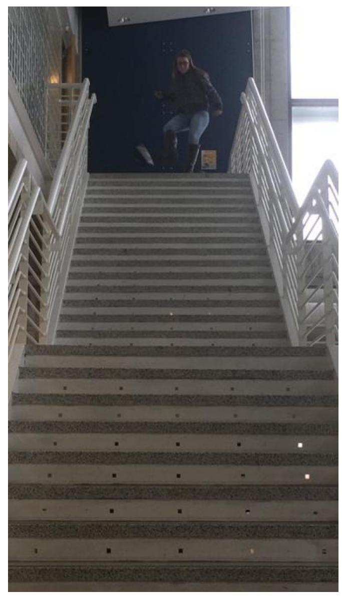


To simulate the BalloonSat’s rough landing after launch, an impact test was performed, as seen in Figure 6.21. The BalloonSat was thrown (with simulated mass) from the bridge that connects the ITLL to the DLC. It survived the fall, retaining its structural integrity. The only damage to the box was a dented corner. Team Wall-E constructed a new box, of the same design, to maximize its strength for flight.

6.2.2 Whip Test

To ensure that rope attachment point will hold amid the violent turbulence during burst and afterwards during freefall, a whip test was performed, as seen in Figure 6.22. This test consisted of spinning the BalloonSat (with simulated mass) at the end of the rope over a team member’s head both clockwise and counterclockwise to ensure that the BalloonSat won't detach from the rope during burst and freefall. The test was conducted away from any windows and in an open area to ensure team members’ safety. The only piece damaged during this test was the washer at the top of the BalloonSat, which came loose from the structure. (Figure 6.24) Team Wall-E reinforced it with hot glue on the new structure.

6.2.3 Stair Test



The BalloonSat (with simulated mass) was kicked down the stairs of the ITLL (as seen in Figure 6.23) in order the stimulate the dragging and bouncing the BalloonSat will experience after landing impact. This test was repeated twice with differing initial velocities to ensure that the BalloonSat could withstand most impact scenarios. The BalloonSat was only superficially damaged after these tests (see Figures 6.25, 6.26, and 6.27), and therefore they were considered successful.

6.3 Sensor Testing

6.3.1 Humidity Sensor

The sensor was exposed to different humidity conditions. The humidity sensor was breathed on twice, raising the relative humidity (RH), before being placed in a cold environment, lowering the relative humidity in the air. These changes can be seen in Figure 6.3.1. The small spikes are voltage noise, a byproduct of the Arduino and not real reflections of sensor readings. The sensor briefly gave an output voltage that corresponded to greater than 100% humidity. This is because of voltage addition error and moisture contacting the sensor. Regardless, the humidity sensor test was deemed successful.

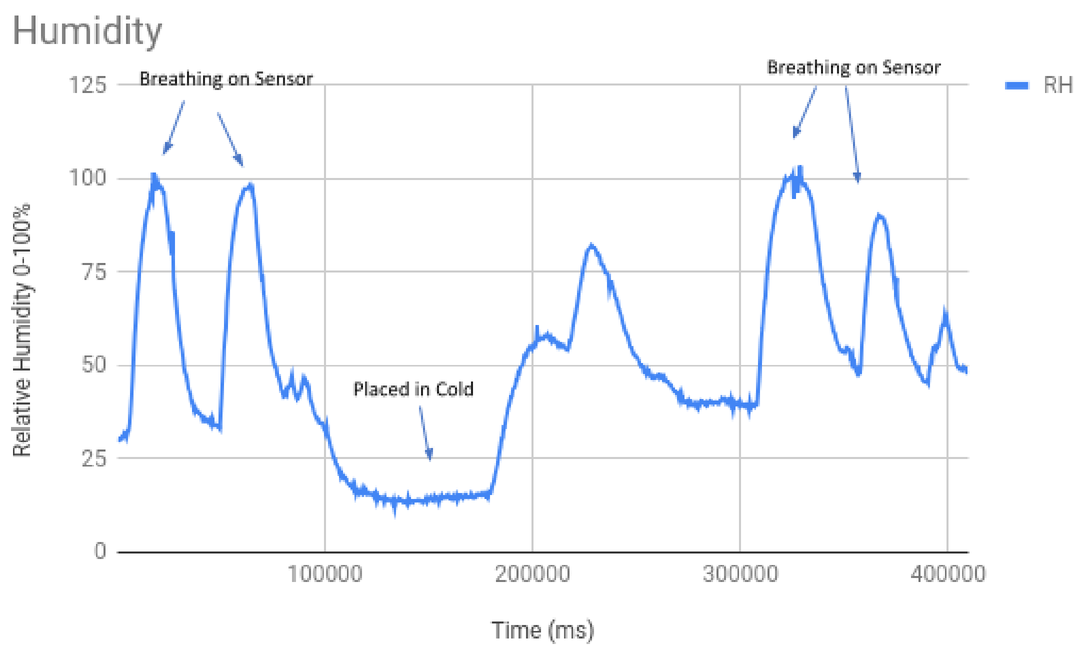


Figure 6.3.1 Humidity Sensor test from Arduino Deep Dive.

6.3.2 Pressure Sensor

The pressure sensor was exposed to different pressures when a solder sucker was activated twice in short succession over the sensor at two different time intervals. There are two sets of pressure changes that can be seen on Figure 6.3.2, and these changes in pressure corresponded to the use of the solder sucker, therefore it was confirmed that the pressure sensor works properly.

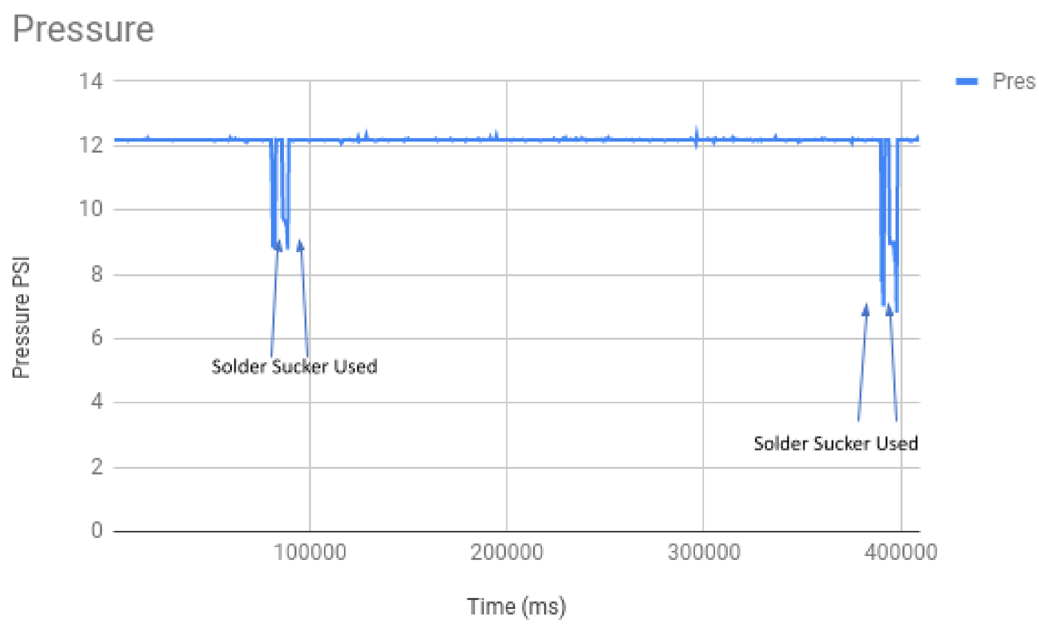


Figure 6.3.2 Pressure sensor data from Arduino Deep Dive session.

6.3.3 Accelerometer

The orientation of the sensor was changed by tilting the three-axis accelerometer to simulate the movement of flight, and the data recorded. The Arduino unit and all sensors were rotated in the x-direction at about 260000 ms and was rotated in the z direction at about time 291000 ms. The accelerometer test was deemed successful.

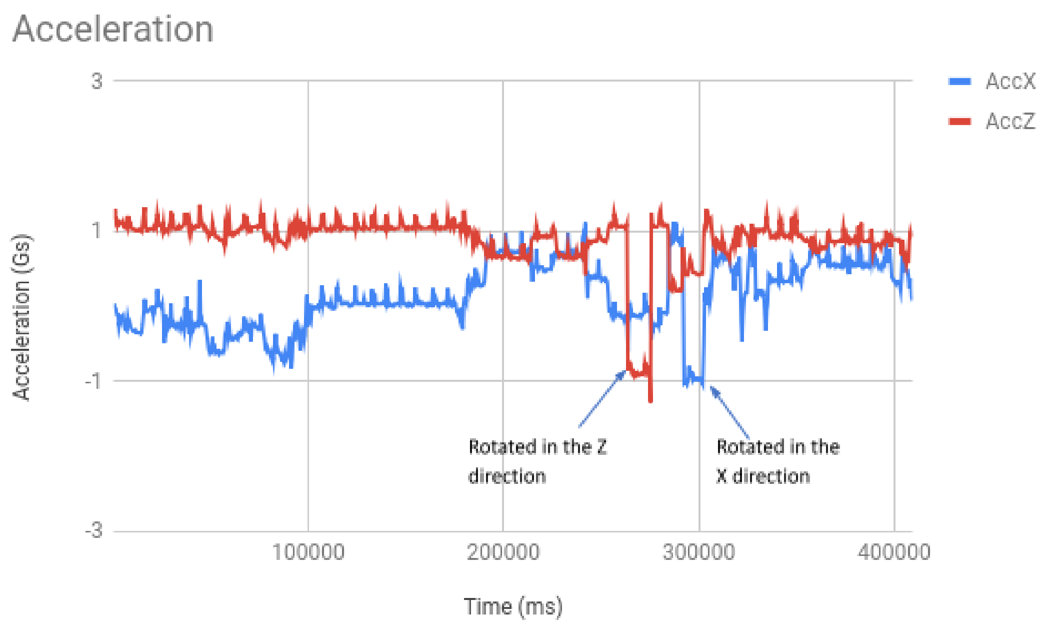


Figure 6.3.3 Accelerometer data from Arduino Deep Dive

6.3.4 Internal and External Temperature Sensors

Team Wall-E's initial external temperature sensor had a broken pin and did not record accurate data about surrounding temperatures. The team obtained a new external temperature sensor from Chris and conducted a test to ensure that it was working as expected. To generate changes in temperature readings, a team member breathed on the internal and external temperature sensors respectively to increase the surrounding temperature. The spikes in the data in Figure 6.3.4 demonstrate this change accurately and the test was considered successful.

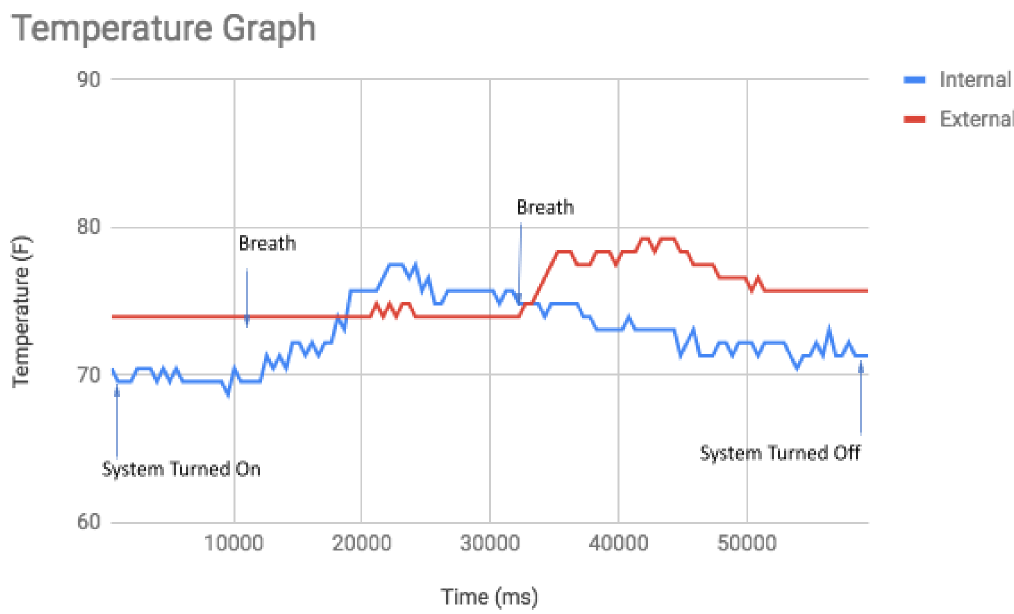


Figure 6.3.4 Temperature sensor data with new external temperature sensor.

6.4 CosmicWatch Testing

Team Wall-E uploaded the code for the CosmicWatch to the Arduino Nano and ran it with no complications. The rest of the sensor was built and tested. The detector read about 2.6 counts per second, which was much higher than the detection rates recommended by the CosmicWatch instructions. The connections were checked, threshold values were adjusted, and now the detector reads about 1.4 counts per second. At sea level, .5 counts can be attributed to muons.

6.4.1 CosmicWatch Specific Mission Simulation Test

In Figure 6.4.1, each blue dot represents an event detected by the silicon photo-multiplier. The red trendline of the data demonstrates that even though times between events varied wildly, the average over time is relatively constant, which was expected due to the constant external conditions throughout the test. In the second graph, each event is recorded on the SD card with a number in the order the events were detected. A linear line as seen in Figure 6.4.2 demonstrates that each event (which increased by one each time) was recorded with relatively similar amounts of time between each event.

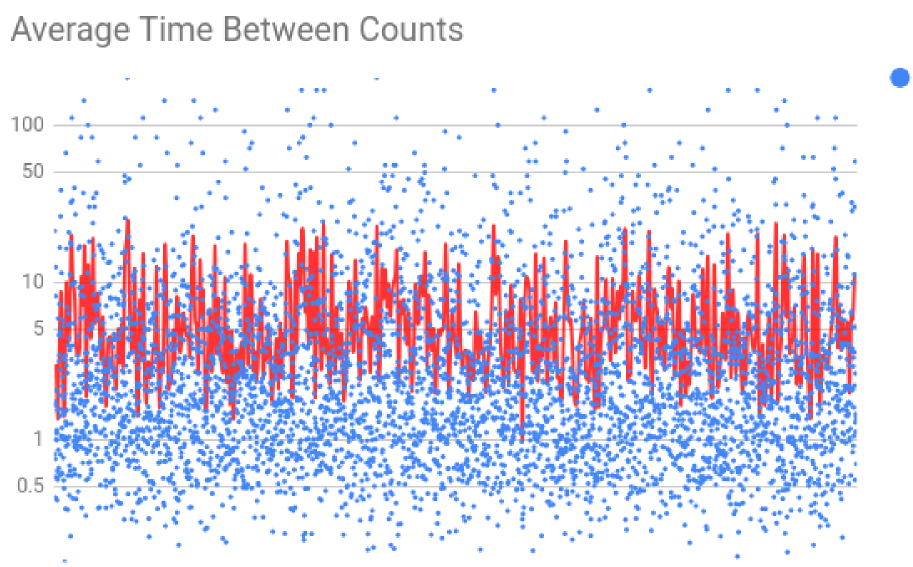


Figure 6.4.1 The CosmicWatch data from the mission simulation test. Note the logarithmic scale on the y-axis.

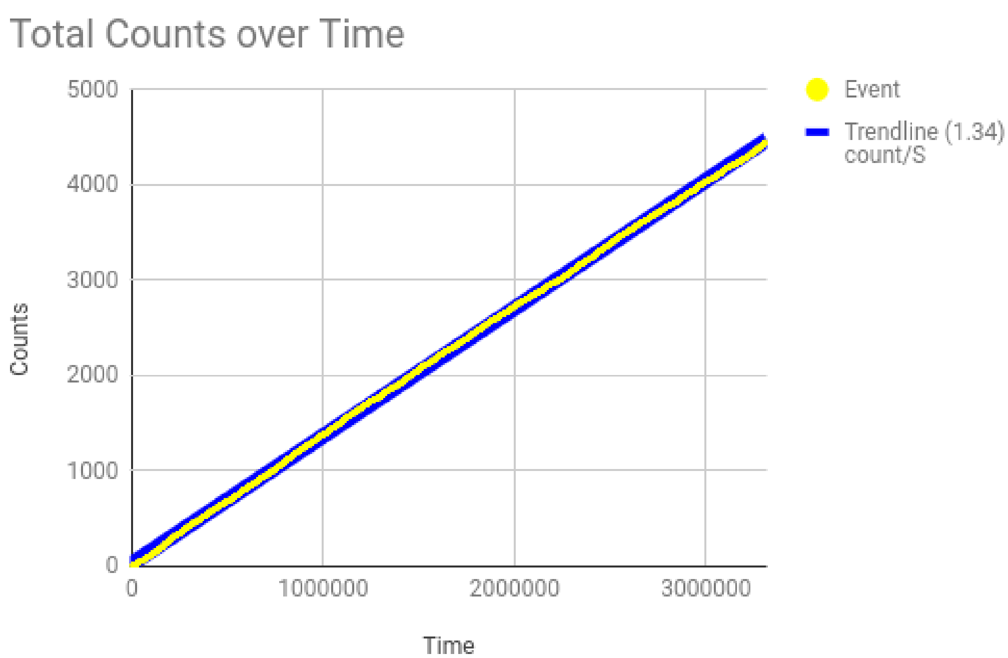


Figure 6.4.2 The straight line of this graph demonstrates that the CosmicWatch was detecting about 1.34 counts per second at ground level. The data fits the trendline with an R^2 value of .99.

6.4.2 Data Collection Test

Due to the extended length of the flight, Team Wall-E wanted to ensure that the CosmicWatch detector would not run out of storage on the microSD card in the OpenLog it is connected to. Team Wall-E wiped the 4GB microSD card that is being used to collect data from the Arduino Nano and connected a test battery to the CosmicWatch sub-system of the payload. The system was turned on and left running for three hours. Team Wall-E obtained a file size of 176KB with 5010 data points. Even if 100x that data is collected, the file size is still very manageable. Team Wall-E determined this test successful and is not concerned with running out of memory storage during flight. Figure 6.4.3 shows the data collected during the test. The linear trend of the data demonstrates the constant number of counts over time; in other words, there were no drastic changes in the muon counts during the test, due to the unchanging conditions the test was conducted in.

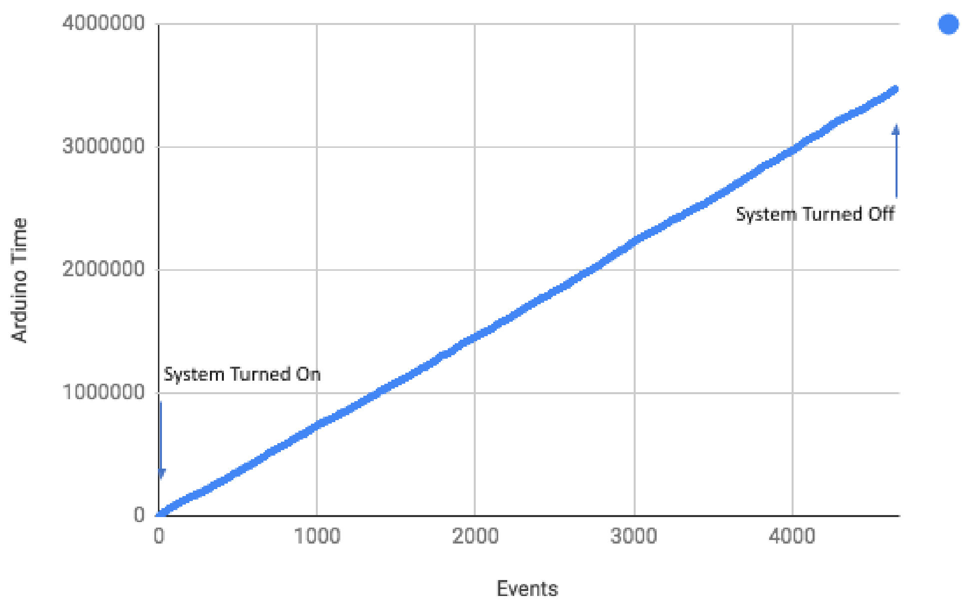


Figure 6.4.3 Data from the CosmicWatch data collection test. No major fluxuations can be seen.

6.4.3 Radiation Test

To determine the CosmicWatch detects what it is supposed to, Team Wall-E first obtained a radioactive ceramic plate from Chris and tested its effects. After no discernable difference was detected, team Wall-E found a stronger radiation source in the form of Uranium Oxide glass appropriated from Hans in the Physics department. The data obtained from the new source is shown (Figure 6.4.4). First the detector was turned on with the glass 6 feet from it and left for 3 minutes to obtain a reliable baseline. Then the glass was placed directly over the scintillator and left for another 2 minutes. The results show a clear marked difference in rate of counts from the 3-minute mark onward. This second test was determined to be a success.

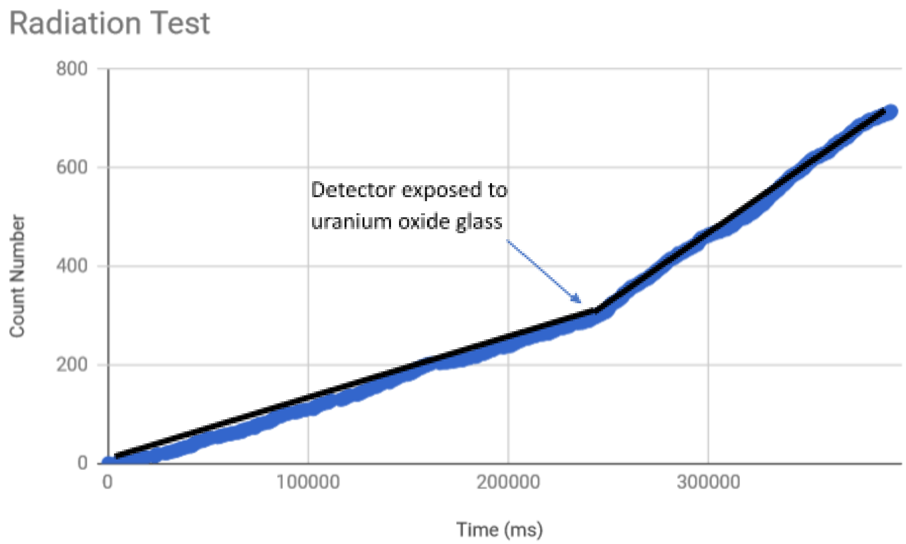


Figure 6.4.4 demonstrates the effectiveness of the detector in picking up high energy particles, even the relatively small number produced by uranium-oxide glass

6.5 Camera Testing

Team Wall-E tested the camera before flying it in Project *Enterprise*. The team turned on the fully charged GoPro at the beginning of one of the team meetings and placed it inside the BalloonSat in the location it shall be in during flight. The GoPro collected video for the duration of the camera's battery life. Once the battery was depleted, Team Wall-E recharged the camera, and remove the SD card for analysis. The video from the GoPro was obtained from the SD card and could be viewed on a team member's computer. The lens of the camera was obstructed at the edges due to the size of the hole in the box for the GoPro (Figure 6.5.1), so foam core was removed from the edges of the hole and another test was conducted. The team was satisfied with the video recorded (Figure 6.5.2) and the camera test was deemed successful.

Figure 6.5.1 Image from camera prior to modifying viewing hole.

Figure 6.5.2 Image after modifying viewing hole.

6.6 General Mission Simulation Testing

6.6.1 Temperature Testing

The external temperature will reach as cold as -55 °C during the BalloonSat's flight. However, the internal temperature of the BalloonSat must stay at or above 0 °C for the scintillator to work correctly. To generate a control, Project *Enterprise* will be turned on and operate for one hour (mission simulation test). To simulate the temperature conditions experienced during flight, the BalloonSat shall also be placed in a cooler surrounded by dry ice (approximately -78.5 °C) for two hours. During this test the Arduino Uno and Arduino Nano shall be recording data and the heater will be on.

During Team Wall-E's first cold test, the heater was powered by one nine-volt battery and subsequently drained the nine-volt battery, as the team did not realize two nine-volt batteries were required to supply sufficient current for the heater. Due to this, the batteries in the BalloonSat cooled considerably, which caused voltage drop and subsequently all the systems to shut down. During Team Wall-E's second cold test, two nine-volt batteries were successfully wired in parallel to the heater, however, there was not enough dry-ice inside the cooler to be representative of the temperatures the BalloonSat is expected to encounter during the flight, and the test was deemed a failure. (Figure 6.6.1) Team Wall-E is conducting a third cold test on November 8, 2018 to test that the BalloonSat is capable of providing and storing sufficient heat for the BalloonSat to meet the mission objectives. The team will use more dry ice than in the second test in an effort to decrease the external temperature further.

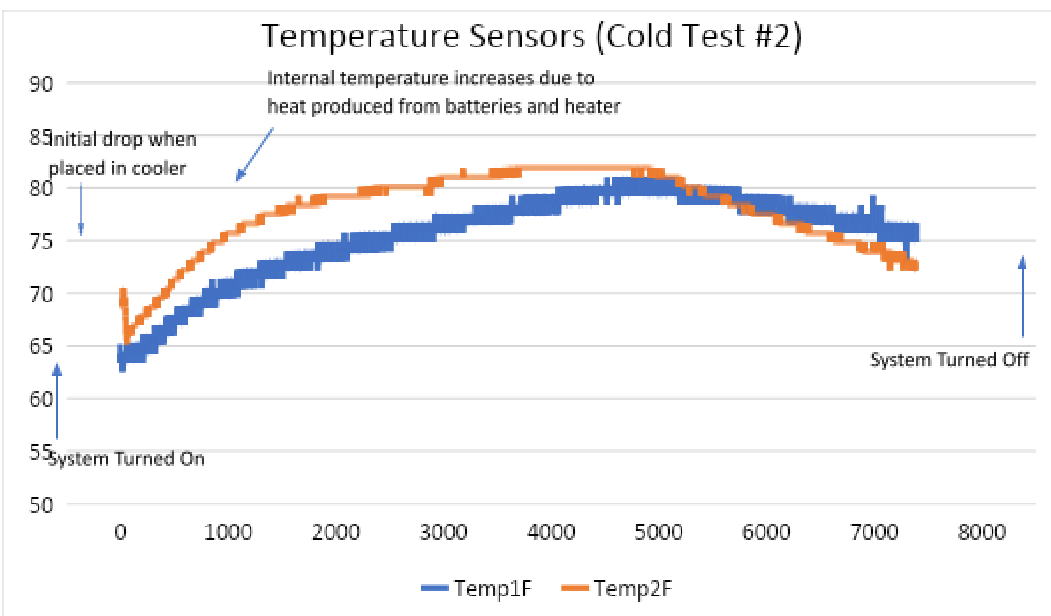


Figure 6.6.1 Cold Test #2 results: the temperature of the cooler did not reach desired temperatures.

6.6.2 Mission Simulation Test

To test all functionality of the BalloonSat and its mission, a full-scale test was performed in class on Thursday, November 1st. Team Wall-E was missing a DC-DC booster at the time of the test, and therefore was unable to run the CosmicWatch system. The team chose not to turn on the heater system because the test was being conducted at room temperature and the team did not want to overheat Project *Enterprise*. Team Wall-E turned on the Arduino Uno sensor system left it running for an hour.

Team Wall-E reconducted the mission simulation test on Sunday, November 4th after completing the CosmicWatch system. All sensors recorded situationally accurate readings (see Figures 6.6.2.1, 6.6.2.2, 6.6.2.3 and 6.6.2.4) and the CosmicWatch collected data on particles detected by the silicon photo multiplier (see section 6.4.1).

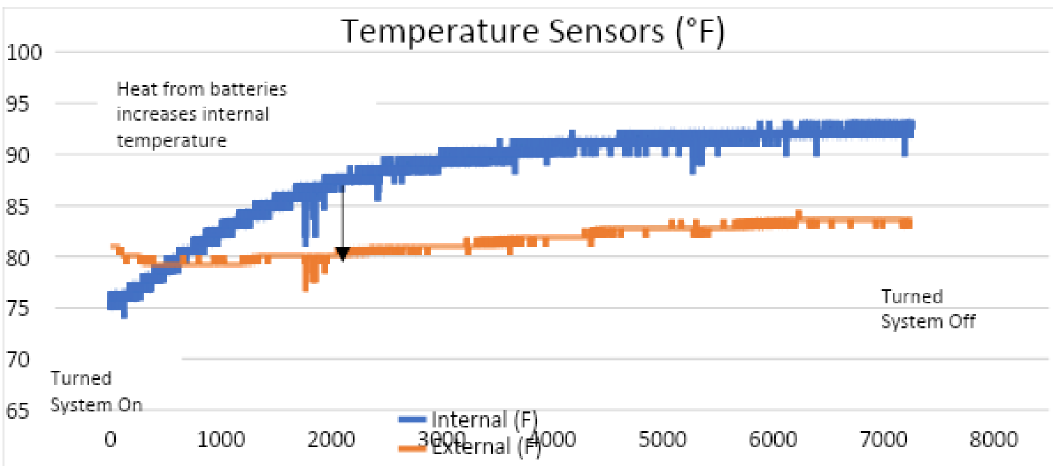


Figure 6.6.2.1 Temperature sensor data from mission simulation test

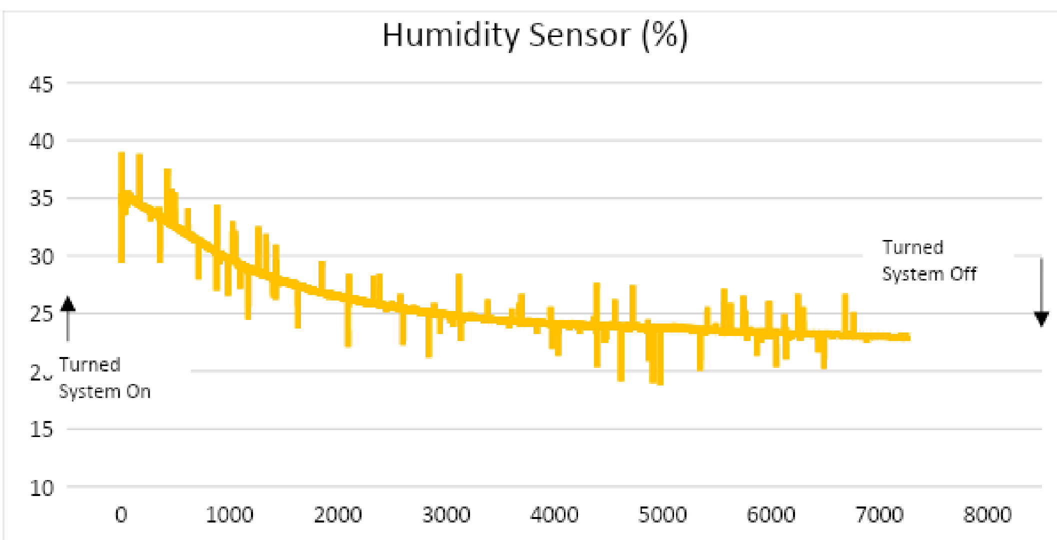


Figure 6.6.2.2 Humidity sensor data from mission simulation test.

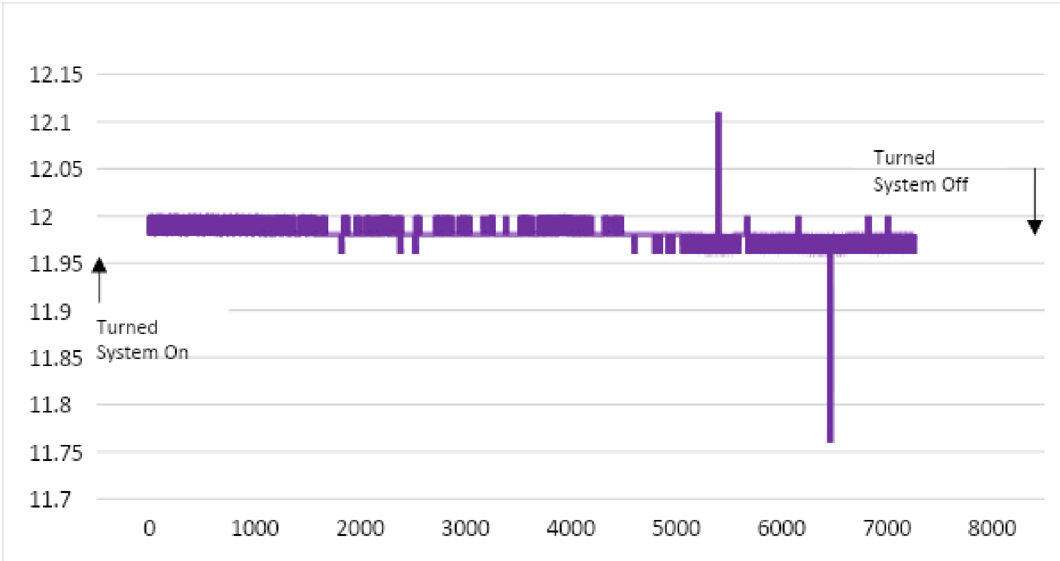


Figure 6.6.2.3 Pressure senor data from mission simulation test.

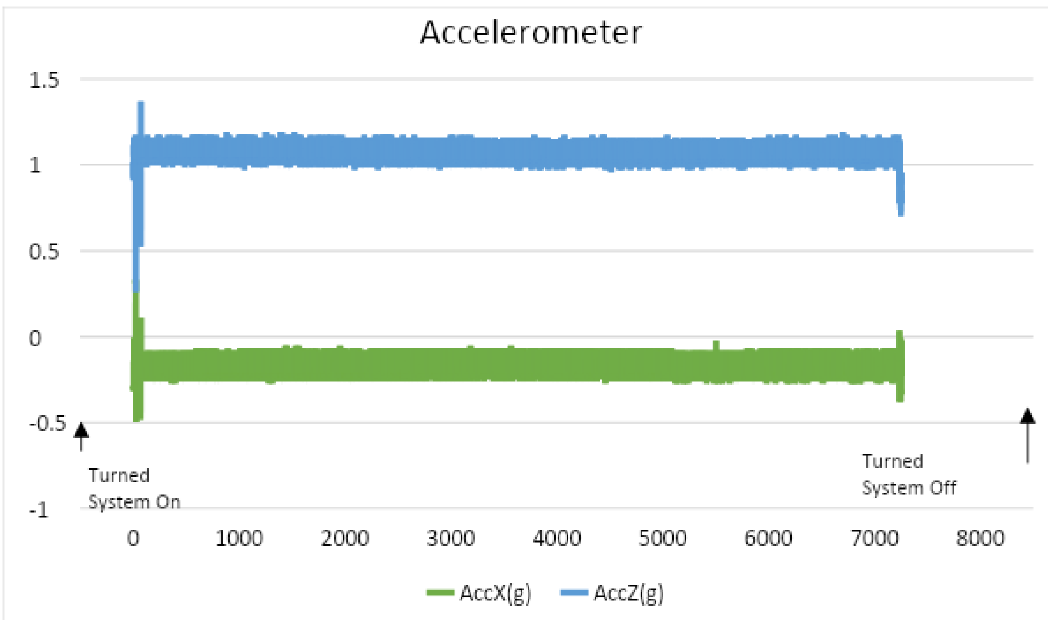


Figure 6.6.2.4 Accelerometer data from mission simulation test.

7.0 Expected Data

7.1 Data Retrieval

A GPS system shall be included on the payload of the balloon prior to launch, which shall relay updates on the location of the BalloonSat experiments down to a computer and the Gateway to Space class. This will insure that the BalloonSat flight string can be found after launch. In addition, Project *Enterprise*'s Arduino Uno shall be coded to collect all of the data recorded by the pressure sensor, internal and external temperature sensors, humidity sensor, and two of the three axes on the accelerometer. The Arduino shall collect data from the sensors once every half second (or 500 milliseconds) throughout the flight. Data from these sensors will be stored on one 8GB microSD card as .txt files. Furthermore, the Arduino Nano will be coded to record the number of muon pulses collected by the CosmicWatch throughout the flight every 500 milliseconds. This information will be saved to a separate 4GB microSD card as .txt files. When the BalloonSat is located via the GPS system, pictures will be taken of the Project Enterprise to document its post-flight conditions. Once back at the University of Colorado Boulder, both the Arduino Uno and Arduino Nano microSD cards will be plugged into a team member's computer, and the data saved on each card can be transferred to Microsoft Excel for analysis.

7.2 Expected Sensor Data

7.2.1 Accelerometer

Team Wall-E expects acceleration to remain mostly constant aside from critical points during flight such as launch, burst, and landing as seen in Figure 7.2.1.

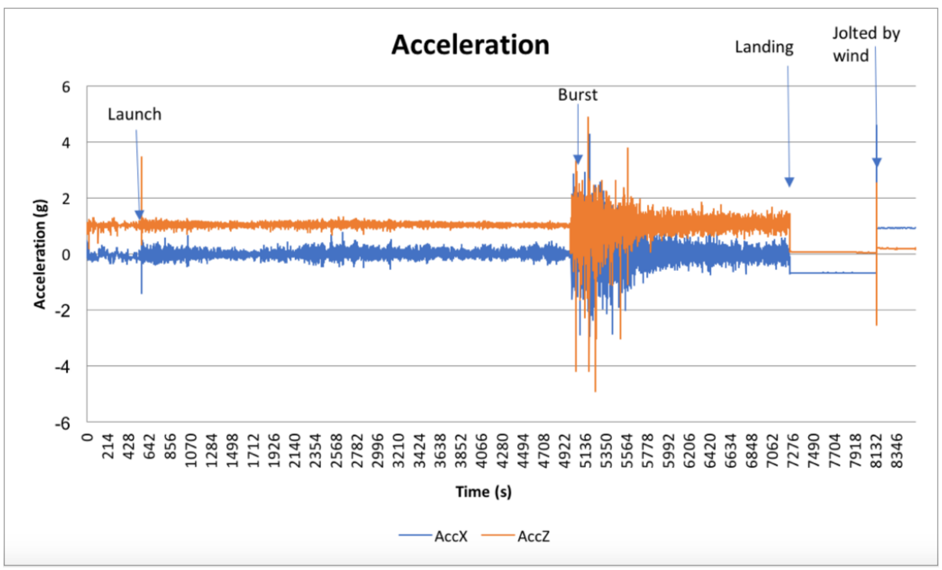


Figure 7.2.1 Data courtesy of Team Area 52 (Spring 2017)

7.2.2 Humidity

Team Wall-E expects humidity to decrease until the tropopause. It shall then remain mostly constant until decent has begun, after which it shall increase, as seen in Figure 7.2.2.

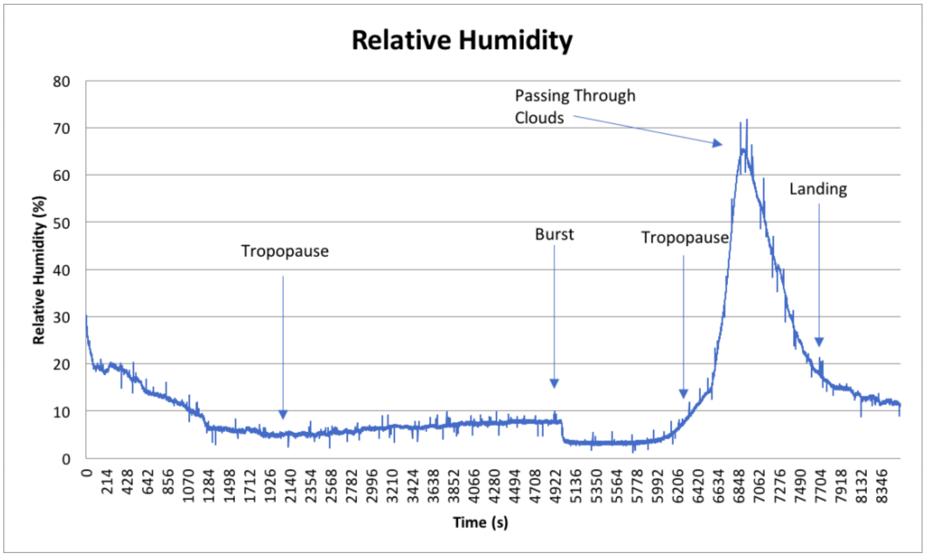


Figure 7.2.2 Data courtesy of Team Area 52 (Spring 2017)

7.2.3 Pressure

Team Wall-E expects pressure to decrease steeply as altitude increases until the tropopause, where it shall then decrease at a slower rate until burst. The pressure shall then increase steeply until it has hit the ground, as seen in Figure 7.2.3.

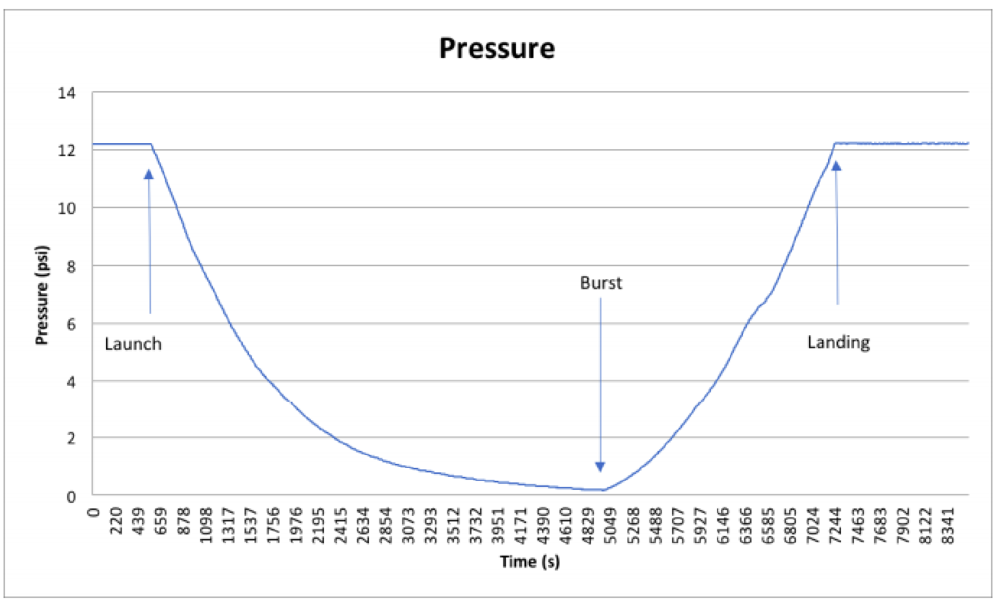


Figure 7.2.3 Data courtesy of Team Area 52 (Spring 2017)

7.2.4 Temperature

Enterprise

Team Wall-E expects both the internal and the external temperatures to decrease as altitude increases. The internal temperature, however, shall remain more consistent and not change as drastically due to the heating pad which shall regulate the internal temperature of the BalloonSat, as seen in Figure 7.2.4.

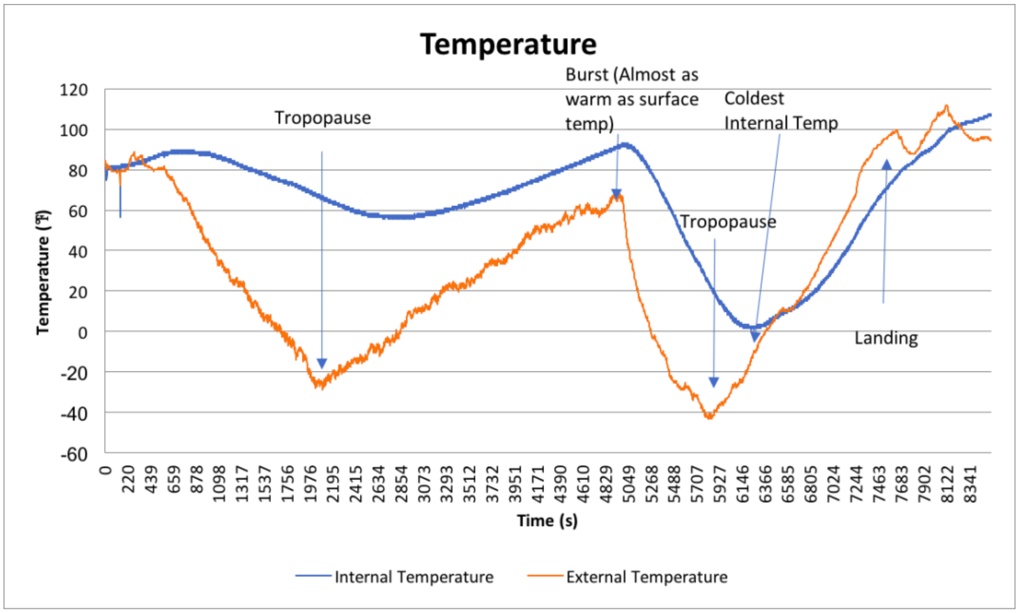


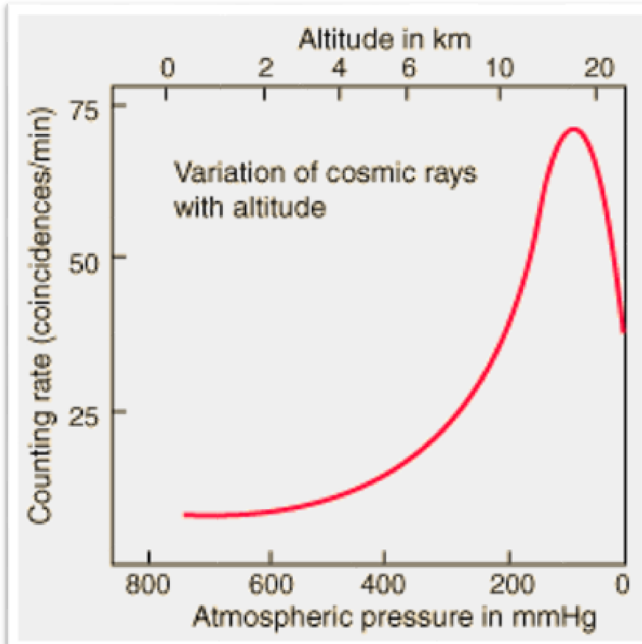
Figure 7.2.4 Data courtesy of Team Area 52 (Spring 2017)

7.3 Expected Camera Data

Provided the GoPro system functions as planned, Team Wall-E expects the camera to record footage of the entire flight. The GoPro will capture unique images of the Earth from an altitude of 30 km, such as the one in Figure 7.3.

Enterprise

7.4 Expected Cosmic Watch Data



Team Wall-E expects that as altitude increases and atmospheric pressure decreases, the muon count from the CosmicWatch detector will increase. At fifteen kilometers, the team expects count to begin decreasing because of the thinning atmosphere, which mean there will not be enough particles for cosmic rays to interact with and degenerate into muons. After burst, Team Wall-E expects the data to be chaotic due to the violent fall conditions, and therefore does not expect to be able to use any of the post-burst data to prove the science hypothesis.

Figure 7.4.1 demonstrates the collection of muons when a CosmicWatch was taken on an airplane that reached a cruising altitude of about ten kilometers. During the time after takeoff, count increased until cruising altitude was met, at which the count rate detection of muons grew steady. Team Wall-E expects to see the same general trend in muon detection while the balloon rises the first ten kilometers of the flight. Figure 7.4.2 demonstrates the trend that Team Wall-E expects to see in the data, particularly from ten to 25 kilometers. Namely, the peak count is expected to occur at about 15 kilometers, after which it should drop off again until burst at 30 kilometers.

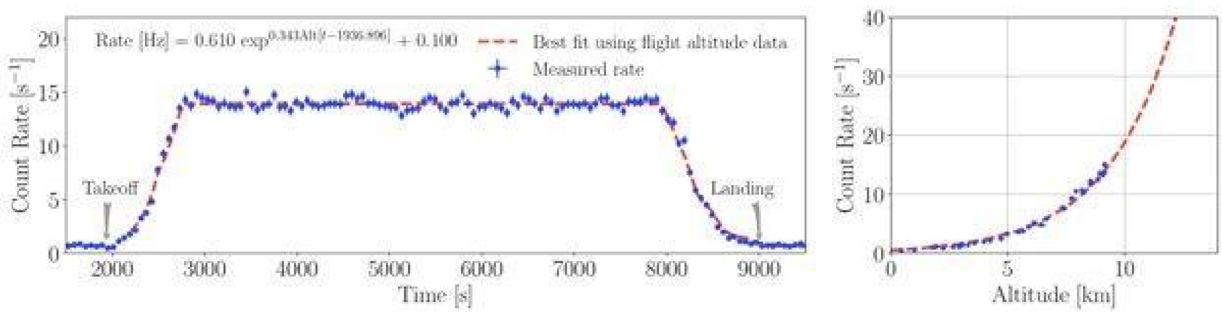


Figure 7.4.1 Data from Spencer Anaxi's flight in an airplane with a CosmicWatch detector.

8.0 Launch and Recovery

All team members of Team Wall-E shall attend the launch of the BalloonSat the morning of Saturday, November 10, 2018. The BalloonSat shall be launched by Holland Morris. Sydney Evans, Nicky Weber and Allison Liu shall ride in the lead vehicle with Chris during recovery and shall be responsible for tracking and recovering the BalloonSat after burst. The balloon is equipped with a GPS system that shall send updates regarding the BalloonSat's location to the

Gateway to Space class. This ensures that the BalloonSat can be located after flight. As detailed in section 7.1, Project *Enterprise*'s Arduino Uno shall be coded to collect all the data recorded by the sensors. Data shall be collected once every half second and data from the sensors shall be stored on one of the microSD cards as .txt files. The Arduino Nano shall be coded to record the number of light flashes from the scintillator indicating muons passing through the scintillator. This shall be saved to a separate microSD card as a .txt file as well. All these data recording processes have been previously tested and confirmed to work. At recovery, Allison shall take pictures of the weather balloon and the exterior of Project *Enterprise* using her phone, to document its post-flight conditions. After taking pictures, switches shall be turned off, batteries shall be unplugged and removed, SD cards shall be removed for safe keeping, and the box and remaining components shall be carried by car back to the University of Colorado, Boulder. Once the team returns to Boulder, photos of the interior of the box shall be taken and data shall then be uploaded to a team member's computer and transferred to Microsoft Excel where it can be analyzed. In previous tests of the systems, data has been successfully transferred and analyzed in this manner.

Launch was successful and every member of Team Wall-E attended. The overall launch went as planned and the payload was launched at approximately 6:40 am, the morning of Saturday, November 10, 2018. Nicky Weber, Allison Liu, and Sydney Evans rode in the lead vehicle as planned, while Jake Pirnack and Tracey Sneed also accompanied the group on recovery. Recovery was successful; the payload was located in Akron, Colorado on rural property. The satellite's box was recovered intact with very minimal damage. The most structural damage sustained were dents on the corners of the box. The Arduino, CosmicWatch, and Go-Pro were all on at the time of recovery while the heater was not. The day following launch, the team was able to recover complete, successful data from all SD cards, and have analyzed the data (see sections 9.0 and 10.0

9.0 Results

All of the sensors connected to the Arduino Uno (accelerometer, pressure, humidity, internal and external temperature sensors) stayed on and collected data over the entirety of the flight. The heater and Cosmic Watch did not stay on for the whole flight. When the BalloonSat was collected, the LED indicating that power was being supplied to the heater was not on. However, based on the internal temperature data, there were no major fluctuations during flight, meaning that the heater must have turned off after landing. As for the CosmicWatch, after reading in the data from the micro SD card, it was determined it stopped collecting data 3 minutes before burst.

9.1 Sensor Results

9.1.1 Accelerometer

Team Wall-E's acceleration data was as expected. The acceleration remained mostly constant aside from critical points during flight such as launch, burst, and landing as seen in Figure 9.1.1.

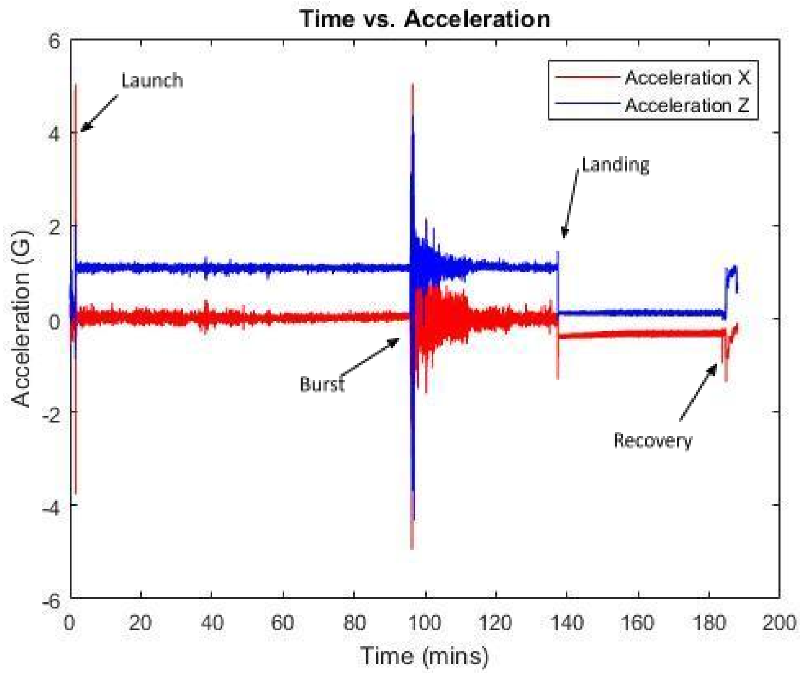


Figure 9.1.1 Accelerometer flight data

9.1.2 Humidity

Team Wall-E's humidity data was as expected. The humidity decreased until the tropopause was reached. It then remained mostly constant until decent, after which it increased, as seen in Figure 9.1.2.

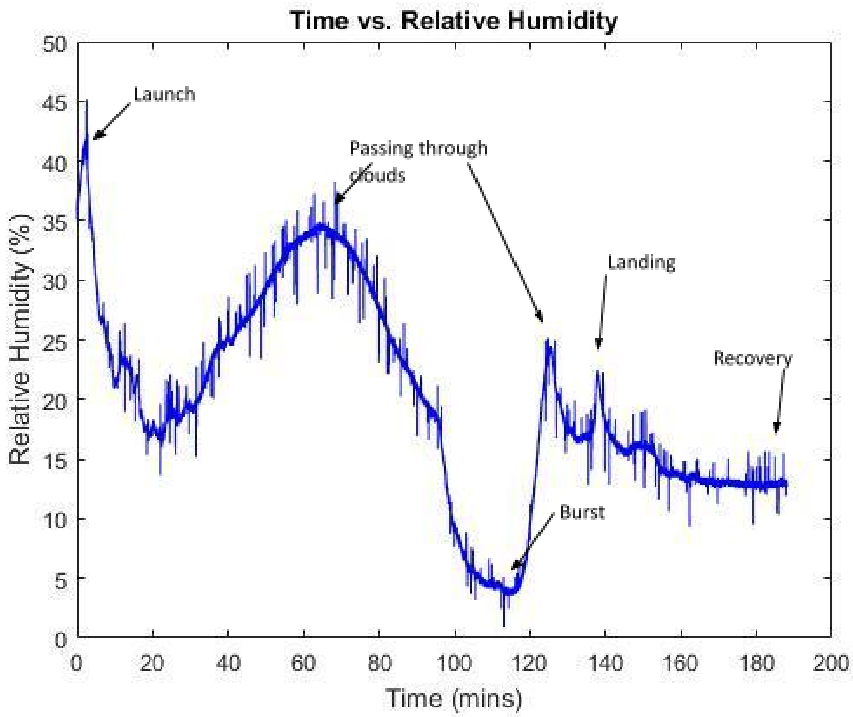


Figure 9.1.2 Humidity flight data

9.1.3 Pressure

Team Wall-E's pressure data was as expected. The pressure decreased steeply as altitude increased until the tropopause was reached, where it then decreased at a slower rate until burst. The pressure then increased steeply until it hit the ground, as seen in Figure 9.1.3. Team Wall-E is unsure what caused the disturbance in the data at approximately 60 minutes. When correlating this with the temperature data, it was noticed that this disturbance occurred directly after the internal temperature reached its lowest point during flight. From this Team Wall-E hypothesized that the low temperature affected the sensor or its connections in a way that made the data spike incorrectly.

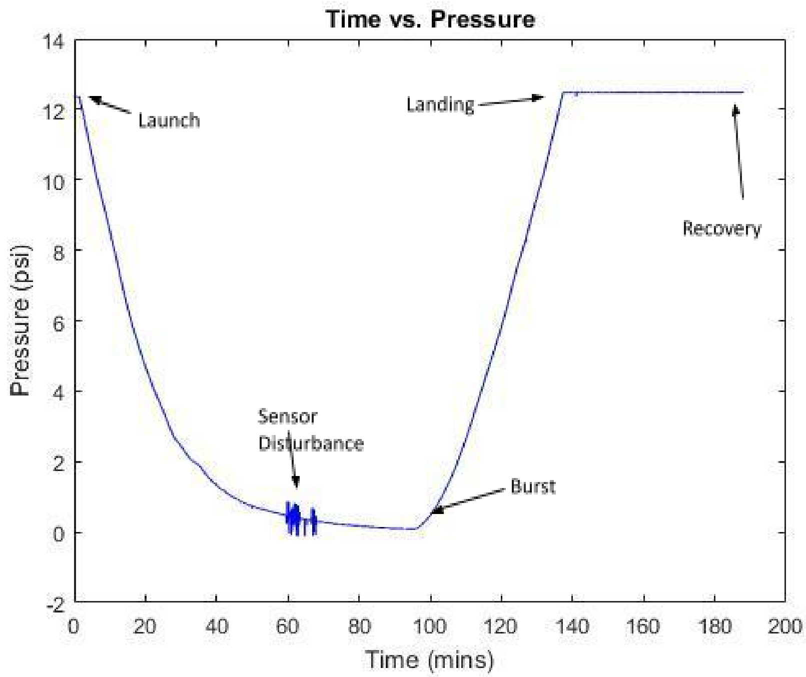


Figure 9.1.3 Pressure flight data

9.1.4 Temperature

Team Wall-E's temperature data was as expected. The internal and external temperatures decreased as altitude increased. The internal temperature, however, remained more consistent and did not change as drastically due to the heating pad which regulated the internal temperature of the BalloonSat, as seen in Figure 9.1.4.

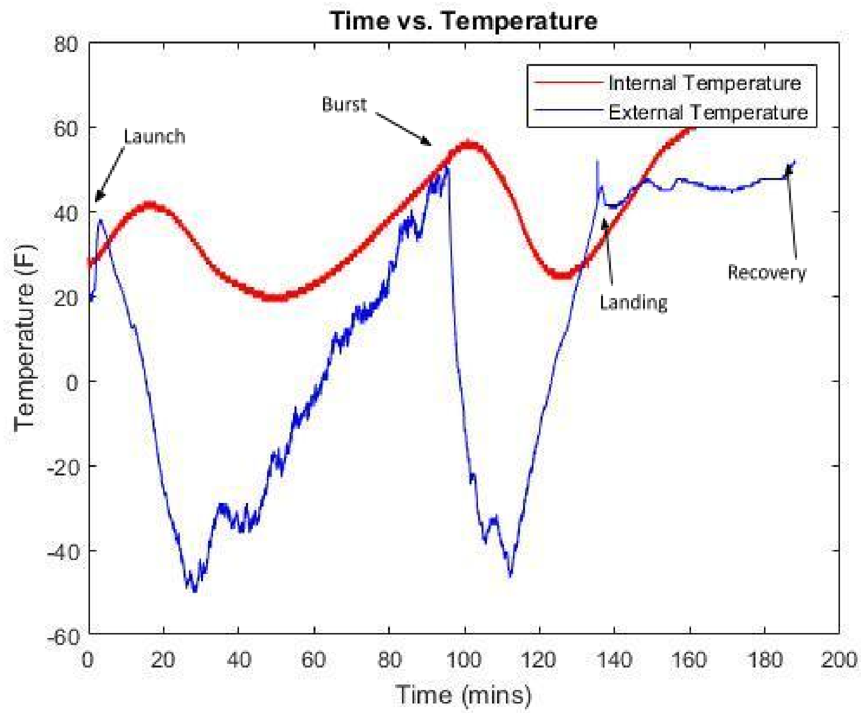


Figure 9.1.4 Temperature flight data

9.2 Camera Results

The GoPro functioned exceptionally. Team Wall-E originally planned for the GoPro to record video, but instead recorded stills during the actual flight, which the team was satisfied with afterwards. The GoPro captured unique images of the Earth from an altitude of 30 km, such as in Figures 9.2.1, 9.2.2, 9.2.3 and 9.2.4.

Enterprise

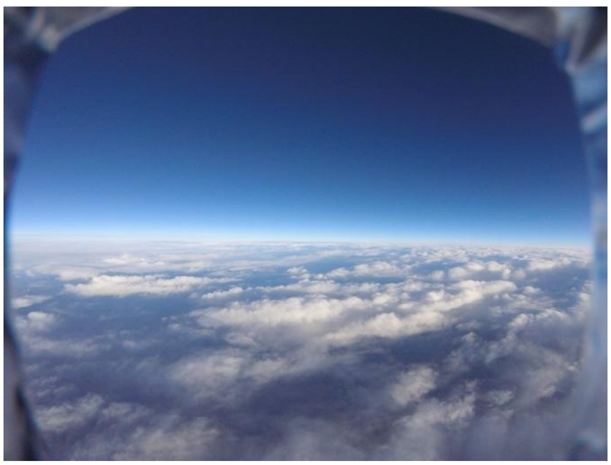


Figure 9.2.1

Figure 9.2.1

Enterprise

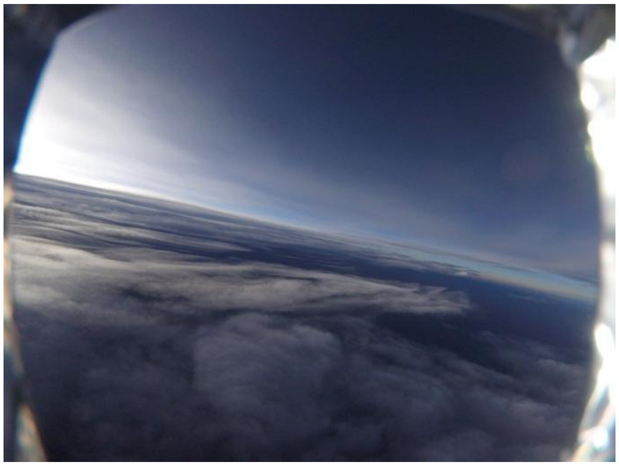


Figure 9.2.3 Figure 9.2.4

9.3 CosmicWatch Results

Team Wall-E collected data from the CosmicWatch from launch until approximately two minutes before burst. The following graphs were created by Team Wall-E in MatLab and google sheets.

Figure 9.3.1 shows time versus pressure and the calculated altitude. Team Wall-E used the hypsometric formula to calculate altitude from the pressure and temperature data. This allowed the team to compare counts to altitude to make conclusion about our hypothesis (which was in regards to counts as a function of altitude), as opposed to counts versus time.

Enterprise

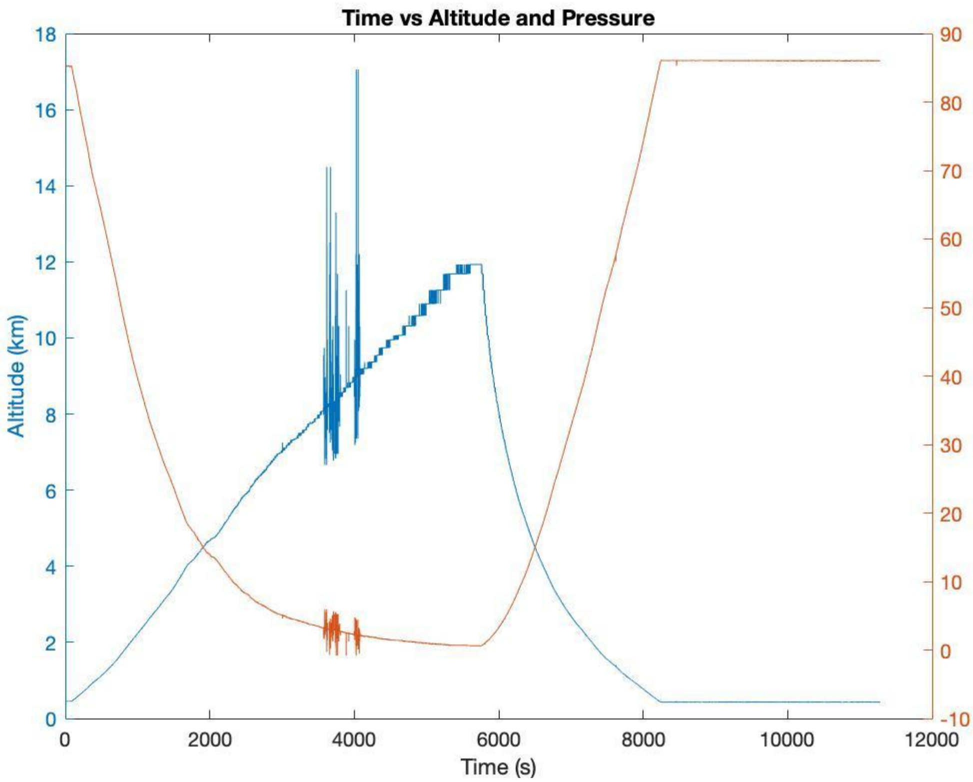


Figure 9.3.1

Figure 9.3.2 shows the count rate versus the calculated altitude. Note that the peak count rate occurs at about 18 kilometers.

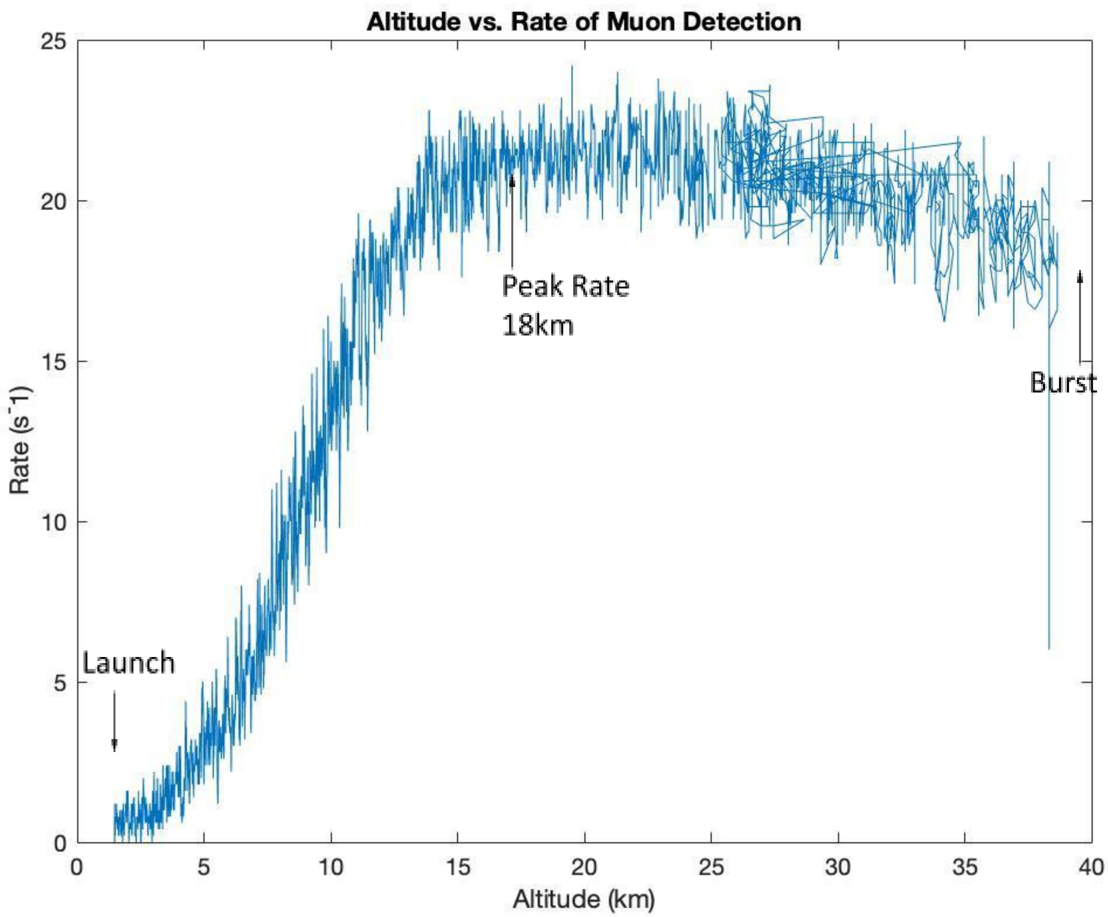


Figure 9.3.2

Figure 9.3.3 shows the average of 100 instant count rates around the time. The changing rate shows a peak detection rate at around 2700 seconds, which Team Wall-E calculated to be 18 kilometers. The normalized distribution of muon intensity using ADC values. It follows roughly a normal distribution.

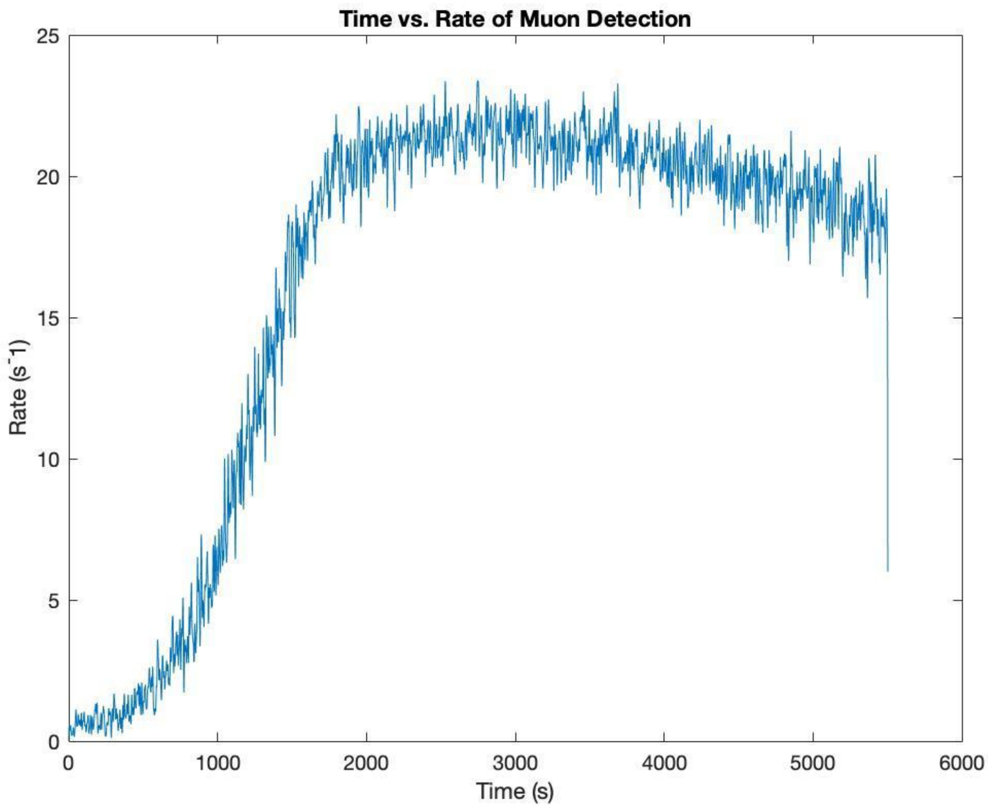


Figure 9.3.3

Figure 9.3.4 is the normalized distribution of muon intensity using ADC values. It follows a roughly normal distribution. When the particles pass through the detector, they make a brighter flash of light the more energy that they have. This larger flash is recorded by the ADC (analog to digital converter) as a higher voltage spike. The data is cut off at the lower end of the normal curve. This is because the team had to set a minimum threshold of 30mV in order to make sure that the particles the team was detecting was only muons. Anything that produced a voltage of less than or equal to 30mV were other forms of radiation such as gamma rays.

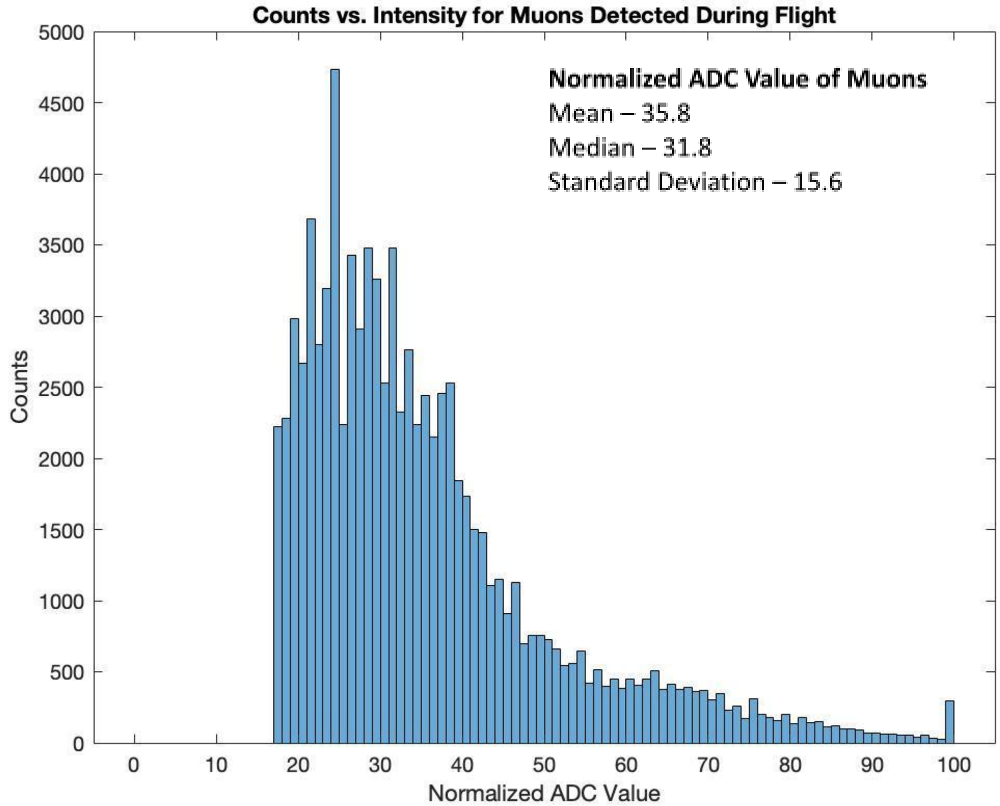


Figure 9.3.4

Figure 9.3.5 shows the average intensity of the muon pulses detected over the course of the flight. The blue bars are the mean intensity of all counts in the first and second half of the time we were recording data. The orange bars are the mean intensity of the first and second halves of the data gathered. The graph shows an increase in intensity of about 3% from the first to second half of the flight.

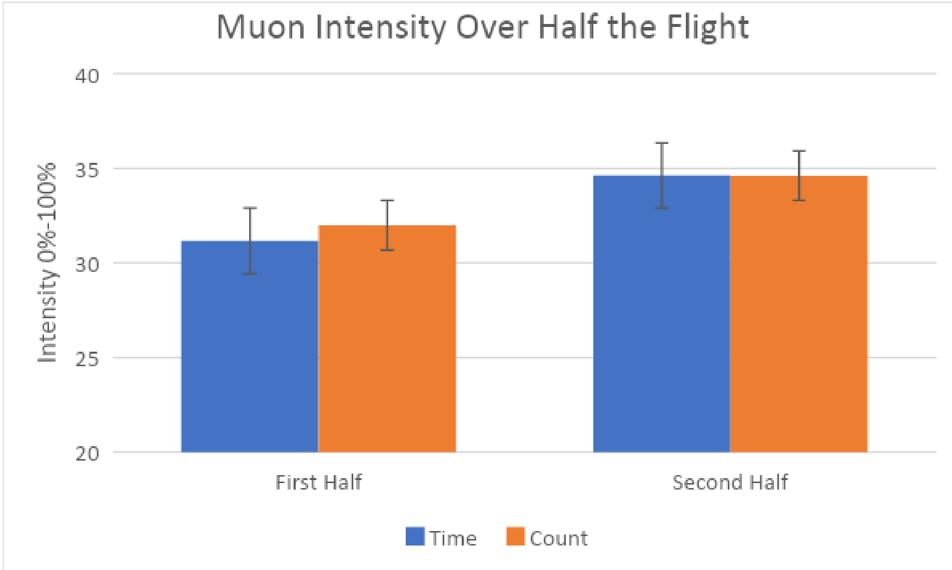


Figure 9.3.5

Figure 9.3.6 shows the same information as in 9.3.5, however with normalized intensity over the time of the flight. The intensity increased as time went on.

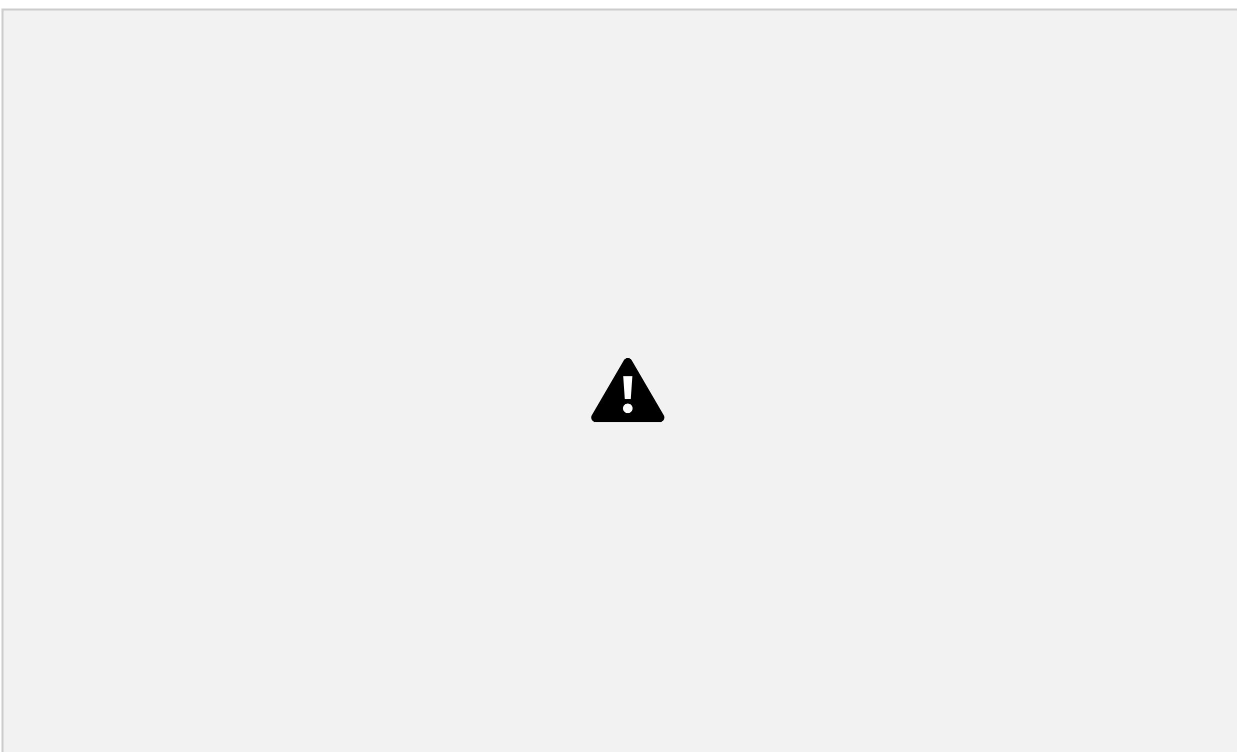


Figure 9.3.6

Figure 9.3.7 shows the counts versus the pressure. The lower pressures occurred at higher altitudes. The decrease on the right side of the graph shows that the lower pressures (which means less particles in the air) corresponded to a drop in the number of counts detected.

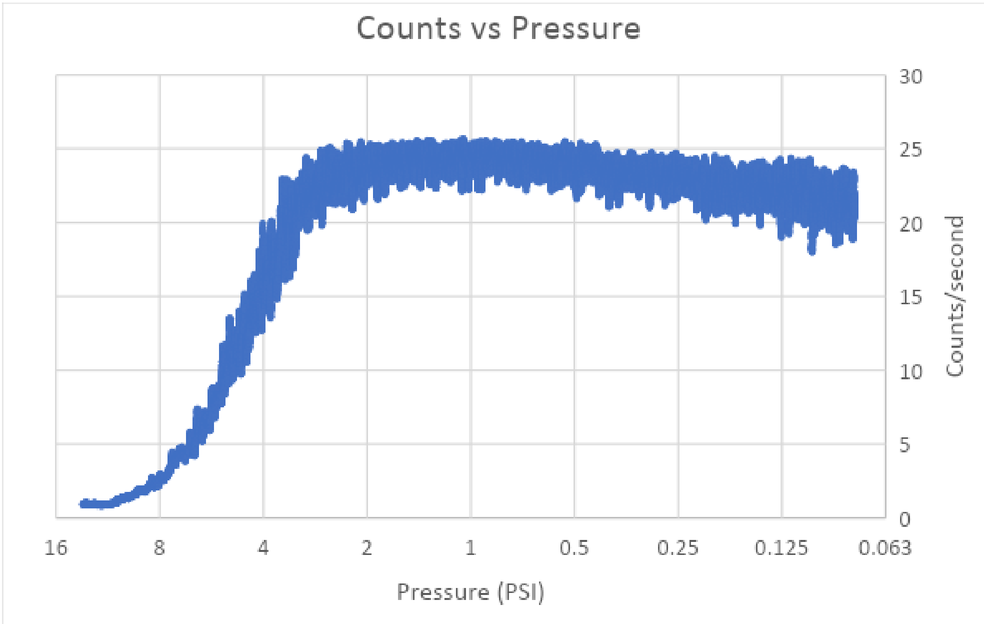


Figure 9.3.7

10.0 Data Analysis

The data Team Wall-E collected through flight is very similar to the expected results. Figure 9.3.2 and 7.4.1 both show count rates as a function of altitude. Figure 7.4.1, however, only has data up to 10 kilometers, and therefore doesn't account for the leveling of rate that Team Wall-E experienced. They both show a count rate of 15 counts per second at the altitude of 10 kilometers, therefore Team Wall-E feels confident that the results are not skewed and the detector worked as expected. Figure 9.3.2 demonstrates a negative slope on the right side of the graph after about 18 kilometers. This was the trend Team Wall-E was expecting based off of Figure 7.4.2, however the team did not see as sharp of a drop. One reason for this is thought to be that Figure 7.4.1 has a logarithmic scale on the altitude axis, and that Team Wall-E did not get high enough to see such an intense decrease as the one presented in the expected data graph.

Nearly as predicted, Team Wall-E found that maximum muon detection happened around 18 kilometers, consistent with some predictions but a little past the teams hypothetical 15km. After future research post-launch it was discovered that 18km closes matches up with the Regener-Pfotzer Maximum, the altitude of approximately 20 km where the generation of secondary cosmic rays (such as muons) balances out with their absorption which leads to an optimization in count rate.

Figures 9.3.5 and 9.3.6 demonstrated that the energy of muons increased as altitude increased. One reason for this could be that higher energy muons are being generated at higher altitudes. Another explanation that Team Wall-E feels may be more accurate, however, is that the muons lose energy as they travel towards the surface of the Earth. This means that as the detector got closer to the generation point of the muons, it was detecting them earlier in their life, and therefore at a point where they had more energy.

After the Design Expo, Team Wall-E took the advice from the judges to create a pressure versus count graph, which can be seen in Figure 9.3.7. The purpose of this was to attempt to show the direct relationship between the density of the atoms in the air with the number of muons generated by the incoming cosmic rays. Based on the team's previous data, it can be implied that higher muon counts corresponds to increased rates of muon generation at that location. From this assumption, the graph in Figure 9.3.7 demonstrates that there are fewer muons generated at higher pressures (such as at or near the surface of the Earth), and more muons generated further up in the atmosphere (where the pressure is lower). The key point of this graph, however, lies in the decreasing trend on the right hand side. Lower pressures mean less atoms in the air, and we can see that the very low pressures correspond to a decrease in counts detected (and hence generated). This confirms Team Wall-E's prediction that above a certain point in the atmosphere, the cosmic rays do not have as many particles to interact with and break down into muons.

11.0 Failure Analysis

Upon recovery when team Wall-E examined Project *Enterprise,* there was no apparent damage to the physical box. When Team Wall-E accessed the LED indicators, all of the LED indicators showed that the all systems were working properly with the exception of the heating system, meaning it failed prior to recovery. Also, upon reviewing CosmicWatch data from the OpenLog SD card, Team Wall-E found that the OpenLog stopped collecting data from the CosmicWatch approximately two minutes before burst.

11.1 Heater System

Team Wall-E's indicator LED for the heater system was not on when the BalloonSat was recovered. However, upon examining the internal temperature sensor data, the data showed a trend consistent with the expected internal temperature had the heating system operated properly throughout the entirety of the flight. Because of the internal temperature sensor data, Team Wall-E has concluded that heating system likely failed after Project *Enterprise* had landed, and therefore has no reason to conclude that the experiment was adversely affected by the failed heating system. Due to this, two batteries were enough for the heater system to last the entire flight and no changes needed to be made.

11.2 CosmicWatch OpenLog

Twice during testing, the OpenLog for the CosmicWatch system failed to record data to the microSD card. The failure was intermittent_after a certain time it would stop recording and not start again for the duration of the tests. The connections were re-soldered and tested, and after no more failures the issue was considered resolved. However, two minutes before burst data stopped being recorded. At landing, the SD card was in place, the batteries powered and detector on. The connections had just been re-soldered, so Team Wall-E further examined the OpenLog. One wire was exposed and frayed. By process of elimination, the team believes that about two minutes before flight, the wire touched another electronic component, therefore bridging the circuit and stopping the data from being recorded. The failure occurred after the main data collection phase, so no great harm came to the mission. In order to resolve the issue, Team Wall-E replaced the wire and re-soldered the connections.

11.3 GoPro Recording Mode

Team Wall-E had planned on taking HD video throughout the entire flight. Prior to flight, however, the GoPro was accidentally set to record stills instead of video. The resulting pictures were still satisfactory to the entire team, so this is a failure in name only.

12.0 Conclusions

In conclusion, Team Wall-E's Project *Enterprise* demonstrated the usefulness of using a low-cost muon detector for determining changes in muon flux through the atmosphere. It is practical to use the CosmicWatch to study muons in the atmosphere, as it is a relatively lightweight, low-cost and robust system. The experiment replicated and verified current models for the relationships between muon flux and altitude and muon intensity and altitude. The data from Project *Enterprise* allows Team Wall-E to make several conclusions about muon generation as follows:

- Above about 18 kilometers, cosmic rays have fewer particles in the atmosphere to interact with, and therefore fewer muons are generated.
- Muons increase in energy the closer to their point of generation. This means they lose energy as they travel towards the surface of the Earth once they are created.
- An altitude of 18 kilometers is ideal for maximum muon generation. This is the altitude at which the difference between muon generation and absorption is optimized.

This estimate could be used to determine the placement of detectors for practices like muon imaging for volcano mapping.

13.0 Ready for Flight

Team Wall-E has reviewed all the systems of Project *Enterprise.* All systems of Project *Enterprise* are ready for launch. Team Wall-E has determined that the structure, heating systems and sensor systems are currently ready for launch. In order to prepare for launch, all batteries have been replaced. As the heater was not on during recovery, it has been analyzed in the data that the heater was working throughout flight and had turned off after flight ,thus concluding that no further correction needs to be made to the heater and other systems. Wiring within the box regarding its components has been addressed, which included re-soldering certain components to ensure connectivity. The payload shall be stored in a dry location at room temperature until second flight. The payload can be activated by flipping the three switches within the flap on the side of the box that correspond with the heater, Arduino system, and CosmicWatch. There shall be an LED for each respective switch that shall illuminate once its component has been activated. The camera can be activated by inserting a finger into the side of the box where the camera is located and pressing the top of the GoPro until a beeping tone is heard and a red light flashes. If the payload has not been launched within six months, the batteries may not be functional, however, all other components of the payload pose no issues.

14.0 Lessons Learned

Team Wall-E has learned several key lessons whilst taking on the task of Project *Enterprise*. First off, Team Wall-E should have adjusted its initial plans for acquiring parts for the Cosmic Watch detector, such as its printed circuit boards, much earlier on. Team Wall-E had originally asked some members of the ITLL to build the two PCBs for the Cosmic Watch design. However, the date for the boards' completion kept on being pushed farther and farther back due to a malfunctioning machine needed to make the boards. At this point Team Wall-E should have made a backup plan or simply ordered the PCBs online from a separate source. When the PCBs finally came in from the ITLL, they were incorrect sizes and Team Wall-E was forced to scramble to acquire these parts before the Mission Simulation Test and Launch Readiness Review. Therefore, Team Wall-E learned that in the future it is okay and highly important to alter an initial plan as early as possible if it appears that it might not work out. This will allow for more time to resolve other future unpredicted issue rather than just waiting around and hoping everything will work out. In addition, Team Wall-E had a difficult time organizing the mission data from the Cosmic Watch into useful and readable graphs. Before flight, Team Wall-E only really focused on that fact that the Cosmic Watch was recording data and didn’t have an exact plan for what it was going to do with this data post launch. A significant amount of time was spent post flight figuring out exactly which data points were important and should be graphed, and which graphs were necessary to illustrate the team’s findings. Therefore, Team Wall-E learned that it is a better idea to do extensive research and planning before experimental data is collected, rather than adjusting and interpreting experimental data after it has been collected.

15.0 Message to Next Semester

Dear future Gateway Students,

The first lecture was very exciting, and right about now you are thinking up your mission proposals. The best advice we have to offer is: start now. Three months might seem like a long time, but it goes by quick, and even quicker when its three weeks to launch and you have not yet started your project. Even if you have no idea what your mission is, you can easily fill the first few weeks perfecting your Arduino and OpenLog while you figure it out. Once you have your mission, start early, meet often, and try to finish a week before the mission simulation in class, that gives you two weeks to debug—which you will need. This class is a lot less stressful and much more fun when you aren’t worrying about your project during the physics and calc exams that seem to happen every other week. The next piece of advice is: don’t be afraid to redo an entire portion of your project. We had a wiring bug that could have ended up crippling our main Arduino during ascent, but two of our team members stayed up and redid all the wiring in our project, for which we are eternally grateful. Also, the main circuit board of our project was completed late and wrong. We could have pieced together a functioning sensor or wait a week for a new one to arrive. We decided to do it the right way, and it payed off later in our presentations when we could show a polished and finished project. Finally, don’t be afraid to ask for help. Tim May was a great resource with our main sensor and helping us solder, but there are also resources outside the ITLL as well. The Idea Forge has great people and so too does the

Duane Physics Lab. If you are doing a physics experiment or any sort of sensor, Hans on the second floor is a great help. Good luck and have a great time!

Best regards,

Team Wall-E