Thermal Analysis of High Altitude Ballooning Payloads

Improving Simulation of Stratospheric Thermal Conditions

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ABSTRACT

Balloon-borne telescopes have the potential to produce almost space telescope quality data, because stratospheric balloons float above 99% of the atmosphere. The stratospheric environment poses unique and unsolved issues especially in the thermal stability of the optics. To inform the design of the future "Testbed for High-Acuity Imaging - Stable Photometry and Image-Motion Compensation Experiment" balloon borne telescope, a team formed to improve thermal models for the stratosphere, especially by including convection. To accomplish such a feat the following thesis tracts the progress in developing, and testing such models as well as outlining the production of another smaller high altitude balloon. The smaller balloon will fly a number of sensors which help to inform about the thermal environment in thin low pressure air.

1. INTRODUCTION AND PROJECT OBJECTIVES

1.1. *THAI-SPICE Objectives*

By flying a telescope on a high altitude balloon, theoretically one can approach the capabilities of space fairing telescopes at highly reduced prices. In the past, other ballooning missions such as BLASTPOL, PoGOLite, SuperBIT and Sunrise have attempted to use telescopes in the upper atmosphere. Unfortunately, a number of issues prevent balloon-borne telescopes from being a low-cost method to observe above most of the atmosphere. The environment at altitude poses unique challenges for telescopes. Pointing, maintaining focus, and collimation while moving at the mercy of the winds all increase the challenge. Some projects have been able to successfully take on some of those issues. For example in 2014, a polarimeter flying on the SPIDER ballooning project achieved relatively good pointing (Shariff 2014). Some balloon borne telescope problems, however, have not been sufficiently solved. To create a useful telescope, designers still need to create better thermal regulation in the high altitude environments. A well functioning telescope requires a precisely shaped mirror. A thermal gradient will cause warping on the mirror, and therefore

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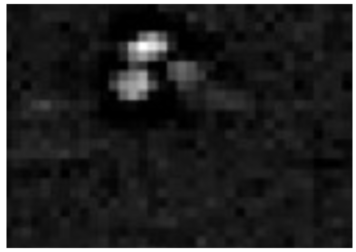

Figure 1. This image from the SuperBIT balloon shows that balloon-borne astronomy has not yet matured yet. The above image should be only one source instead of three. Because of the optical imperfections in their system, the one image appears to be three.

render the telescope unusable. This thesis documents attempts to accurately model the thermal environment of a balloon-borne telescope in order to better mitigate disastrous mirror warping. In the past, missions have been unable to overcome those issues and produce stable useful images. Below illustrates such problems from an image taken by SuperBIT of what should be a single point source.

In order to maximize flight time, balloon-borne telescopes fly on enormous long-lasting balloons, especially so called "super-pressure" and "zero-pressure" balloons, which use pressure variations to prevent popping. NASA's Balloon Program typically operates zero-pressure, and super-pressure balloons between 110,000, and 125,000 feet. At these altitudes, balloons experience pressures between 3 and 8 Torr (whereas typical atmospheric pressure is roughly 760 Torr) (Young, 2015).

Typically ambient air temperatures hover around -50 °C but vary some based on location. A telescope floats in the stratosphere above 99.3% to 99.6% of the atmosphere and therefore, heat transfer through convection plays a much more minor role. Radiative transfer seems to play the much more important role in heat transfer. The mirror of the telescope points to the frigid, 2.7 Kelvin cosmos, and attempts to radiatively cool to that temperature. The earth, heated by the sun, creates an extremely wide, and constant heat source. During the day time, the sun provides an acute thermal load. Balancing those, as well as any heat sources on board has proven yet too difficult to surmount.

The University of Virginia Astronomy department has stake in one such ballooning project, the so called Testbed for High-Acuity Imaging - Stable Photometry and Image-Motion Compensation Experiment or THAI-SPICE. According to the science and technology proposal, this balloon seeks to achieve success through the following technologies: "(a) high-frequency motion compensation, (b) passive thermal control of the OTA and (c) real-time continuous monitoring of the OTA's [Optical Tube Assembly] wavefront error" (Young et al. 2017).

In order to support the THAI-SPICE ballooning project, this thesis follows the creation and beginning steps of a UVA ballooning group concerned with improving low pressure thermal modeling, as well as development of smaller balloon borne sensor packages. The group hopes to improve modeling accuracy at the rarefied, and frigid conditions encountered by high altitude ballooning mission. Professor Skruskie and I divided the workload for other undergraduates in two categories: thermal modeling, and experimental data gathering. Six engineering undergraduate students, in addition to myself have joined to participate, and advise the building process. The improved modeling will hope to aid design which improve the thermal environment for THAI-SPICE's optical system.

Ultimately, the goal of the project seeks methodologies for more thorough modeling of the environment of a balloon borne telescope. Thermal modeling for similar projects only included radiative and conductive heat transfer. Questions have been raised about the efficacy of models which do not concern themselves with the convection in the low pressure fluid environment of the upper atmosphere. Aerospace engineers heavily employ the use of fluid modeling software, which already uses heat transfer in flows in order to design other objects in our atmosphere. Since previous ballooning projects assumed convective heating by fluids has little effect at such low pressures, computational fluid methods have not yet been included in thermal design. The simulation team sought to research those existing methodologies and apply them to the environment of a balloon-borne telescope. The experimental design team, in parallel, needed to design a test of a thermally similar environment in order to quantify the accuracy of the simulation team's models.

Once the experimental design team shows our simulations have sufficiently improved accuracy, the thermal modeling group plans to iteratively increase the complexity of their models until they closely resemble those of the future gondola, while noting how design change affects thermal stability of the modeled of the optical system. By being able to accurately predict the thermal environment, the designers of the THAI-SPICE gondola can iteratively test and improve thermal stability to which the telescope optics are exposed.

The Department of Astronomy here at UVA and specifically Professor Skrutskie already have some experience designing and flying balloons. The final section of this thesis will discuss the design of another much smaller scale ballooning mission in aid of the THAI-SPICE mission. These balloons fly for a much shorter amount of time and can only carry four pounds of payload per FAA regulation. The previous flight overseen by Professor Skutskie already produced useful atmospheric conditions data like air pressure. The next balloon seeks to gain even more knowledge of the thermal environment through use a sensor suite and a thermal reflector. This new balloon will be flown locally for data collection and to demonstrate the ability to observe heat and radiate it away from a sample. Largely, the smaller mission hopes to inform and help shore up correlations found from testing.

2. LOGISTICAL ORGANIZATION

Other undergraduate students produced much of the work contained within this thesis. Much of my work focused on management of the two teams. Effective management required regular task delegation and communication. Specific strategies evolved through the semester. However, before any management strategies could be attempted, we needed to recruit members for each team. The proposal called for six undergraduates to support those teams.

In order to find the most useful possible team members, we selectively advertised the project to undergraduates with related knowledge, interest and skills. Only one undergraduate, Haotian Liu, found the mission on their own accord, leaving us to find at least five more qualified students. To advertise the exciting THAI-SPICE project, I wrote a short one page document including a description of the overall objectives of the project, which Professor Skrutskie ultimately re-wrote. To distribute that advertisement, undergraduates studying aerospace, computer and mechanical engineering received the advertisement per department email. Astronomy and astronomy-physics students could access the listing in a departmental database of available research positions. Finally, students involved in an advanced computational fluid dynamics class also learned about the project as a potential final class project. The project originally planned for roughly six undergraduates besides myself. Through self selection exactly that number of undergraduates joined.

As I mentioned above, managing these students effectively required organization and communication. The students split themselves during the first meeting based on their personal interest between the simulation team and the team creating the relevant physical model. Since the meat of the research hopes to apply fluid simulation to modeling the thermal environment of a balloon borne telescope, which had not yet been successfully done, the teams were unevenly split with four of the members joining the simulation group. The other two students were delegated to the experimental group. The two individual groups then self-elected a leader. Those two were Haotian Liu for the experimental group and Rachel Weeks for the simulation team. They both then organized and delegated specific work week to week as well as dealt with scheduling of subsystem meetings. A faculty member also assisted each of the subgroups. Department research scientist Matt Nelson assisted Haotian Liu and his group build useful physical models, while department engineer Garrett Ebelke spent time with the simulation team. All of the undergraduate researchers, as well as Professor Skrutskie, Garrett Ebelke, Matt Nelson and senior scientist John Wilson also met weekly to discuss the progress and findings of the week as well as delegate future tasks.

Setting clear goals to complete each week ensured progress. How to communicate and delegate those goals was just as important as the goals themselves. We attempted to use the collaborative project management software Trello to track individual and group progress. Updating the Trello with new tasks typically happened once every two weeks, inspired by the length of sprints used by other undergraduate engineering projects like the Virginia CubeSat Constellation. The Trello board allows for easier communication and task delegation. The usefulness of a board such as ours also

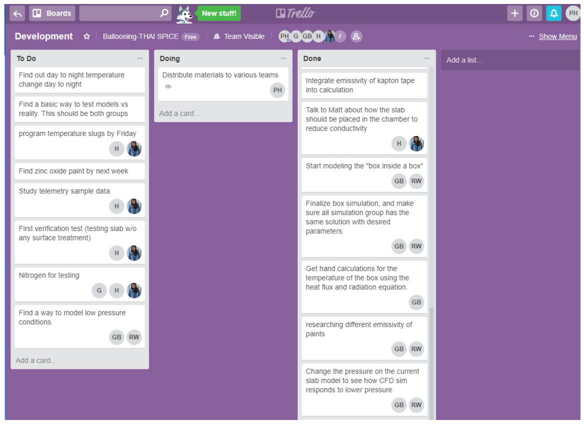

Figure 2. Above is a snapshot of our Trello board now. For most of the semester the group regularly kept the board up to date; however, nearing finals the board fell apart.

stems from the immediate ability to find an overview of what each team and member worked on.

A key aspect to managing unpaid undergraduates pursuing technically challenging degrees happens to be getting the students to continue to show up, thus the weekly or biweekly workload varied based on individual student availability. The Trello board, however, essentially applied social pressure to force students to produce some amount of work week-to-week. In each meeting, we discussed the progress from each team and what the logical next steps for each group should be. Then, the teams in turn were expected to update the Trello board with task delegation as well as marking who had been assigned each task. The tasks fit into three categories: To-Do, In Progress, and Done.

3. SIMULATION TEAM

As discussed, the simulation team specifically set out to produce the most accurate possible thermal simulation of the low pressure environment to which a high altitude telescope would be subjugated to. In the past, the thermal simulations for previous balloon borne telescopes have failed since the previous balloons flew with imperfect optics due to thermal stress. Most of these previous studies implied that the fluid dynamics of the atmosphere had negligible effects.

3.1. *Finite Element Simulation*

Initially, this team researched the previous ballooning thermal modeling methodologies to find what they may lack. We settled on studying the assumption that fluid thermal transfer in low pressure environments has negligible effects. Despite an extremely thin atmosphere being present, almost no other previous balloon borne telescope accurately accounted for the convection carried out by the air or how the various heat sources affected the air environment. Typical investigations into air breathing environments have been modeled using finite element analysis (FEA) methodologies, especially C&R Technologies' "Thermal Desktop." For our first models, the simulation team produced a similar finite element analysis model. Of course to produce that data, they needed to produce a model testable with the resources of the department. Additionally, the first physical models run by the other team should mimic those FEA produced results as they were run at pressure lower than the upper atmosphere.

Fortunately, the astronomy instrumentation group already had access to a functional cryostat with mounts which can hold a 24 inch by 12 inch block. The thickness of that block can vary. The environment within the cryostat mirrored the upper atmosphere as closely as possible to maximize applicability. How that was achieved is discussed in the following section on the cryostat team. The simplest test which still gives applicable data involves just setting a slab of aluminum in the chamber. Students from both teams determined the thickness of the block of aluminum to best suite our experiment. In order to produce quality high resolution data, both teams had to agree on a volume of aluminum which reaches thermal equilibrium between 24 - 48 hours using different methodologies.

The simulation team completed simulations with varying volumes of aluminum, within the simulated environment of the cryostat. At first, only finite element methods had been used to simulate the slab in a cryostat experiment. The main reasons being that radiative transfer does dominate the macro effects of heat transfer, and it gives us data useful for comparison. The students used the finite element analysis software ANSYS to iterate through thicknesses of aluminum alloy 6061-T6. These models took into account only a uniform emissivity on each face. The simulation gave each face of the block an emissivity of 0.02. To simulate the environment of the cryostat the top and sides of the block radiated to 300 Kelvin while the bottom radiated to a frigid 77 kelvin.

Each simulation finished when the blocks reached thermal equilibrium. To know when that occurs, one must first define equilibrium. The team decided "[e]quilibrium is defined as temperature staying accurate [and steady] to the tens place (0.1) for [at least] 30 minutes" (Heat Simulations, 2018). Then by iteratively increasing thicknesses of aluminum simulated until time to equilibrium fit in the desired times, the group came up with their answer. Their model predicted the ideal block thickness to be 0.25 inches. The following graph shows the relation between time and temperature for that block. The line denotes exactly time the block needs to reach thermal equilibrium.

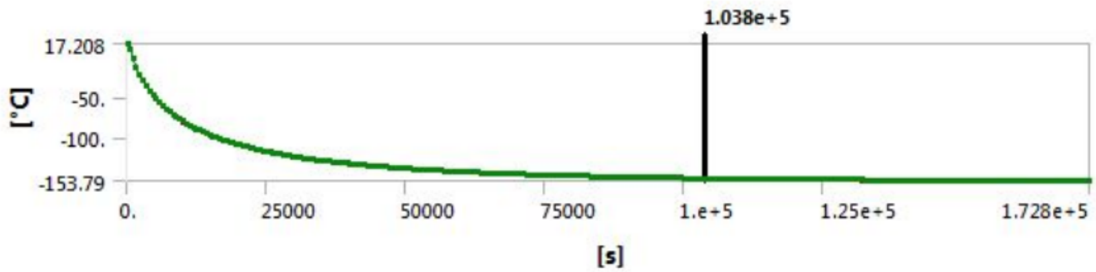

Figure 3. The ANSYS produced graph which shows the length of time required to reach equilibrium for a 0.25 inch by 24 inch by 12 inch slab of Aluminum 606. Their simulations predicts a cooling time of 28.8 hours

Now it is important to point out that equilibrium does not mean the block reached an isothermal state. In fact, these simulations produced results which showed a small thermal gradient in the slab. The following graph shows the final state of the block from one simulation. Notice that the gradient occurs as a function of the distance from the center of the rectangular slab in a oval pattern.

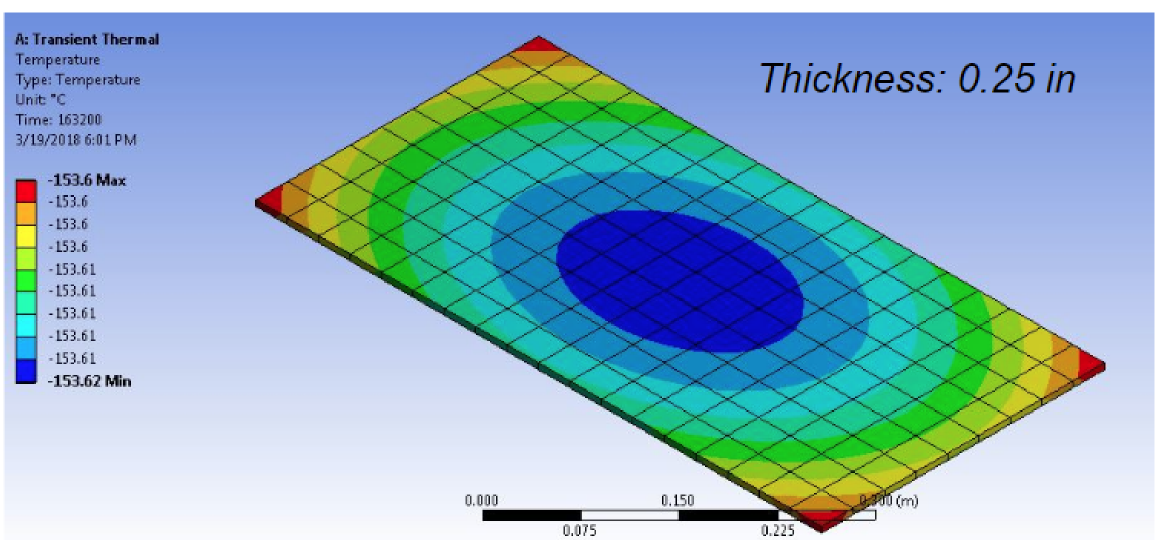

Figure 4. The ANSYS simulated equilibrium state for the block of aluminum

One should note the tiny range of temperatures shown in the graph. The slab only varies a total of 0.2 K. The expected equilibrium temperature varied somewhat from test to test, and by doing multiple tests, the simulation team reported the block reaches an average equilibrium temperature 122.36 K.

The next step in producing a more accurate model involves including convection and even fluids in general. The team identified that neglect as the main potential source of error in previous projects. All of the students in the simulation group study aerospace engineering and therefore have some experience modeling fluids from multiple required classes. One of the most important and interesting classes introduces the concepts of Computational Fluid Dynamics or CFD. CFD software packages use numerical analysis to solve and analyze fluid flows through the application of fluid mechanics. The University of Virginia holds an especially lucky and distinguished connection to CFD, since many of the required aerospace courses in CFD are taught by AutoDesk CFD inventor, Professor Rita Schnipke.

Typically, however, researchers use computational fluid dynamics in higher air densities than those experienced by the high altitude balloons at operating altitudes. In fact, in rarefied atmospheric environments, many aerospace engineers hold the belief that computational fluid dynamics cannot produce results of any worth. In order to deem whether or not CFD might present any use in stratospheric balloon projects before any simulation work started in CFD, I asked Dr. Schnipke for her advice.

Professor Schnipke felt relatively confident that at the 2-8 Torr range a well made model in CFD would produce reasonable results. She warned us that pressures in the milliTorr range cause CFD to produce untrustworthy results, so the simulations bump up right to the edge of its capability. Armed with that knowledge, the computational team began exploring how CFD handled low pressure environments similar to those in the stratosphere.

Orientation, also, can produce even larger issues for balloon borne telescopes. A telescope mirror needs to change orientation with respect to gravity if that scope points anywhere except to the zenith. In the stratosphere, a telescope mirror, as it radiates to space, would cool the air in contact with it. If the mirror stayed perpendicular, the air would cool, and settle in the mirrors concave bowl. That might actually be a good effect, as optics tend to do best in cold environments. We expect, however, whenever the scope pivots, gravity pushes the colder, denser air off. This essentially creating a cycle as air cools falls off and is replaced with new air. The mirror cools that new air. The air then becomes denser and sloughs off the mirror. Such a thermally variable environment needs mitigation if one hopes to have an unwarped mirror. For that reason, the first set of CFD tests involved testing conditions where gravity pulls in directions not perpendicular to an aluminum block. Once again the simulation used the same sized aluminum block because it was the simplest to model and the simplest to verify. The block approximated a mirror as it was cooled by setting it's boundary conditions to reflect radiatively cooling to roughly 3 K.

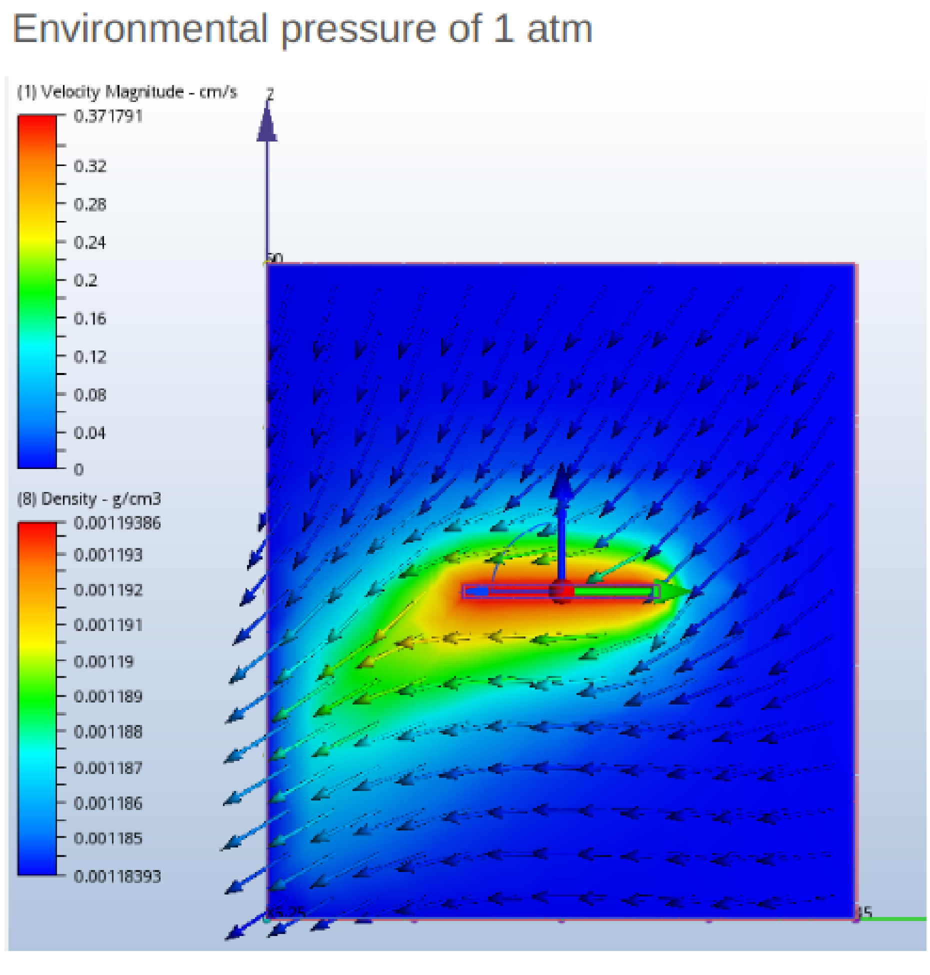

Figure 5. The density from this simulation seems to actually fit reality.

Unfortunately, the simulations at low pressures produced sometimes inconsistent and puzzling results. Running the exact same simulation on different computers actually ended up producing almost exactly opposite results in some cases, even where the only difference had been using a desktop with Autodesk CFD 17 instead of Autodesk CFD 18 on a student's laptop. When running simulations in sea level atmospheric conditions, the simulation passes the eye test. The following cross section from the simulation shows what we roughly expected:

However, the low pressure makes the CFD produce the strange results. Gravity does not seem to affect the density in 5.

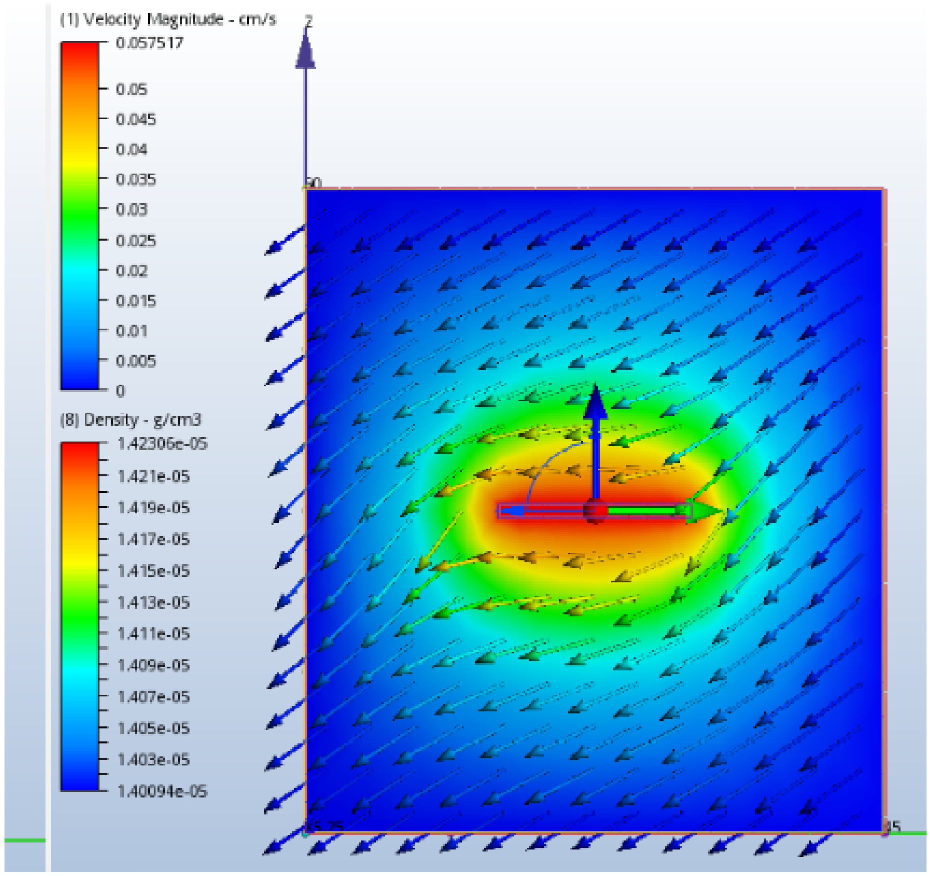

Figure 6. At an ambient pressure of 9 Torr, the simulation seems to break down. Note that the arrows show the direction of the gravity.

The interaction between the low pressure environment and the aluminum cooling do not seem to follow what would be expected given colder air should be denser and therefor sink under gravity.

3.2. *Future Work*

Because of the strange and inconsistent results, plenty of future research should be done onto producing a working model with AutoDesk CFD. The simulation team plans on spending more time with Professor Schnipke to pick apart the strange behavior produced by the models. Some simulations have been performed, but due to the strange behavior, don't necessarily communicate anything of use.

If the CFD and pure ANSYS calculations end up not panning out, we have begun to search for alternative fluid models. Researchers studying rarefied air often times use particle based, cell based and Monte Carlo simulations instead of CFD. Unfortunately, these simulations can be time consuming and computationally expensive in a way which engineering software like Autodesk CFD cannot afford to be. We also discussed exploring alternative computational fluid dynamics software like ANSYS's CFX or FLUENT CFD and integrating CFD software into Thermal Desktop.

The simulations produced through the semester do not even accurately represent temperature and pressure. The cryostat used to test the simulations does not immediately have an environment which immediately has the desired pressure and temperature. The test aluminum must mounted in ambient conditions, before the cryostat is closed, so the environment approaches the desired conditions. The simulations from discussed and shown above only account for a steady environment, which immediately has low pressure and temperature. Future simulations hope to reflect that gradual change, and in fact the ability to change conditions with time is one of the strongest motivators for using a new software suite .

Additionally, future simulations will include preforming computational fluid modeling to better represent the environment in the stratosphere, accounting for the sun and the earth's thermal contribution. Currently, these models simulate the test slab in a similar environment to the stratosphere, but not exactly the same. The modeling work for ANSYS simulates the aluminum slab in the cryostat. The work simulating the heat sources and sinks during the day time began prematurely. Unfortunately, since even the more basic models aren't necessarily producing results similar to those of the cryostat, these models, too, will need to be improved. At least the power of the radiative transfer from the sun and the earth has already been calculated. For simulations in the future, students aim to apply the following boundary conditions to the sunlit and earth facing sides of the aluminum block. To just simulate the radiative transfer, power from the heat sources of the sun and the earth were calculated, and then set as boundary conditions for the slab. For the top to simulate the sun's power the following equation is used:

$$P_{sol} = (L_{sol} * A_{aluminum} * \frac{1}{4\pi r^2} \tag{1}$$

where L_{sol} is the luminosity of the sun, $A_{aluminum}$ is the surface area of the top of the aluminum slab, 12 inches by 14 inches, and $\frac{1}{4\pi r^2}$ is the surface area of sphere where r is the radius of earth's orbit around the sun. This equation gives us a power acted on the slab from a simulated sun would have to be 52.7 Watts. Then in order to properly account for the effects of the earth, the team used an average value for the albedo of earth of 0.37 and found the bottom of such a the slab to arrive at 19.4 Watts. Those power values will be included in future simulations, once the cryostat verifies the simulation methodologies accuracy.

Before using the model in completely realistic stratospheric conditions, the model needs to accurately represent the conditions present within the cryostat. The cryostat experiments should reflect the ANSYS models since the cryostat test reached a much lower pressure, and therefore one would expect to less radiative transfer. Further models still need to more accurately model even that simpler experiment

4. CRYOSTAT TEAM

The cryostat team mainly focused on producing tests relevant for testing our observational models of a low pressure system. As discussed above, the simulation group sought to involve fluid mechanics in order to produce a more perfect thermal model. That investigation is worthless without the ability to do any sort of verification.

From previous work in the lab, specifically involving the building of spectrograph, we had access to a cryostat capable of producing pressures and temperatures similar to those encountered by a balloon-borne telescope. In order to investigate the environment's fluid and thermal properties, we had to know what the environment a balloon might encounter. To do so, Garrett Ebelke produced a model using The US standard atmosphere. Another atmospheric model NRLMSISE-00 basically agreed with the values of interest, at least to first order.

Next, the cryostat team used simple radiative transfer equations to model the relationship between size and cooling rate to compare results to the simulation team and test the accuracy of the novel simulation methodologies applied here. In order to make meaningful inferences, the following requirements were determined:

1. Pressure should approach rarefied conditions on the orders of 2-8 Torr like the conditions experienced by high altitude balloons.
2. Temperature should reach temperatures similar to stratospheric conditions on the order of -50 degrees ambient.
3. Sensors should take data at interesting points along thermal gradients, while minimizing their own thermal influence on the plate.
4. The test block should reach thermal equilibrium between 24-48 hours.
5. The test aluminum block also should be able to fit within the mounts of the cryostat.

4.1. *Cryostat Configuration*

Luckily, past experiments performed in the cryostat had some of the same conditions. Filling the cooling chamber with liquid nitrogen allowed the cooling floor of the cryostat to cool to the target temperatures. For safety, the team fitted an exhaust tube for transporting nitrogen out of the lab. The cryostat also already had been configured to reach and record the low pressure systems desired using a vacuum pump connected to the test chamber. The pressure varied between a near vacuum and just below the pressure in the high atmosphere. The pump lowered the pressure to the near vacuum for the first half of each experiment, and then raised for the second half. The near vacuum one would expect to follow the behavior of the ANSYS simulations since those simulations neglected fluid effect.

Finally taking data along the thermal gradients predicted by the simulation team required attaching temperature sensors taking data roughly in a line across from corner to corner. Special temperature lugs used in past cryostat experiments, were thermally coupled to the slab. These lugs had been designed for past experiments so that they minimize their thermal effects on the test slab. The lugs attached at each corner, the middle, and just offset from the middle.

4.2. *Unpainted Aluminum Test*

Now the cryostat team needed to find a test block which fits into the cryostat volume. Remembering that only the thickness can vary due to the fixed mount position. For the test block, as mentioned above both groups independently calculated the time required until thermal equilibrium. Haotian and Isabell took a macro approach with simple physics. They used the definition of power, and the Stefan Boltzmann Law to calculate the time to reach. They assumed the initial temperatures to be the following:

Table 1. The temperature assumptions

System Part	Temperature (K)
Slab Temp:	300
target Temp :	77.25
Environment :	100

The following equations shows the relationship through definitions of power, and then relates to the Stephan-Boltzman Law multiplied times the area:

$$P = \frac{\Delta Q}{\Delta t} = e\sigma A(T^4_{alum,i} - T^4_{alum,f}) \tag{2}$$

where P indicates Power, Q heat, t time, e emissivity, and A the area of the block. By creating a system of six equations and using MatLab to iterate through and solve it, the experimental group actually came up with a value just under 48 hours for the test involving just a bare slab of aluminum.

4.2.1. *Results*

The following graph shows the temperatures experienced by each peg, and the pressure read out with respect to time. The slab reached equilibrium at a much higher rate than either team expected, at roughly 12 hours. While that significantly differs from the calculations, but more importantly the simulations produced a minimum temperature more than 80 degrees off. Some of the simulations, like the one I show above does a better job, but even then a significant difference can be seen.

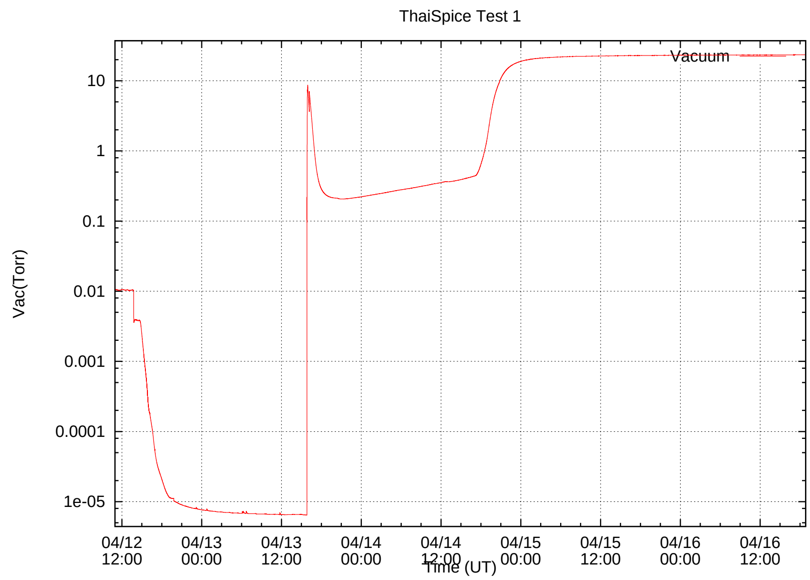

Figure 7. The pressure profile for the first bare aluminum test. Notice the initial militor reading which should correlate roughly to the ANSYS models while the second step more resembles the pressures stratospheric balloons

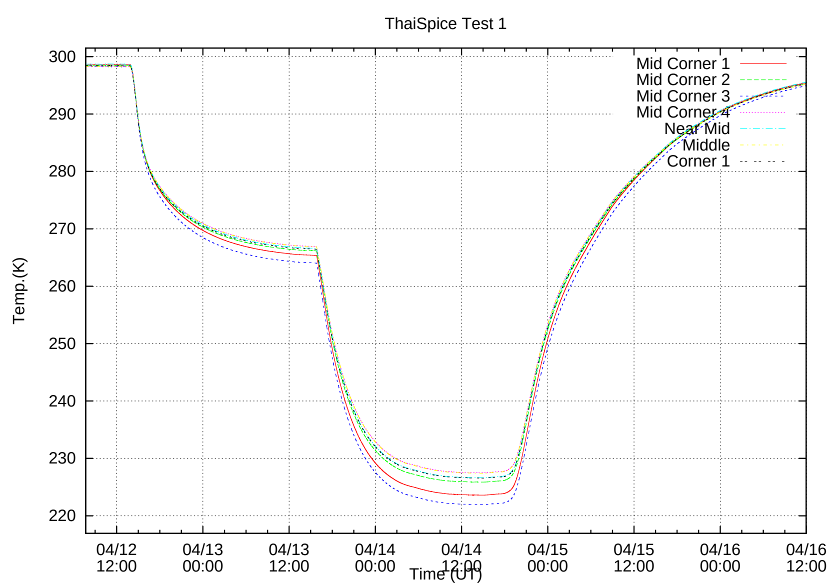

Figure 8. The steps correlate with the change in pressure. Notice that in the regime closer to stratospheric conditions the temperature drops much more significantly.

Clearly some inconsistency exists between the models and the real results. Clearly

4.3. *Painted Aluminum Test:*

Some of the radiation might never transfer to the shiny mirror-like surface of the aluminum slab. After receiving the data from the from the first experiment the simulation team varied the emissivity in their model. They found that with different values the simulation did tend to fit the data better. So to effectively change the emissivity without significantly changing the thermal mass, we decided to paint the block. The university had some non-reflective zinc oxide paint,

Clearly the temperature profile shows values closer to the predicted, simulated values, but still does not reach the lows. There are some interesting features in the graphs. The lowest pressure regime approaches a temperatures significantly higher than we expected, only dipping roughly 30 degrees, while also keeping the individual temperature data points seem to stick closer together, like in the simulation.

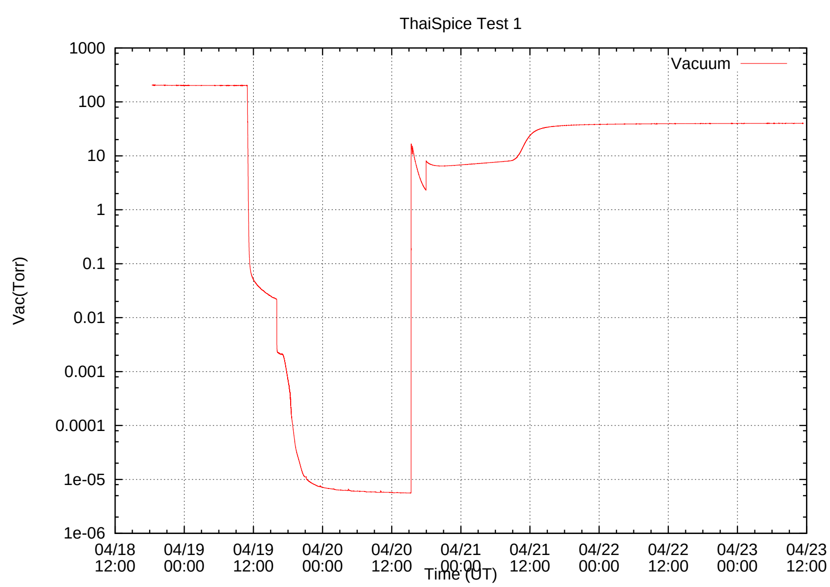

Figure 9. The pressure profile for the second test with a lower reflectivity. It pretty much is identical to the first pressure profile

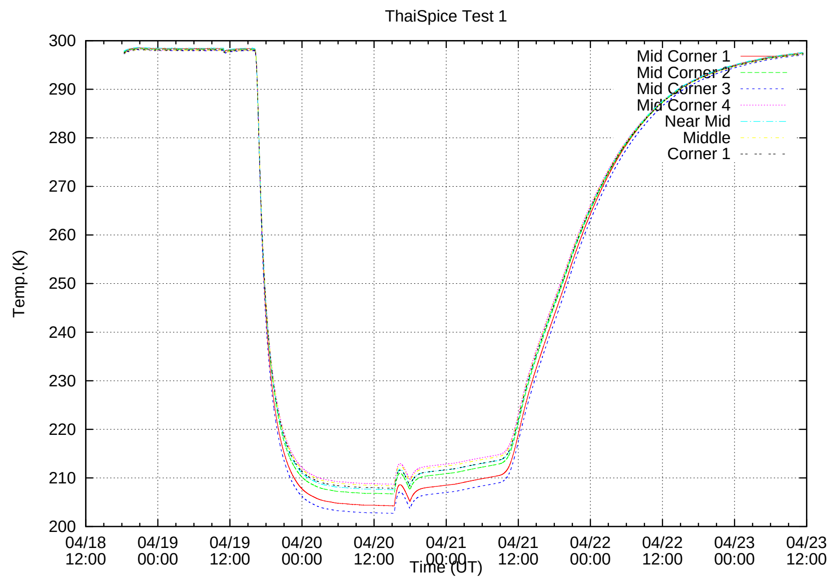

Figure 10. The temperature profile of the painted slab test.

For work in the future, we should first take the individual sensor data and sample at the same locations in the simulation. The individual ratios between the locations would be interesting to check. Given the small change in temperature across the simulated model, I suspect the cryostat data experienced significantly larger temperature differences.

5. SMALLER SCALE HIGH ALTITUDE BALLOON

5.1. *Goals and Usefulness*

Smaller size ballooning costs a smaller proportion of cost compared to the costs of a large ballooning project like the THAI-SPICE balloons. NRLMSIS and the standard atmosphere do not necessarily give realistic estimates, or the full picture of the thermal environment experienced by high altitude balloons. In order to more fully characterize the thermal effects of similar altitudes a small scale balloon with variety sensors useful to fully characterize stratospheric conditions.

Small Scale High altitude ballooning to the University of Virginia, and Professor Mike Skrutskie is not a new concept. Recently Chloe Downs and HeeSeok Joo flew a preliminary flight, including a suite of sensors, tracking and imaging devices among others. That flight in 2016 already some useful data relevant to the THAI-SPICE project, in addition to kicking off our ballooning program. My involvement in high altitude ballooning work came from verifying sensor packages as well as testing the data against different models.

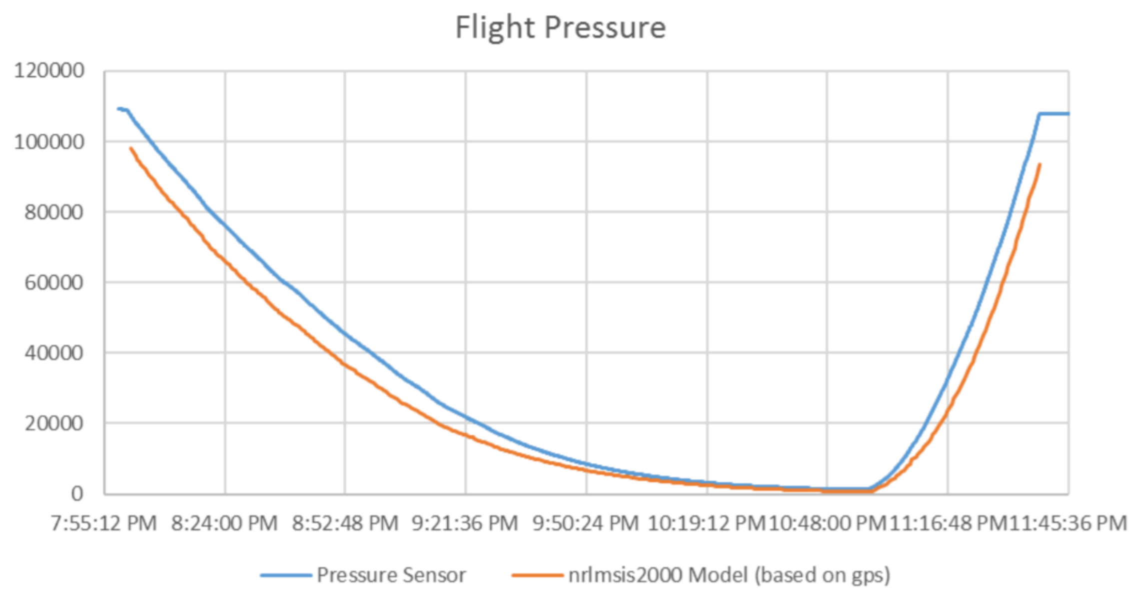

Figure 11. Flight pressure data plotted against expected pressure data as predicted by NRLMSIS. They seem to agree, especially at high altitudes

The original pi package included an MEMs pressure transducer in addition to temperature sensors. By testing the accuracy of the pressure sensor in a lab vacuum chamber, against a calibrated sensor. Then using that calibration factor, I analyzed the data package taken from Chloe and HeeSeok's flight and analyzed the data. By feeding temperature data, and tracking data into the NRLMSIS discussed above, I produced a predicted pressure encountered in flight. The value of that graph is two fold. For one any large fluctuations would hint at data integrity issues and it roughly tests the usefulness of those models. The graph below shows that to a large degree the values are pretty reasonably accurate, especially as the atmosphere thins.

A new iteration of the small scale ballooning project began development shortly after that first flight. This flight has a more significant implications on the thermal behavior in stratospheric conditions. In order to accurately simulate conditions a telescope would experience within the upper atmosphere, this balloon package studied effects of heat dissipation. In order to do so the next balloon borne sensor package included a IR camera focused on a target. Infrared light can be calibrated to temperature.The target is only a place holder, and planned to be a small piece of mylar for observation.

The target, much like any balloon-borne telescope, needed to be isolated from heat sources. The sun provides the strongest heat source, of course, and larger balloons have enough mass budget to utilize reaction wheels, and point temperature sensitive instruments away. Unfortunately four pounds does not allow for the same ability. On a small balloon, with a regulated maximum payload of four pounds and a flight time of roughly three to four hours, utilizing reaction wheels would be foolish. It is much easier to just launch the balloon after the sun has fallen.

The earth on the other hand never sets. To block the sun, I designed a dish to house the target. It essentially is a lightweight 3-D printed skeleton to which lightweight mylar will be fixed to. The target lies at the deepest point of the dish, below the focal point. The balloon is slated to launch at sundown. Assuming a nominal burst altitude of roughly 30,000 feet, then from trigonometry, the sun would still be present for an extra four degrees. The dish then needs to be deep enough that the target has no line of sight which could possible contain the earth plus those extra four degrees. The final dimensions for the dish comfortable blocks out all possible heat sources with a depth of 2 inches and a radius of four. I designed the target to sit just ever so slightly elevated so as to minimize thermal short circuiting between the radiatively heated reflector and the target.

The 3-D printed reflector connects to the main body using a relatively short connection. All of the data, and sensors are managed by a Raspberry Pi computer. The close side to the main instrument box. The Lepton Flir camera is mounted on the close side of the of that connector, to minimize the length of wire necessary. Also in the reflector included a DS1820 temperature sensor embedded in a small aluminum block and placed within the scene, so that the data can be accurately correlated in the future. The program running the Flir camera takes images at a rate of once every six minutes, while the aluminum embedded temperature sensor takes temperature data at a higher rate. The wires running to the temperature sensor.

That carriage, and a significant portion of the original instruments which originally inhabited it, come from the balloon developed by Chloe and HeeSeok. The Arduino running the APRS tracking software, the GoPro, and the physical structure of the box have stayed the same. The main instrument box has a bright orange foam covering, in order to protect the electronics. Across from the reflector, a gimbaled back country tracker is mounted in foam. The foam protects the electronics from the extreme conditions, while the gimbal attempts to keep the tracker in an upright position so that it never loses it's connection to the tracking service provided by BackCountry. While the model of Raspberry pi has changed, the same MEMs sensor, and raspberry pi camera also will fly with the balloon sensor package.

5.2. *Flight Path Predictions from Charlottesville*

When launching this smaller scale ballooning project, it is of course important to be able to recover the balloon. Unfortunately at our location balloons for much of the school year get carried out east which likely means they would get carried out to the Atlantic ocean. During certain parts of the year the winds in the region turn around. When the wind turns around, and starts blowing in a more westerly direction the balloon travels a shorter distance from Charlottesville as the mountains slow down the wind and provide a barrier for the balloons to hit.

In order to know when to launch the balloon we utilized a free, specifically high altitude balloon prediction service named the "CUSF Landing Predictor 2.5" from "habhub" which is set of high altitude ballooning tools from the United Kingdom High Altitude Society (UKHAS). This service is available on the open web. Cambridge University Space flight maintains the site and prediction algorithms in order to assist in finding gas volume necessary in a balloon to achieve a desired burst altitude or ascent rate.

In order to characterize the time when this turn around occurs in Charlottesville, weekly predictions were produced. The software predicts flights based on previous landing prediction software, and NOAA GFS models. Like all prediction services, and especially those which involve weather, predictions have greater accuracy closer in time rather than farther in the future; therefore, only predictions for flight paths within the week of creation were considered trust-able. The following table summarizes the input parameters used to produce any of the flight data:

Table 2. Input Parameters for Flight Path Predictions

Parameter Name	Value
Latitude (degrees):	38.0356
Longitude (degrees):	78.5149
Launch Altitude (m):	0
Ascent Rate (m/s):	$3-5$
Launch time (Local times):	30
Burst Altitude (m):	30000

The following flight path shows one of the early year flight path, where the winds push the balloon east towards the ocean:

Then below in that one can see a more favorable flightpath taken in early May where roughly the turn-around occurs.

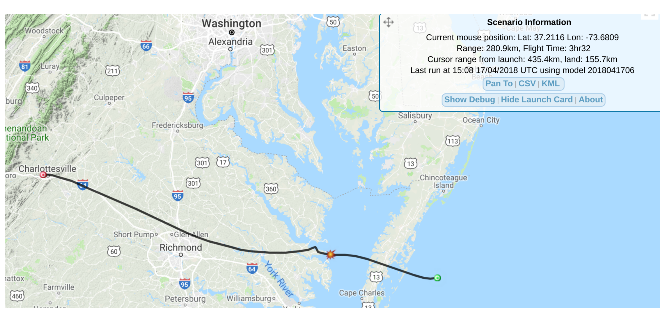

Figure 12. This is an early in the year before any turnaround. The balloon when it travels west clearly travels quite a bit farther than in total than any single

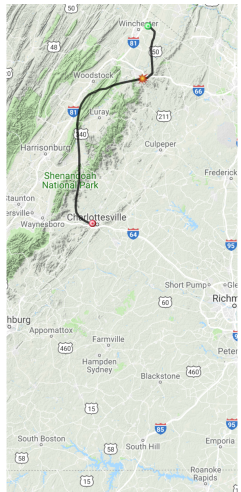

Figure 13. A late season

Unfortunately the second to last data point happened to be the only data point in which the turn around behavior had been predicted. Without steady predictions showing a flight path west, it's difficult to say the certainty that the wind turn around occurs in May.

5.3. *Current Status*

As in any project, hurdles have been encountered. Specifically, a number of simultaneous problems lead to delays, and inability to fly. The code sensor code, testing, most of the prototyping and printing has occurred. Links to each part, and code can be found below in the appendices. Helium, and a contract to track the balloon from Backcountry still needs procurement. To fly the balloon, some assembly is required. Check the appendices for a block diagram useful for wiring and for schematics for the balloon.

6. CONCLUSIONS

The research presented here still is ongoing. Before attempting additional costly large scale experiments, designers should strive to create ever more accurate models of the rarefied environment of the stratosphere, especially in cases where thermal stability is so key. Ultimately, the research presented above fails to produce a definitive solution to thermal modeling , but only poses more questions. As the data stands, computational fluid dynamics do not solve the issues, but I hesitate to definitively write it off before more discussion with Professor Schnipke, as well as testing. Tradi-tonal methods of using finite element analysis, however, clearly do not work. Perhaps future work will show the necessity of using more computationally expensive models, and perhaps some small mistake has prevented any correlation. Only time and undergraduate labor can tell!

I would like to thank first off Professor Mike Skrutskie for his guidance and for the enormous number of opportunities he has given me, from occultation work to these high altitude ballooning projects. I'd also like to thank Garrett Ebelke for his guidance and engineering help, as well as his work assisting the undergraduate teams. Research scientist Matt Nelson for all his help, especially in terms of the guidance and contribution to the cryostat work. Finally, I would like to thank all the undergraduates for their work. They contributed and worked an enormous amount. On the simulation team I'd like to thank: Rachel Weeks, Joe Brink, Abhishek Gupta, and Genna . On the cryostat team I'd like to thank: Haotian Liu and Isabel Arayo. They completed a large amount of the work presented here.

Software: astropy (?), Cloudy (?), SExtractor (?)

APPENDIX

A. APPENDIX INFORMATION

A.1. *A. Small Ballooning Project*

A.1.1. *i. Cad Models*

Below one can find images from a SolidWorks rendered models of the high altitude balloon:

Then below lies a zoomed in rendering of just the box and the science payload.

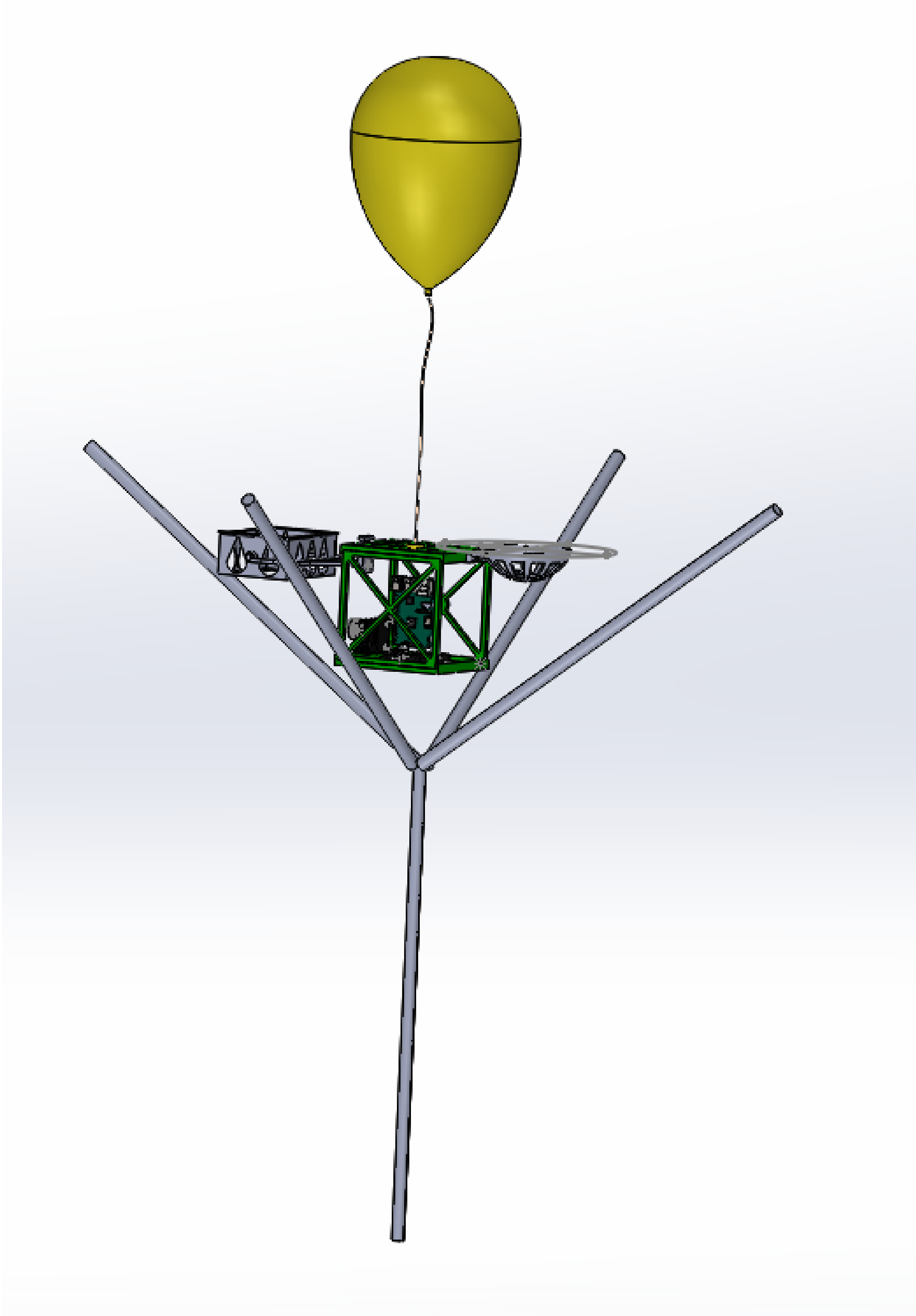

Figure 14. The overall structure of the

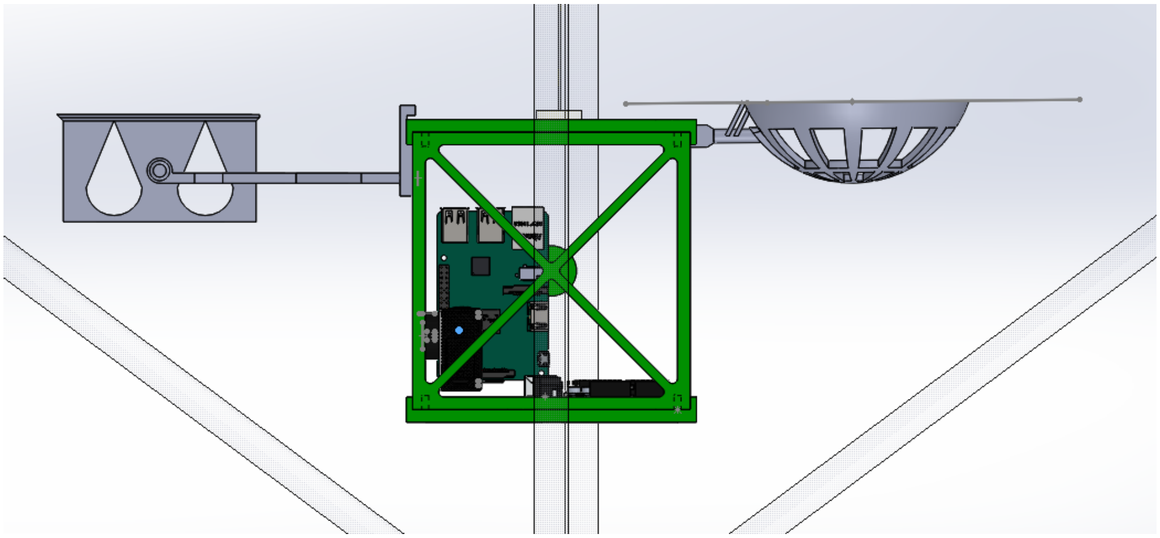

Figure 15. A zoomed in rendering of the sensor borne payload. The reflector on the right and the gimbaled tracker on the left. Additoinally the Rraspberry Pi is set flat againts the opposite wll. The GoPro camera lies in the lower left hand side of the box as well

A.1.2. *ii. Part Diagram*

Here is an typical 2 panel view of the assembly:

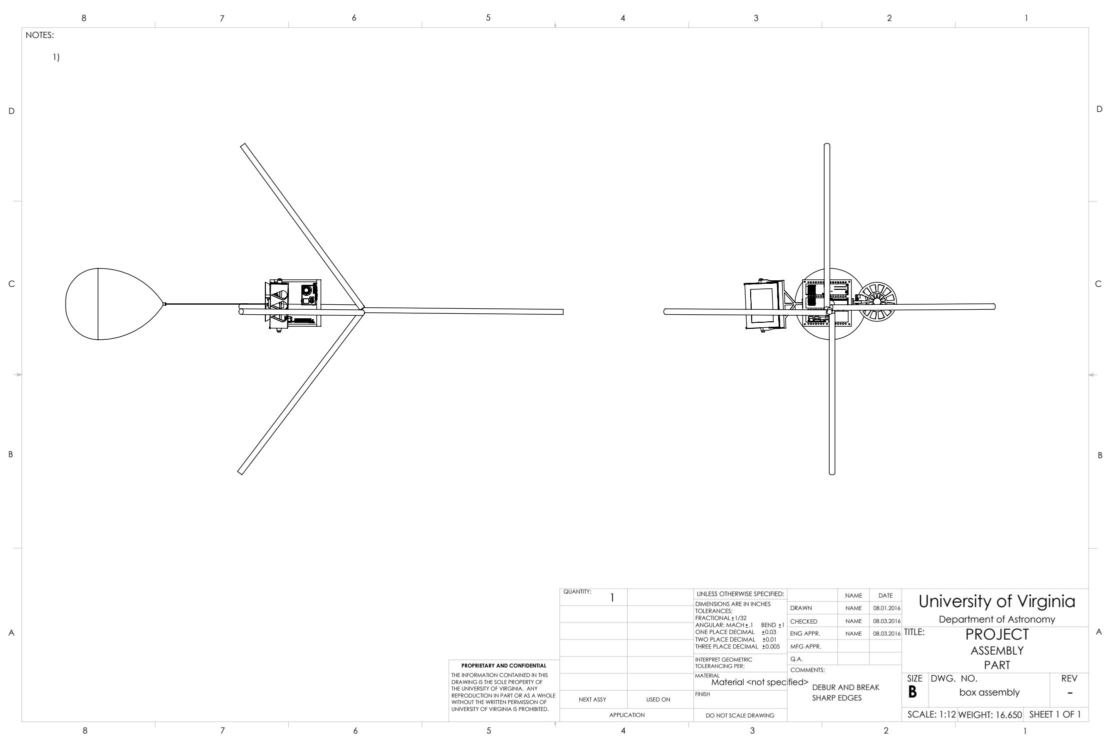

Figure 16. A quick engineering diagram showing the balloon borne package. The antenna is the large cross structure. The balloon is the long structure and the payload between them.

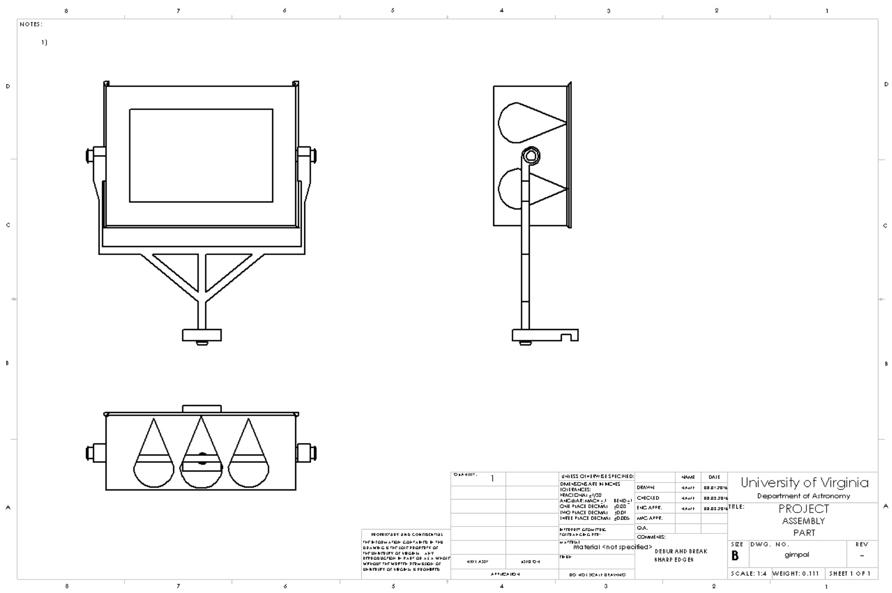

Figure 17. The gimbals assembly which attaches to the box. This assembly holds the tracking device for the balloon

Then the following image shows the gimbaled assembly to hold the backcountry tracker with greater detail. Note that parts covered in foam including the box and the back country tracker have been hidden to give better detail

Finally below, show a more realistic version of the entire assembly, rendered from SolidWorks:

A.1.3. *(*

iii. Weight Budget)

Component	Weight (g)	Weight (lbs)
Rasberry Pi	22.7	0.050044874
Infrared Camera	8	0.01763696
Arduino + Antenna Cable	84	0.18518808
Antenna	107	0.23589434
Arduino Battery	129.5	0.28549829
RPi Battery	129.5	0.28549829
Regulator	28.5	0.06283167
Cage	166.3	0.366628306
Insulation	118.1	0.260365622
GPS Antenna	56.3	0.124120106
Spot GPS	117.1	0.258161002
GoPro & Case	144.7	0.319008514
Payload Total	**1111.7**	**2.450876054**
Parachute	127.4	0.280868588
Balloon	1200	2.645544
Reflector	122.4	0.269845488
Total	**2561.5**	**5.64713413**

Figure 18. The mass budget from the balloon project

A.1.4. *iv. Wiring information*

First ensure the battery is FULLY charged, and battery life has not degraded to the point where it will not draw power for a full four hours. Next following the following block diagram wire in each of the following sensors:

More practically one should follow the following diagram for specific plug locations:

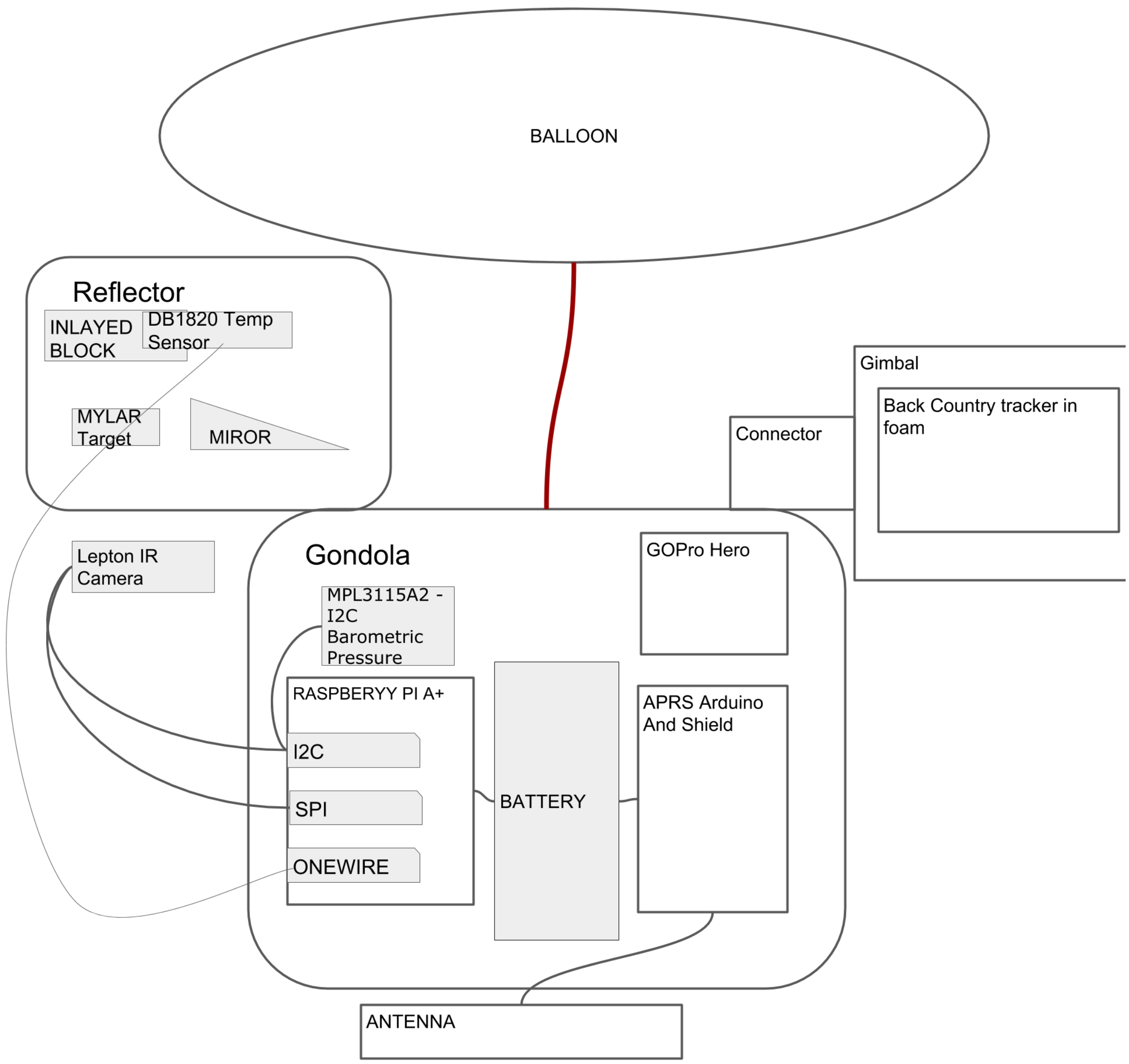

Figure 19.

Remember that I2c components must be wired with short wire source since I2C protocol results in degradation of communications correlated with wire length.

A.2. *Links to cad files and programs*

Please follow the following link to access the programs and cad models which make up the as well as digital version of the data found above: https://drive.google.com/open?id=1R5QjJ8u7p0AelOGGyr1iVXS0OXHrs2OW

Additional information is available from above.

REFERENCES

Shariff, J. A., Ade, P. A. R., Amiri, M., Benton, S. J., Bock, J. J., Bond, J. R., Young, E. Y. (2014). Pointing control for the SPIDER balloon-borne telescope. ArXiv:1407.1880 [Astro-Ph], 91450U.