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# An Analysis of Burst Altitude for Weather Balloons

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The ability to accurately estimate balloon burst altitude is important when modeling balloon flight predictions in preparation for a high altitude balloon launch. Variables considered for the study of burst altitude include the time of day of the flight, the manufacturer of the balloon, and the ascent rate of the balloon during the last ten minutes before burst. Additionally, the reliability of the commonly used APRS tracking system was studied. To study these variables, we ran statistical tests on data collected by APRS.fi for more than seventy balloon flights carried out by researchers across America.

## Nomenclature

$\alpha$	Significance Level
$\lambda$	Wavelength (m)
ANOVA	Analysis of Variance, a statistical test
APRS	Automatic Packet Retrieval System
$c$	Speed of Light $\text{m/s}$
Diurnal	Daily
Excel Macro	Programming Script
$f$	Frequency (Hz, $\text{1/s}$ )
$F$	Ratio of two Mean Square values
GPS	Global Positioning System
HAB	High Altitude Balloon/Ballooning
$H_\alpha$	Alternate Hypothesis
$H_0$	Null Hypothesis

UT	Universal Time
UV	Ultra-Violet
mb	Millibars, a unit of pressure
MHz	Megahertz, a measurement of frequency
$n$	Number of Moles of Gas
Payload	Container for research equipment
$P$	Pressure (mb)
$p$ -value	Conditional Probability
$R$	Ideal Gas Constant
$T$	Temperature ( $^{\circ}$ Celsius)
Telemetry	Remote real-time data transmission
$T_g$	Glass Transition Temperature
$t_{\alpha}$	Critical value for the $t$ -test
$t$ -test	A statistical test that studies the difference between means
$\alpha$	Significance level for Statistical tests
$V$	Volume ( $\text{m}^3$ )

## I. Introduction

High Altitude Ballooning provides a reliable way to launch scientific research experiments into the Earth's atmosphere. The practice relies upon using readily available hardware to keep costs low to ensure that HAB is accessible to researchers at many levels, from high school teachers to corporate scientists. Eventually, the balloon bursts, and the payloads fall back to earth via a parachute. For a launch to be successful, the payloads must be found and retrieved so that researchers can collect the information collected throughout the flight.

To find and retrieve the grounded payloads, researchers need reliable predictions of the balloon's flight path. These predictions are based on the ascent rate and the burst altitude of the balloon, as well as on the weather conditions for the particular flight day. Accurate flight path predictions aid in tracking the balloon while it is in the air and help researchers find the balloon if tracking is lost during the flight.

A goal of this research project was to observe balloon burst and deviation from manufacturer standards to improve the accuracy of flight predictions by including accurate balloon burst altitudes. Additionally, it was the intent of this study to observe variables that affect balloon burst altitude. These variables include the time of day the launch took place and the manufacturer of the balloon.

Additional motivation for this research is an upcoming total solar eclipse, which will take place on August 21, 2017.<sup>1</sup> Total eclipses occur when the orbits of the moon and the earth align in such a way that the moon comes between the earth and the sun, thereby blocking out the sun and causing night-like conditions during daytime. Total eclipses are short, with the sun blocked for up to three minutes in any particular location. The rareness of this occasion creates a unique research opportunity that should not be missed; the last eclipse that passed over continental U.S. occurred in 1979. The path of this eclipse makes it even rarer: it will cut a swath across the central United States, as can be seen in Figure 1. The last time an eclipse crossed the entirety of Central America was in 1918.

Because of the rarity of this event and the short window of opportunity for observing total solar eclipse conditions in the atmosphere, it is imperative that weather balloon researchers have their balloons at the correct altitude at the correct time. This would be impossible if the balloon were to prematurely burst.

In addition, the reliability of the widely used APRS tracking system was examined. APRS relies upon GPS receiving and transmitting hardware to supply location and other telemetry information in close to real time.<sup>2</sup> It is not uncommon to lose APRS tracking for portions of a flight. On occasion APRS tracking is lost entirely. In this case, the signal is sometimes reacquired when researchers approach the balloon after it has landed on the ground. However, it should be noted that APRS performance was studied while the balloon was in the air, and that re-acquirement of the signal was not considered for this project.

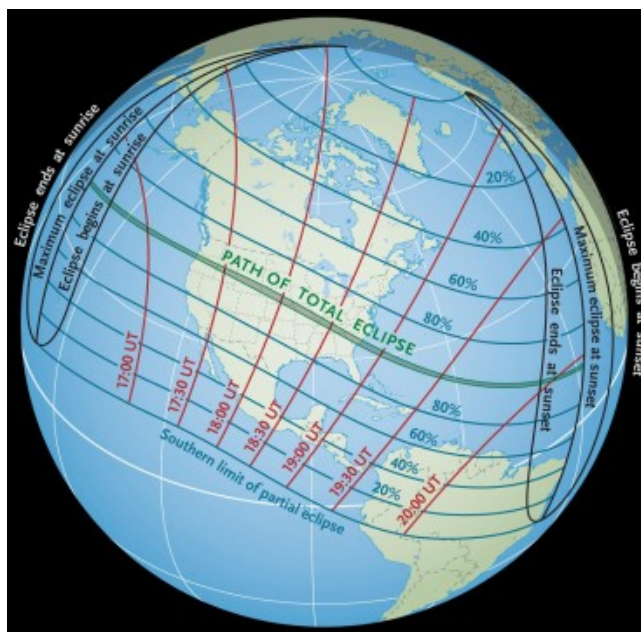


Figure 1. The path of the upcoming 2017 solar eclipse.<sup>1</sup>

## II. Background

### II.A. Atmospheric Physics

HAB is used to study conditions in the stratospheric region of the atmosphere because of its ability to reach a height above the reach of airplanes. Additionally, HAB is a relatively low-cost option, costing approximately 500 US dollars per flight as opposed to multiple thousands of US dollars for the launch of another research platform, the sounding rocket.<sup>3</sup> Therefore, it is important to understand atmosphere and how conditions such as temperature, pressure, and the amount of UV radiation change throughout the atmosphere and through the course of a typical day.

#### II.A.1. Regions and Temperature

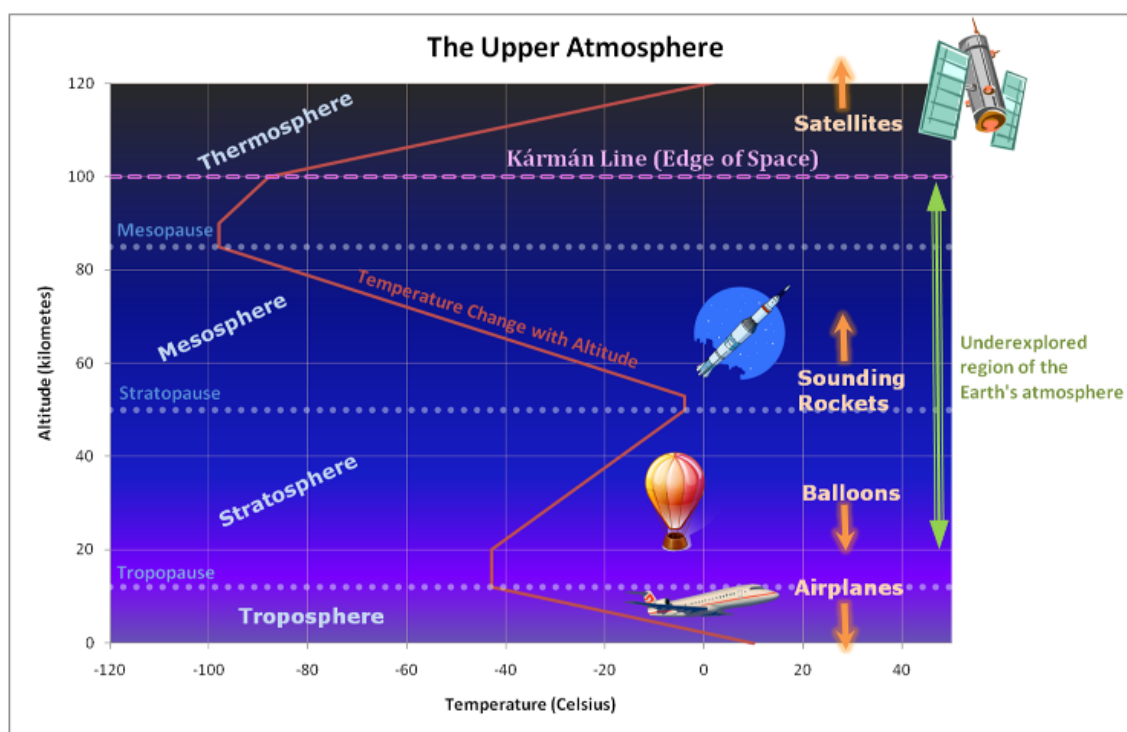


Figure 2. Layers of the atmosphere, showing typical devices which operate in the different levels. Courtesy of Trevecca University.<sup>4</sup>

The regions of the atmosphere are categorized by ranges in temperature.<sup>5</sup> While one might believe the temperature steadily decreases at greater heights, this is not the case; temperature does decrease initially through the troposphere, but then continues to fluctuate through the stratosphere and mesosphere. This variation of temperature with respect to altitude is illustrated in Figure 2.

The region of the atmosphere corresponding to the first temperature descent is known as the troposphere.<sup>5</sup> The troposphere ends at approximately 11 km and contains almost all weather activity, as well as much of the Earth's water vapor. Because of the large variance in temperature within a relatively area, the troposphere is turbulent and unstable. Its upper boundary is called the tropopause, which is home to the jet stream, a predominantly westerly wind which a typical balloon flight will encounter that "reaches its maximum intensity between the troposphere and the stratosphere."<sup>6</sup> The direction of the wind is dependent on the climate of the land over which it travels; in colder climates, it curves towards the equator, while the opposite is true for warmer climates.

Above the troposphere is a region of space which has been sorely under-explored in humanity's research of space. This region, the stratosphere, extends up to approximately 50 km above the Earth's surface and is bounded at its highest point by the stratopause.<sup>5</sup> It is of particular interest since balloons typically burst here and rarely go above the stratopause. Through the stratosphere, temperature actually increases because of higher concentrations of ozone, which absorbs UV radiation more efficiently than air.<sup>7</sup> Warmer, denser air near the stratopause ensures that the stratosphere is a stable layer of the atmosphere.

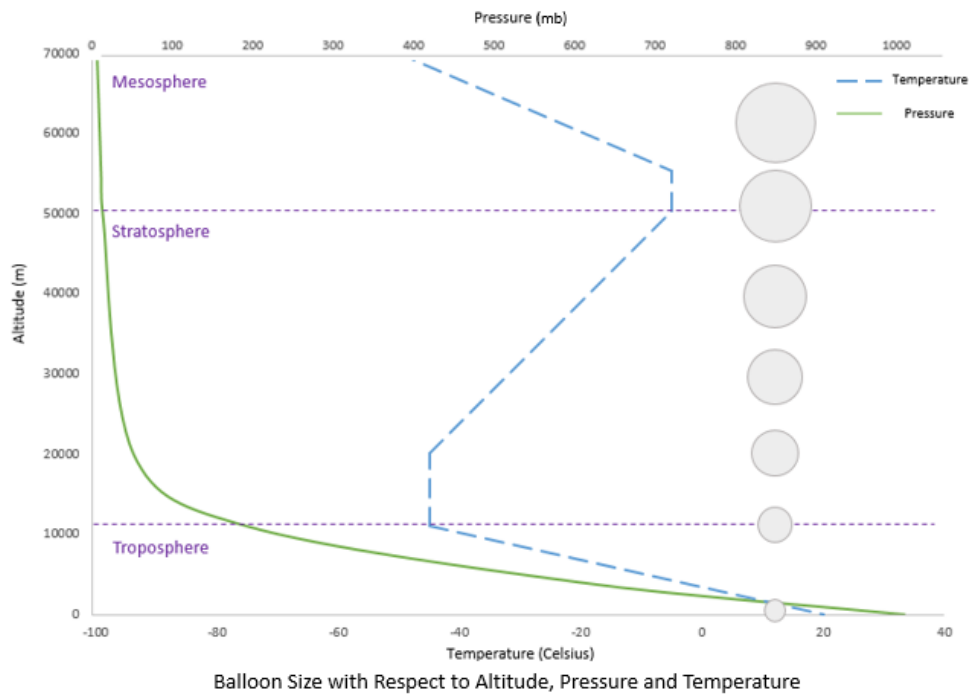
Above the stratosphere is the mesosphere.<sup>5</sup> It too is an under-explored region of the atmosphere, out of the reach of the average weather balloon. As shown in Figure 2, the typical vehicle of exploration in the mesosphere is a sounding rocket, which tends to be too expensive for researchers to use on a regular basis.<sup>2</sup> The mesosphere is 85 km above the Earth's surface and is below the thermosphere.

### *II.A.2. Pressure*

Atmospheric pressure on Earth results from the weight of the air above us. As an object ascends through the atmosphere, there is less air above it, so both pressure and density decrease,<sup>6</sup> as shown in Figure 3. Additionally, the rate at which the pressure and density decrease remains almost constant between the winter and summer seasons,<sup>6</sup> which might be of interest for future studies. Regardless, pressure and temperature are both important aspects which greatly affect the balloon's performance.

### *II.A.3. Diurnal Variations*

Diurnal variations of the atmosphere are conditions that arise due to the twenty-four hour rotation of the Earth with respect to the sun.<sup>8</sup> During the day, higher quantities of UV radiation interact with the atmosphere and the Earth's surface, causing them to absorb different amounts of heat. For instance, the ground will take in greater amounts of energy than typical air. Heat can transfer from this warmer ground into the lower levels of the



**Figure 3.** A representation of the change in temperature and pressure in the atmosphere, and the resulting change of volume of a weather balloon through those atmospheric regions.

troposphere, but because this form of conduction is inefficient, we notice a greater change in diurnal temperature closer to the ground. The diurnal variation in UV intensity and temperature in an atmospheric region and the typical amount of radiation being absorbed and emitted from the Earth is shown in Figure 4.

The different chemical compositions of the atmospheric regions interact with UV radiation in a variety of ways. For instance, the stratosphere contains 90 percent of the atmosphere’s ozone,<sup>7</sup> while the troposphere contains much of the atmosphere’s oxygen. Both of these gasses absorb heat energy from UV radiation, meaning that during the day they are gaining heat energy.

## II.B. Ballooning

High Altitude Ballooning plays a very large part in the motivation of and data collection for this project. Understanding the history and practices of HAB research provides context for the study detailed in this paper.

### II.B.1. History

Weather ballooning has existed as a viable research platform since 1896, when French meteorologists regularly launched balloons to study the atmosphere.<sup>9</sup> The process is as follows:

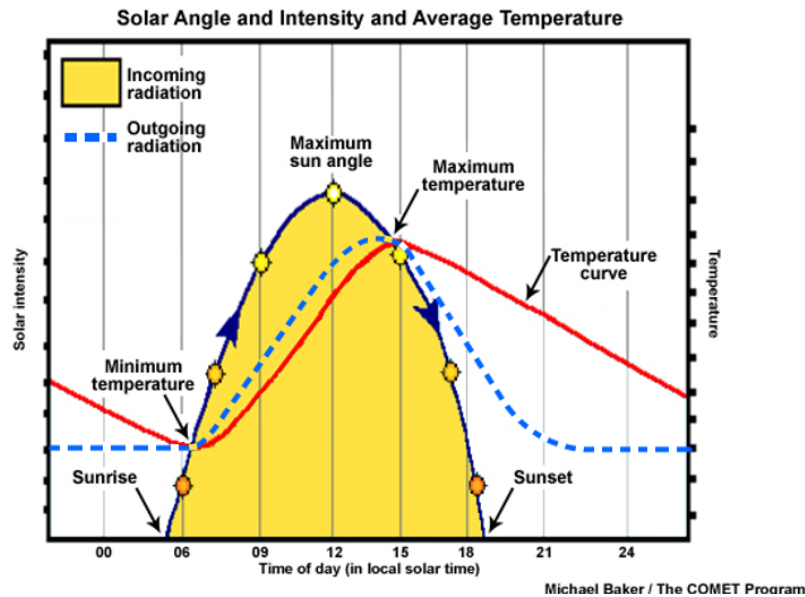


Figure 4. The solar intensity and temperature variations through an entire day.<sup>7</sup>

researchers design experiments, which are housed in payload boxes and suspended with a parachute beneath the balloon. Buoyant gasses, such as helium or hydrogen, gives the balloon lift to travel upwards into the atmosphere. As the balloon ascends, the pressure of its environment decreases, and the balloon begins to expand. This expansion continues until the material of the balloon is stretched to its breaking point, causing the balloon to burst. This typically occurs at stratospheric altitudes between 30 and 35 km. After the balloon bursts, the payloads fall back to Earth via a parachute.

### II.B.2. Practices

A weather balloon launch takes planning. First, the researcher uses flight path prediction software to search for a starting location that will keep the balloon out of highly populated areas. On launch day, the experiments are turned on and sealed into their payloads. The payloads are attached through the use of strong but lightweight string to the parachute and the balloon. Once everything is ready, the researchers don gloves to protect the latex of the balloon<sup>2</sup> and begin filling it with helium to the correct lift. The amount of lift is checked by testing the balloon's ability to lift water jugs weighing roughly the same as the payloads. Once the proper lift is achieved, the filled and sealed balloon is released, a process which can be seen in Figure 5. On a typical flight the parachute is left to hang; it will open during descent once the atmosphere becomes thick enough for it to catch the wind. After release, researchers on the ground track and follow the balloon to the landing site. After it



has landed, researchers collect the payloads and bring them back for analysis. Much of the actual balloon material is lost in the burst process.

An important decision while planning a balloon flight is the choice of which balloon to fly. There are a variety of balloon sizes and colors available to HAB researchers. Balloons are typically identified by their weight and their manufacturer, where the weight of the balloon is taken while the balloon is empty. As for the color, researchers must choose carefully so as not to interfere with any of the experiments they are running; typically, balloons are white.

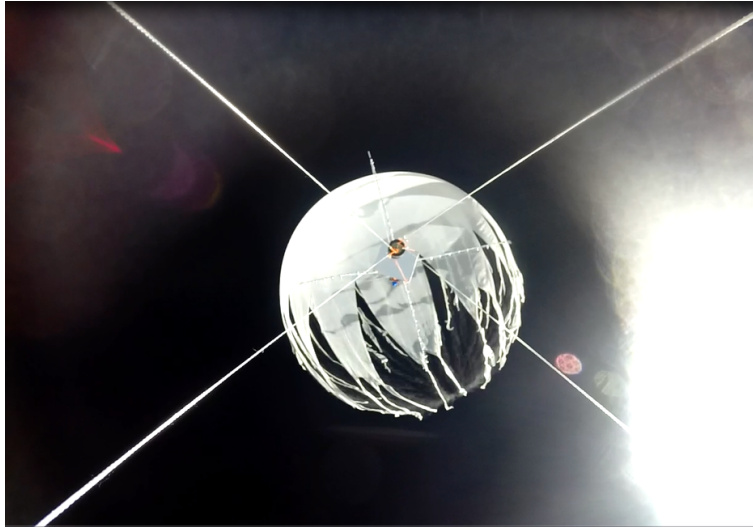
The height balloons typically reach are referred to as ‘near space altitudes,’ which is defined as the region above the troposphere and in the lower part of the stratosphere.<sup>4</sup> The average height a weather balloon reaches can be seen in Figure 2. As of yet, this region remains under-explored, giving room for new and interesting scientific experiments. In their ascent, weather balloons typically travel through the region in which planes fly; for this reason, weather balloon flights are regulated by the Federal Aviation Administration under the Federal Regulations FAR 101.<sup>10</sup>



**Figure 5.** A picture of the St. Catherine Ballooning Team preparing to launch a balloon, featuring Professor Erick Agrimson and Dr. Kaye Smith of St. Catherine University.

### II.B.3. Balloon during a Launch

As a weather balloon ascends through the atmosphere during a flight, it is subjected to radical changes in both temperature and pressure. As helium is a noble gas it is possible to calculate the volume of the balloon at each stage of its ascent, using average temperature and pressure values and the ideal gas law,  $PV = nRT$ , where  $P$  is the pressure,  $V$  is the volume,  $n$  is the number of moles,  $R$  is the ideal gas constant, and  $T$  is the temperature. The results of this calculation can be seen on Figure 3. Additionally, a picture of a balloon bursting in the atmosphere can be seen in Figure 6.



**Figure 6.** A picture of a balloon bursting in the atmosphere, taken during the St. Catherine Balloon Team’s flight in June of 2015.

### II.C. Tracking Software

Researchers use a variety of tracking hardware to follow the path of the balloon in the air. Common tracking systems include APRS and other forms of GPS receivers and transmitters.<sup>2</sup> It is not uncommon for any particular tracking system to fail due to the harsh conditions of the flight. This, combined with the utter importance of knowing the location of the balloon, drives many researchers to use redundant tracking systems.

Accurate flight predictions can be used to locate payloads after landing in the case that all other tracking systems fail, or if short-range tracking systems are being used. As a last resort, researchers can go to the location of the predicted landing sight to begin their search. This is another incentive for increasing the accuracy of balloon predictions.

The tracking site APRS.fi was instrumental in gathering the data used in this study. As described on its website, “APRS is a digital communications information channel for ham radio.”<sup>11</sup> Ham radio operates in the 30 to 300 MHz frequency range, which is very low, lower

than the frequencies used by broadcast radio stations. Regardless, ham radios are capable of transmitting information, including position, weather information, telemetry and messages in real time.<sup>12</sup>

Radios transmit data using electromagnetic waves, which are emitted from antennae using electricity.<sup>13</sup> Radio waves travel at the speed of light until they encounter another antenna, which echoes the original electrical signal used to create the waves, which in turn transmit it to further antennae. However, a single radio wave is not capable of carrying useful information, so it is important to note that these waves can travel with different frequencies or wavelengths, but always move at the same speed, the speed of light. This relationship is described by the equation  $c = \lambda f$ , where  $c$  is the speed of light,  $\lambda$  is the wavelength and  $f$  is the frequency. Both the frequency and wavelength of that wave are determined by the transmitting antenna. Radio waves of different frequencies have different wavelengths, so that a sine wave of a low frequency wave will appear more stretched than that of a high frequency wave. This can be seen in Figure 7.

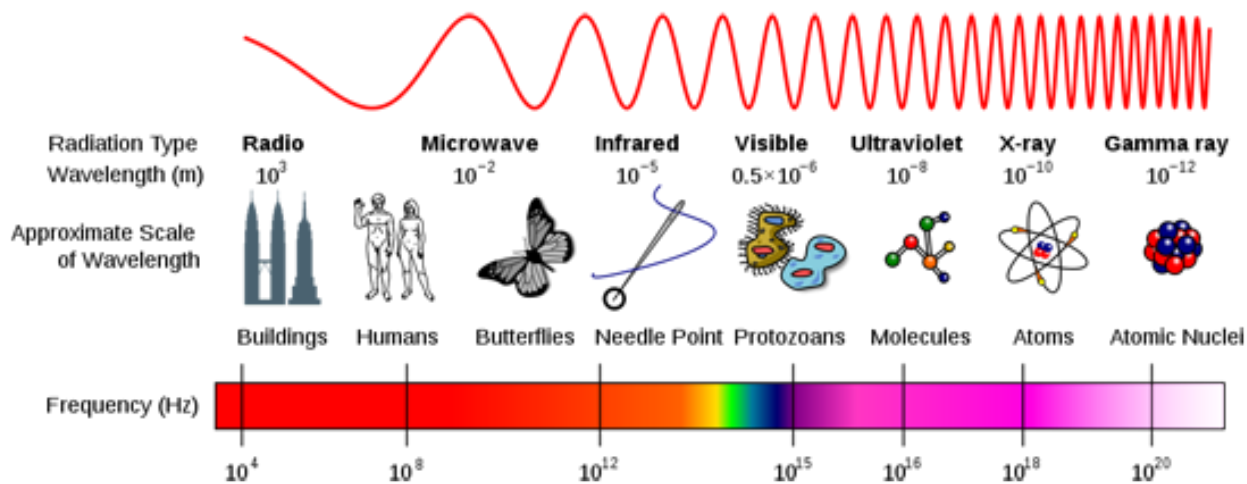


Figure 7. A graph showing the electromagnetic spectrum, along with wavelengths and frequencies.<sup>14</sup>

For a flight, we send transmitters up with the balloons; these transmitters are equipped with GPS so that they can send information in close to real time. APRS.fi uses a network of receivers to pick up signals from nearby transmitters, which it makes available to the public on a free online server. Additionally, APRS.fi stores all gathered information from a flight for a period of time, and keeps some values such as altitude and longitude for years after.<sup>12</sup> This means that researchers are able to access and export their raw data directly from the site, and can share it with others by giving them the unique call sign designated to their transmitting device.

## II.D. Variables that affect burst altitude

A number of variables affect the burst altitude of a balloon. This study focuses on the following variables: balloon manufacturer, size, time of day of the launch, and final ascent velocity. In particular, balloons created by the companies Kaymont Consolidated Industries, Zhuzhou Rubber Research & Design Institute Co., Ltd, and Project Aether were compared.

### II.D.1. Manufacturer

Kaymont balloons are a product of Kaymont Consolidated Industries, which have produced latex balloons for more than thirty years.<sup>15</sup> Their balloons are used by the U.S. Space Program, and are also popular for high-altitude rocket release and other forms of HAB research. Kaymont states that the burst altitude will be 32,000 m for a 1500 g balloon and 33,500 m for a 2000 g balloon.

Hwoyee brand balloons are manufactured by Zhuzhou Rubber Research and Design Institute Company, Ltd.<sup>16</sup> They have been in production since 1964, and are reportedly the largest meteorological balloon manufacturer in China. Though they produce a large selection of balloons, HAB researchers often use the 1600 g sounding balloon, which is made from natural latex rubber. According to Hwoyee, the burst altitude of the 1600 g balloon should be greater than 36 km.

The last balloon manufacturer used by contributing researchers was Aether Industries, which is a relatively young company, founded in 2009.<sup>17</sup> They have interests that range from high bandwidth radio to high altitude balloons. Like Hwoyee and Kaymont, Aether Industries creates a large variety of balloons in different sizes and weights. However, the only model used by data contributors was the 1200 g weather balloon, which the manufacturer claims to have a burst altitude of 35,000 m. A summary of the manufacturer guarantees for Hwoyee, Kaymont and Aether Industry balloons can be seen in Table 1.

Balloon Manufacturer Specifications		
Manufacturer	Balloon Weight (g)	Burst Altitude (m)
Kaymont	1500	32000
	2000	33500
Hwoyee	1600	30000
Aether Industries	1200	35000

Table 1. Balloon Manufacturer Specifications.<sup>15–17</sup>

## II.D.2. Day or Night

The time of the flight may also be a variable that impacts balloon burst altitude. For this study, flights were separated into ‘day’ and ‘night’ flights, which were distinguished by nautical twilight. According to the United States Naval Observatory, nautical twilight is defined as the point when the center of the sun is twelve degrees below the horizon.<sup>18</sup> Figure 8 shows this phenomenon. Day flights occur when the sun is less than twelve degrees below the horizon or above the horizon for launch and landing; if launch and landing occur when the sun is greater than twelve degrees below the horizon, it is a night flight. None of the flights used in this study took place both during the day and the night, so that category is not needed. As mentioned above, the conditions in the atmosphere vary greatly over

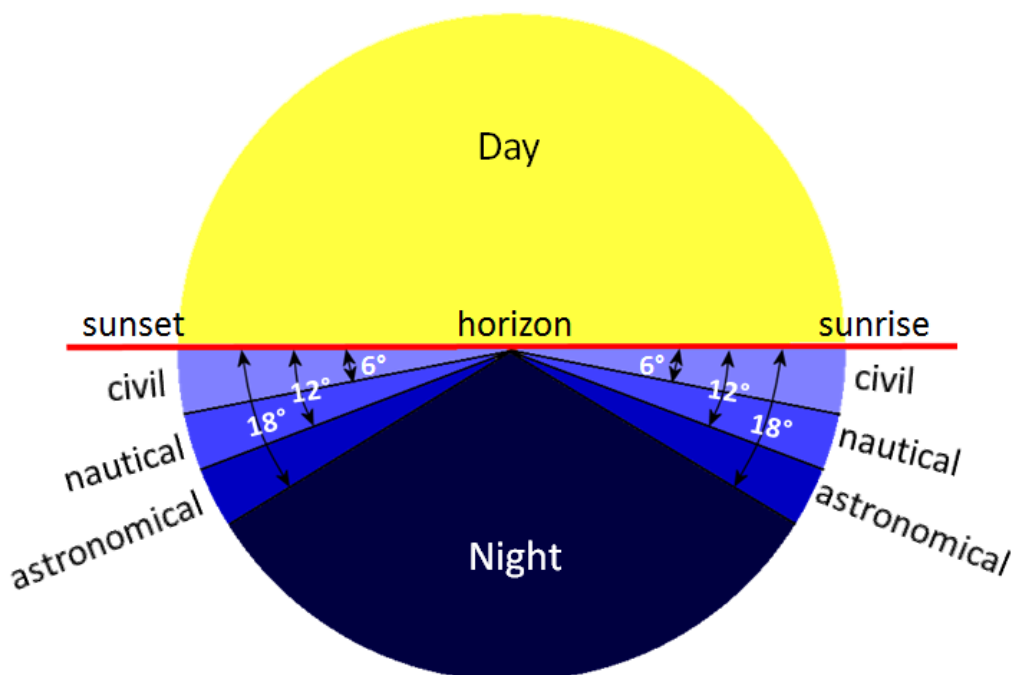


Figure 8. A representation of the categories of Twilight. For this study, Nautical twilight was used as the distinction between day and night flights.<sup>19</sup>

the course of one day. We were interested in seeing how these conditions might affect the performance of the balloon. There were a number of reasons we believed day flights and night flights would burst at different altitudes. For instance, it is known that UV radiation is harmful to latex. Exposure to UV light causes brittleness in latex, and if this occurs when the material is under strain, as it is during most parts of a flight, it could cause a point of fatigue which would further damage the material.<sup>20</sup>

It is possible that UV radiation indirectly hinders the performance of the balloon in another way. This idea arose from an interesting phenomenon in physics called emissivity,

which is defined as the ability of a material to radiate energy.<sup>21</sup> This property is reliant on the material, but the color of an object might also affect its ability to absorb radiation. For instance, a white object such as a typical weather balloon is able to reflect most of the UV radiation shining on it. This causes the air surrounding the balloon to heat up due to a convective energy transfer. As the balloon rises, some of the heated air remains, leaving a trail of heated air behind.<sup>3</sup> This is a subject of interest within the HAB community; known as thermal wake, it is one of the primary research areas for the St. Catherine University Ballooning Team.

Another important factor to consider is the variation in temperature between the day and night, since many materials are known to act differently in different temperatures. For this study one concern is that the temperature might drop down below the glass transition temperature ( $T_g$ ) of the natural latex used to create the balloons. Going below the  $T_g$  would cause a definite change in the behavior of the material; materials above their  $T_g$  still retain elasticity, whereas those cooled below their  $T_g$  become glassy and brittle.<sup>22</sup> This may cause the balloon to burst more quickly, especially considering the pressure and changes of volume the balloon experiences in its ascent. The  $T_g$  value of natural rubber latex is  $-73^\circ$  Celsius.<sup>23</sup> Since an average day flight will see temperatures of below  $-40^\circ$  Celsius in the upper troposphere should night temperatures drop to the range of  $-65^\circ$  Celsius, it is possible that the natural latex rubber of the weather balloon will experience temperatures that would cause it to undergo glass transition.<sup>24</sup>

### *II.D.3. Ascent Velocity near End of Flight*

The vertical velocity of the balloon as it nears its burst altitude also may impact balloon performance, since it will affect the rate at which the volume of the balloon changes. Volume changes over shorter spans of time create more stress on the material, making it more likely to fail. Therefore, if the balloon is ‘going up hot,’ or rapidly ascending through the atmosphere, it may be possible that it will ultimately burst earlier than it would have had it experienced a more gentle ascent.

## **III. Methods**

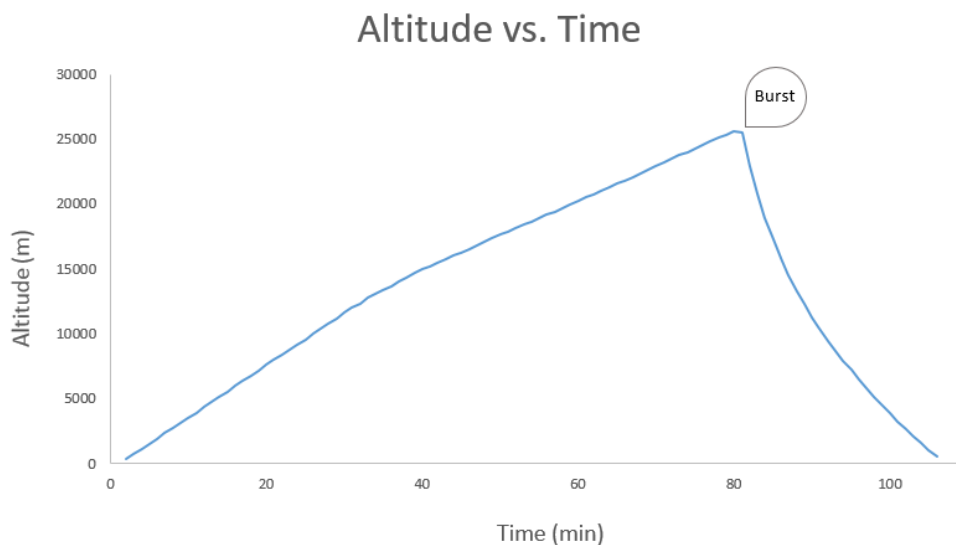
### **III.A. Data Collection**

In order to analyze the variables which affect balloon burst height, data were collected from a variety of balloon researchers, a list of which can be seen in the Acknowledgment Section. This information was categorized into flights that occur during the day or in the night. In addition, data were organized with respect to manufacturer and weight of balloon,

manufacturer altitude prediction, actual balloon burst altitude, rate of ascent, and course and speed before and after burst.

With permission from the researchers, we retrieved data from the online stores kept for each APRS call sign on APRS.fi. Before contacting researchers, guidelines for acceptable values had been established. For instance, APRS.fi data which preceded the year 2010 were not included because some researchers do not document the manufacturer of the balloon they are using for each flight, and their recollections may not be accurate. In some cases, the researcher stated that certain information should not be used, so those data were avoided as well.

Each flight was examined to make sure researchers were not testing something which affected the vertical course of the balloon and, therefore, its burst altitude. For example, the researcher who collected the data shown in Figure 10 appears to have been testing a procedure that allowed her balloon to float at a certain altitude before bursting, which means that this flight would not be suitable for use in our study. A more typical flight can be seen in Figure 9.



**Figure 9.** A typical flight path, with burst at approximately 90 minutes; courtesy of Professor Michael Davis of Truman College in Missouri.

APRS.fi can export data into an Excel file. Once the information was exported into an unprocessed file, we used an Excel macro to organize the data. I created the code for the Excel macro previously for an internship at the University of Minnesota. Excel macros are unique in that they can be created through recording the actions taken while in Microsoft Excel. The program is able to capture the actions taken while a macro is being recorded, and then can repeat the steps at any time.

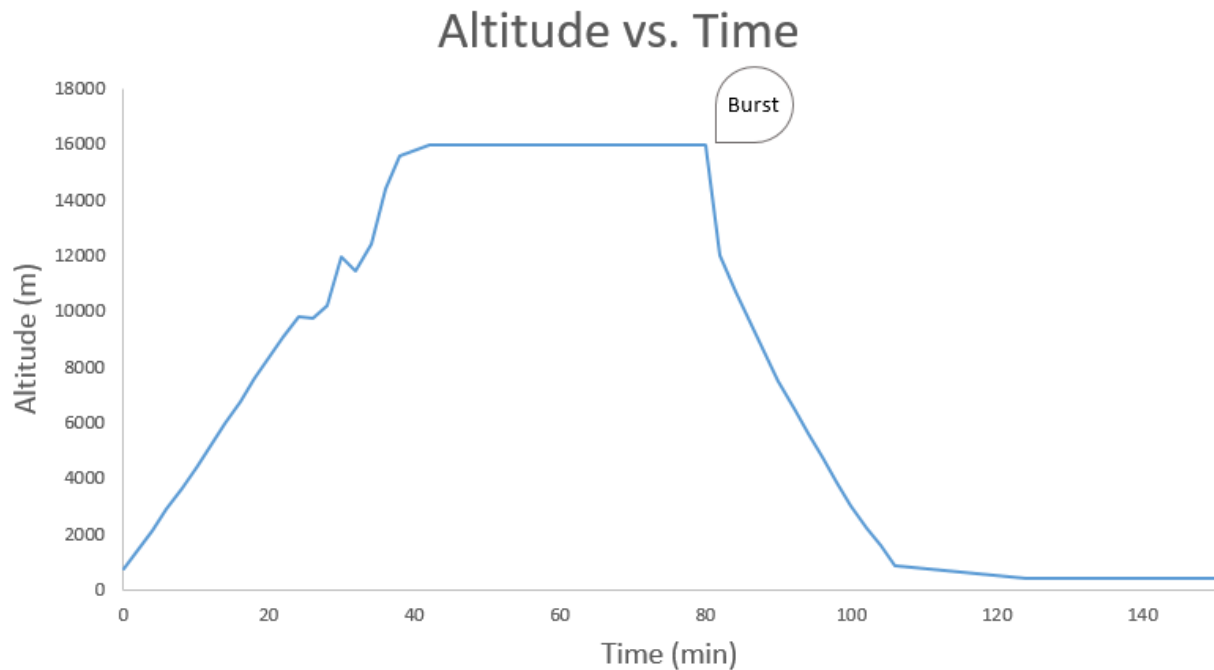


Figure 10. An unusual flight path displays a constant altitude for approximately forty minutes. The APRS information was courtesy of Dr. Kendra Sibbersen of Metropolitan Community College in Nebraska.

time	lasttime	lat	lng	speed	course	altitude	comment
5/5/2015 15:35	5/5/2015 15:35	44.16233	-93.9055	41	287	1032.05	MNSGC High Altitude Balloon
5/5/2015 15:36	5/5/2015 15:36	44.16467	-93.913	41	282	1349.04	MNSGC High Altitude Balloon
5/5/2015 15:37	5/5/2015 15:37	44.16633	-93.9222	44	288	1645.01	MNSGC High Altitude Balloon
5/5/2015 15:38	5/5/2015 15:38	44.16867	-93.9293	41	306	1957.12	MNSGC High Altitude Balloon
5/5/2015 15:39	5/5/2015 15:39	44.17183	-93.9343	37	316	2251.25	MNSGC High Altitude Balloon
5/5/2015 15:40	5/5/2015 15:40	44.17533	-93.9392	28	306	2569.16	MNSGC High Altitude Balloon
5/5/2015 15:41	5/5/2015 15:41	44.17833	-93.9422	15	331	2891.33	MNSGC High Altitude Balloon
5/5/2015 15:42	5/5/2015 15:42	44.18033	-93.9452	20	335	3211.37	MNSGC High Altitude Balloon
5/5/2015 15:44	5/5/2015 15:44	44.18633	-93.9488	17	335	3830.42	MNSGC High Altitude Balloon
5/5/2015 15:45	5/5/2015 15:45	44.18883	-93.9485	19	37	4153.51	MNSGC High Altitude Balloon

Figure 11. Raw data exported from APRS.fi from a flight completed by the St. Catherine University Ballooning Team in May of 2015.



Time (m)	Time since Start (min)	Change in Time (min)	Lat (deg)	Lng (deg)	Speed (m/s)	Course (deg)	Altitude (m)	Rate of Ascent (m/s)
935	1.00	0.00	44.16233	-93.9055	41	287	1032.05	
936	2.00	1.00	44.16467	-93.913	41	282	1349.04	295.97
937	3.00	1.00	44.16633	-93.9222	44	288	1645.01	312.11
938	4.00	1.00	44.16867	-93.9293	41	306	1957.12	294.13
939	5.00	1.00	44.17183	-93.9343	37	316	2251.25	317.91
940	6.00	1.00	44.17533	-93.9392	28	306	2569.16	322.17
941	7.00	1.00	44.17833	-93.9422	15	331	2891.33	320.04
942	9.00	1.00	44.18033	-93.9452	20	335	3211.37	619.05
944	10.00	2.00	44.18633	-93.9488	17	335	3830.42	161.545
945	11.00	1.00	44.18883	-93.9485	19	37	4153.51	279.81

Figure 12. Data after processing from the same flight completed by the St. Catherine University Ballooning Team in May of 2015.

Furthermore, we looked at the altitudes at burst and at ten minutes before burst, and estimated the pressure of the atmosphere at both of these points. This allowed us to use Boyle’s Law,  $P_1V_1 = P_2V_2$ , where  $P$  is pressure and  $V$  is volume, to look at the ratio between the volume at burst and the volume ten minutes before burst.

### III.B. Data Analysis

Values were separated into different groups based on the balloon manufacturer used, the time of the flight, and the APRS performance. APRS performance was categorized based on the definitions given in Table 2. This separation into groups allowed for the statistical examination of altitudes with respect to manufacturer and day vs. night. In statistical terms, this process divided the sample, or all the flights gathered for this study, into groups.<sup>25</sup> These groups are portions of the sample that share some key characteristics. For instance, some groups from this study include ‘Day Flights,’ ‘Night Flights,’ ‘Kaymont 1500g Balloons,’ etc.

Initially, we calculated the standard deviation and variance of each sample, both of which are used to judge the variability of the data. In other words, these values tell us how much a set of measurements fluctuates relative to its mean, otherwise known as its average.<sup>25</sup> Smaller variance values allows for greater confidence in the data because it indicates that there is less spread in the sample group. These values were calculated in order to utilize statistical tests which compare calculated values to critical values which are chosen to reflect a significance level,  $\alpha$ . For this study we used a significance level of 0.05.

#### III.B.1. Manufacturer Analysis

To analyze manufacturer and time of day data, tests of hypotheses were performed. These tests rely on the formulation of a null hypothesis ( $H_0$ ); the researchers will either reject or fail to reject this hypothesis by comparing a calculated value to a benchmark value of significance, which differs between tests.<sup>25</sup> For many tests the null hypothesis states that

Flight Categorization	Description
Day Flight:	Flight took place after Nautical Dawn and before Nautical Twilight.
Night Flight:	Flight took place after Nautical Twilight and before Nautical Dawn
Full Flight:	APRS Tracking was not lost for more than three minutes throughout the flight.
Partial Flight:	Tracking was lost for more than three minutes, but was regained before landing.
Lost on Ascent:	Tracking was permanently lost before full altitude was reached.
Lost on Descent:	Tracking was permanently lost after balloon burst.

**Table 2. Categorizations of data.**

there is no significant difference between the means of the sample groups being tested. If the null hypothesis is rejected, then the alternative hypothesis ( $H_a$ ) is accepted; in this case, the difference in means is found to be statistically significant.

There are tests that measure the amount of variance between sample groups. One such test is the Analysis of Variance (ANOVA), the computation of which results in an  $F$  statistic, which is compared to an  $F$  value which is determined by  $\alpha$ , or the significance level. Following convention, an  $\alpha$  value of 0.05 was used for these tests. The comparison of these values gives information about how the means of sample groups are related. R Project for Statistical Computing (R) was used to generate the ANOVA test, and it produced both the  $F$  and  $p$  values, which were 2.78 and 0.0473, respectively. The null hypothesis was that the mean of each sample group was equal to the means of others; in the day vs. night case, it was assumed that balloons flown at night performed equally to balloons that flew during the day, and likewise for the manufacturer analysis. Assuming a 5% error in data, the ratio to which the calculated  $F$  statistic will be compared is  $F_{.05} = 1.64$ .

Note that an ANOVA is used for random, independent samples with normal distributions and same variance.<sup>25</sup> Statisticians use Levene's test to judge whether an ANOVA is still a valid method of comparing means when dealing with groups whose variances appear to be different. Should the Levene's test yield a favorable value, an ANOVA might still be run

even though standard deviations of the groups differ. Again, Levene's test can be performed using statistical software; for this study the program R was used.

If the results of an ANOVA show that the null hypothesis is rejected, this means that at least one of the group's mean is different from the others.<sup>25</sup> In this case it is possible to run further tests which reveal more information about the situation. For instance, a Tukey test is a multiple comparison method which can give insight as to the interactions of the means of pairs of samples. This gives information about whether the means of two specific groups differ, and helps generate a more thorough understanding of the situation.

### *III.B.2. Day versus Night Analysis*

For the time of day data, a two-tailed  $t$ -test was performed. This test is used for small, random samples that are normally distributed.<sup>25</sup> The null hypothesis assumes that there is no statistical difference between the means of each sample group. In order to test the null hypothesis, a sample  $t$  value, is calculated from the means, sample sizes, and variances of the samples being tested.

A  $t_\alpha$  value is used as a threshold; it is found using either a standard  $t$  value table or statistical software. In this case, the  $t_\alpha$  value was supplied by R. To test the null hypothesis, the  $t$ -value is compared to the  $t_\alpha$ . The null hypothesis will be rejected if the  $t$ -value is greater than the  $t_\alpha$  value or is less than the negative  $t_\alpha$  value.

### **III.C. APRS and Final Velocity Analyses**

We used simpler methods to look at APRS performance and the final velocity data. For the APRS data, after we separated the population of data into the correct sample groups, we looked at the percentages. For instance, 82.9% of the flights were full flights. In doing this we can see how often each category of flight occurred.

To look at the final velocity, we graphed the data to try and see if there was any sort of correlation. However, we were careful to only look at day flights to avoid incorporating diurnal temperature shifts. Additionally, the change in volume could only be calculated if we had altitude data ten minutes before burst occurred, which limited the data used for this portion of the study. Unfortunately, further statistical analysis was not possible, because we couldn't separate the population into samples without affecting the randomness of the data. However, graphing the volume ratios against the burst altitudes allowed for some inkling of the relationship between these two variables. This graph can be seen in Figure 16.

Manufacturer	Burst Altitude (m)	Manufacturer Altitude (m)	Number of Flights	Percent Difference (%)
Kaymont - 1500 g	26265.32	32000	30	-17.9
Kaymont - 2000 g	24227.56	33500	25	-27.7
Hwoyee	28314.21	30000	13	-5.6
Project Aether	20511.98	35000	7	-41.4

Table 3. Analysis of Manufacturer Altitude with actual burst altitude.

## IV. Results and Analysis

### IV.A. Manufacturer Results

Table 3 shows a comparison of manufacturer specifications and experimental data. Manufacturers predicted the burst altitudes of their balloons with varying levels of precision. Hwoyee balloon performance closely matched predictions, with only a 7% difference between manufacturer specifications and experimental data. However, actual Project Aether balloon data was much lower than predicted, with a 52.2% difference.

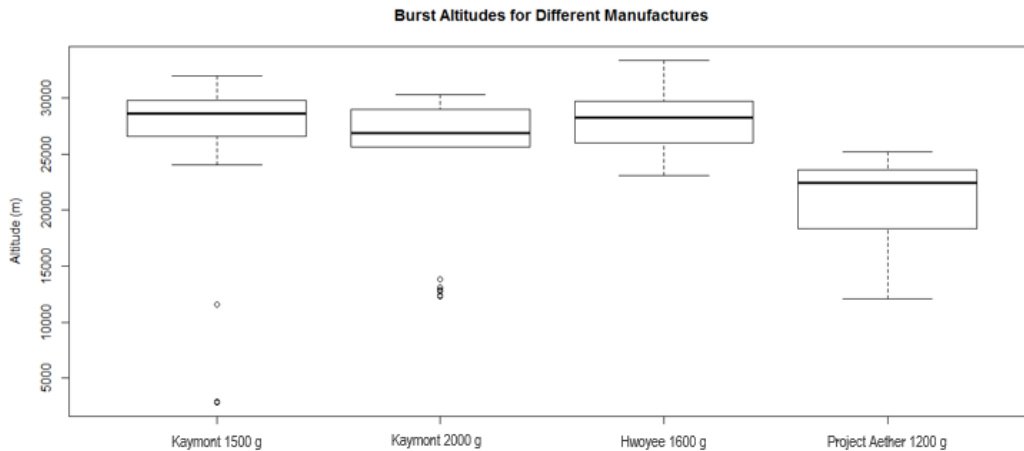


Figure 13. The burst altitudes of Hwoyee, Kaymont, and Project Aether balloons.

Manufacturer performance can be seen in Figure 13. Sample sizes of the manufacturer categories ranged from 6 to 29 flights, with Project Aether being the most underrepresented and Kaymont the most plentiful. Outliers were present within both of the Kaymont groups and are points that are beyond the low or high values for the spread of data; on Figure 13 they are the points beyond the whiskers of the two Kaymont balloon groups. Since this indicates that the data may not be uniformly distributed, there was a concern over the distribution of manufacturer data. After running a Levene's test, we found that the standard deviations of the groups were not so dissimilar as to render an ANOVA unusable. The results of an ANOVA performed in the statistical program R can be seen in Table 4.

ANOVA Table for Comparing Manufacture Values					
Source of Variation	<i>dof</i>	Sum Sq	Mean Sq	<i>F</i> Value	<i>p</i> Value
Treatments	3	$33.4 \times 10^7$	$11.15 \times 10^7$	2.78	.0473
Error	71	$285 \times 10^7$	$4.01 \times 10^7$		

Table 4. The calculation of the *F* and *p* values for Manufacturer Altitudes.

The ANOVA test yielded an *F* value of 2.78, as can be seen in Table 4. From the results of the the ANOVA run in R, we rejected the null hypothesis, which was that the means for the sample groups are not statistically different. In rejecting this hypothesis, we have established a statistically significant difference between the performances of balloons from different manufacturers. To further compare the means of each sample group, a Tukey test was performed, again in R. It shows the differences between the means of each group in the sample when compared to the others, and a graphical representation of the test’s results can be seen in Figure 14. It indicates that there is a significant difference in means between the Project Aether and Hwoyee groups, since their comparison did not include the 95% family-wise confidence level. All other groups did, and so differences in their means are more likely to be statistically insignificant.

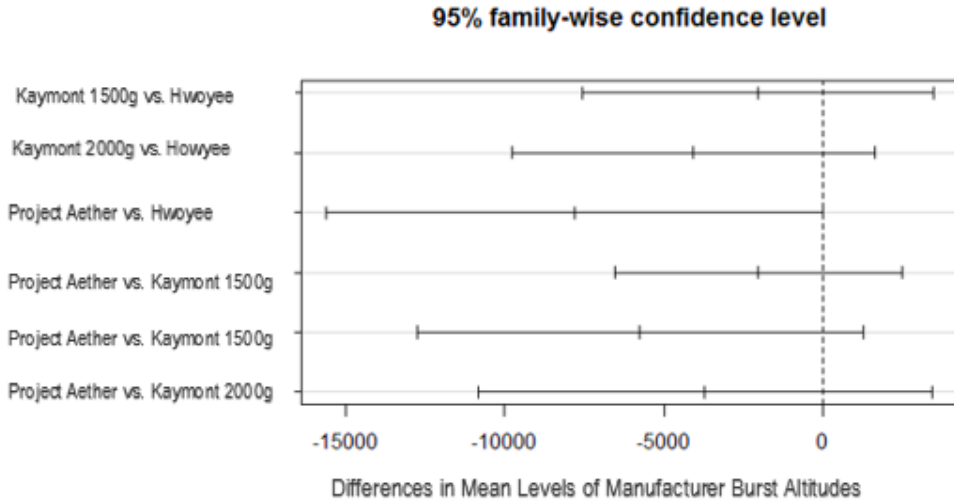


Figure 14. Results of a Tukey test performed on the manufacturer altitude data.

#### IV.B. Day vs. Night Results

Day and night flight performance information can be seen in Figure 15. Again, outliers were present in the day sample, and night flights were very underrepresented, with a sample size of four out of sixty-five flights. To analyze the difference of burst altitude in day and night

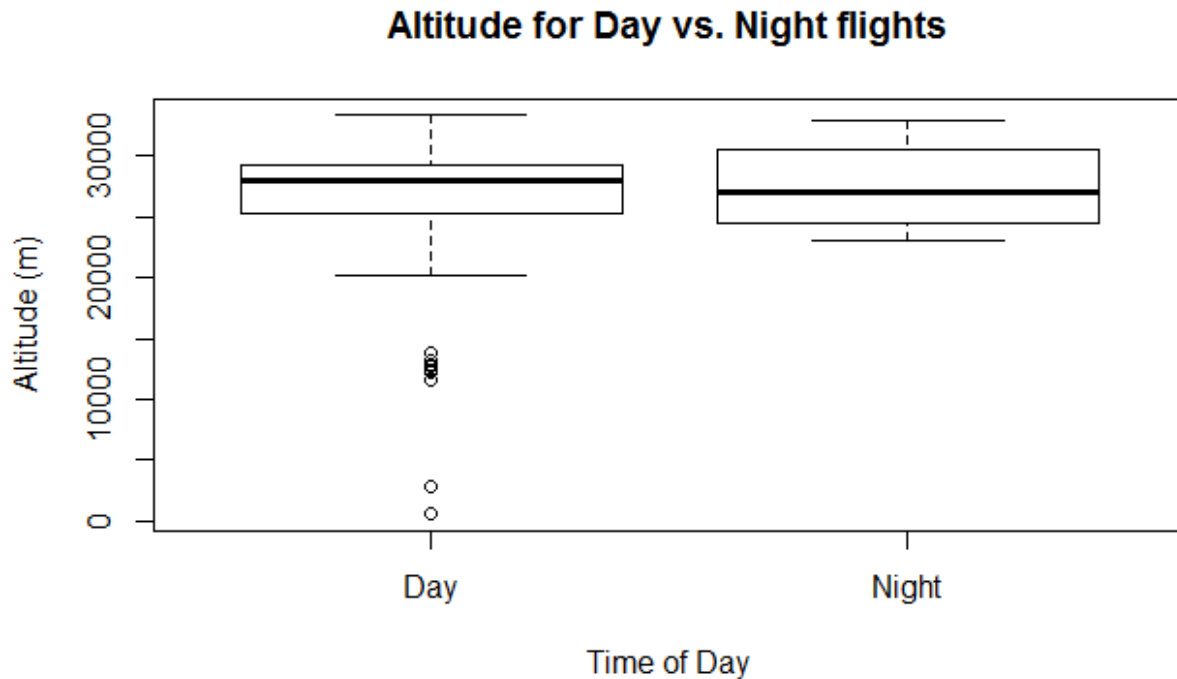


Figure 15. The burst altitudes, in meters, for day and night flights

flights, a  $t$ -test was performed in R. The test resulted in a  $t$ -value was 1.243 and a  $p$ -value of 0.3587. Since this value is less than the  $\alpha$  value of 0.05, and the  $t$ -value supplied by R was greater than the calculated  $t$ -value, the null hypothesis is rejected, and the differences in night and day launch altitudes are found to be statistically significant. However, this does not appear to match up with what is happening in Figure 15; in that Figure, one can see that the medians of both groups are very close to each other. For this reason it is likely that the outliers present in the Day flight's data are interfering with the results of the  $t$ -test. It would be prudent for further work to examine the presence of these outliers, and to determine whether there are other factors affecting their burst altitudes.

#### IV.C. APRS Performance Results

APRS performed well more often than not; 83% of flights were full flights, and 11% of the time tracking was only partially lost. This indicates that APRS is a fairly reliable tracking system. Reasons for faulty tracking were not examined; however, topography and weather conditions are both capable of interfering with transmission.

APRS Performance	Number of Flights	Percent of Occurrence (%)
Full Flight	21	58.33
Partial Flight	10	27.78
Lost on Descent	4	11.11
Lost on Ascent	1	2.78
Total	36	99.98

Table 5. APRS Performance Data.

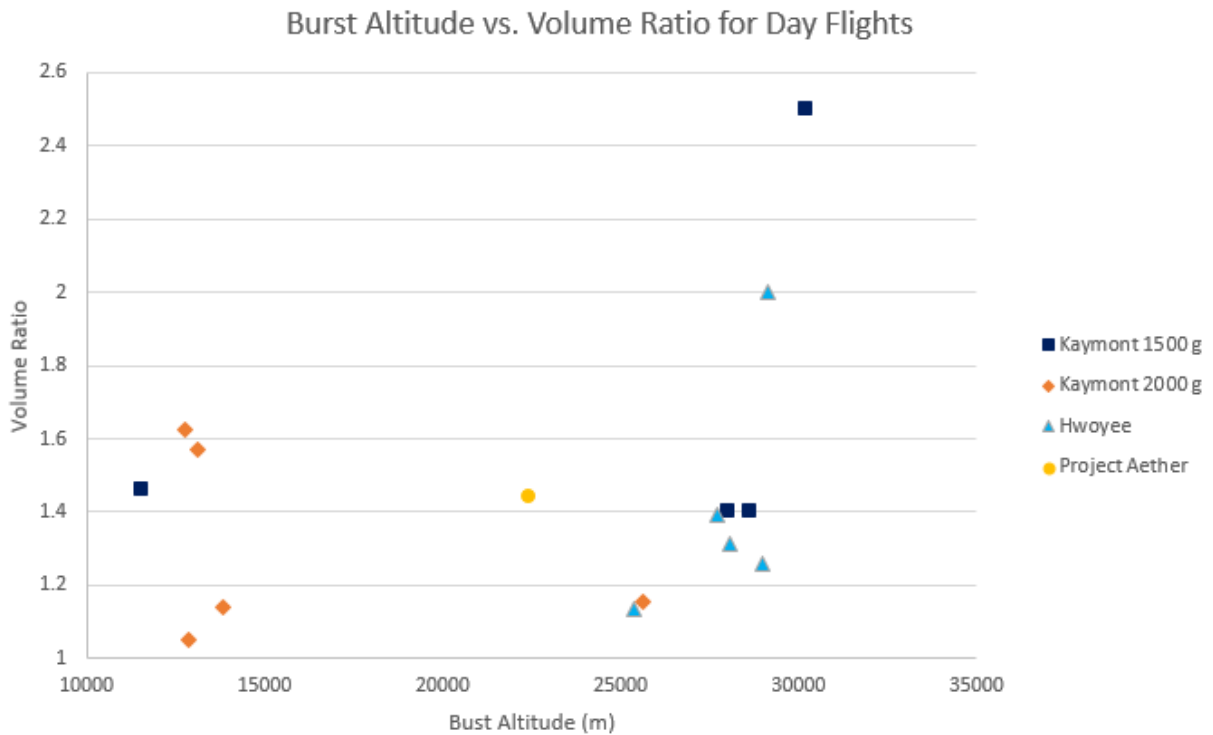


Figure 16. The ratio of the volume at burst to the volume ten minutes before burst, compared to the burst altitude of the balloon.

#### *IV.C.1. Final Velocity Results*

The ratio of the final volume to the volume ten minutes before burst had an average of 1.4. This means that, on an average flight, the volume of the balloon increased by a factor of 1.4, so if the balloon's volume were 10 m<sup>3</sup> ten minutes before, it would be 14 m<sup>3</sup> at burst. Considering the overall change in volume of the balloon, this shows that a only approximately 5% of the total change in volume occurs in the last ten minutes before burst.

After graphing the velocity ratio against the burst altitudes, we can see that the values appear to be random and show little sign of a relationship. However, without more strenuous statistical testing, this fact cannot be certain. We would need much more data in order to test this hypothesis further.

It should be noted that pressure data is not stored on APRS.fi. To get the pressure of the atmosphere around the balloon ten minutes before burst and at burst, we had to look at the altitude of the balloon and infer the pressure from a graph. This is an imprecise method of gathering pressure data, and therefore this is significant potential source of error for this analysis.

#### *IV.C.2. Analysis*

Dealing with small sample groups is notoriously bad for statistically significant analyses. It is likely, but not certain, that this phenomenon has affected the reliability of the analysis completed for this study. In addition, other sources of error might have affected the analysis, such as human error or tracking issues. For instance, the slow transmission rates of the primary tracking system that collected altitude data for this study could have negatively affected the accuracy of the data collected. Typically, packets arrive in one minute intervals. Some researchers have adjusted the transmission rates so that time gaps between data collection are different sizes. However, unless the transmission rate is continuous, it is possible that the true burst altitude was not actually collected.

An additional significant source of error stems from the nature of the Lost on Ascent APRS tracking category. Since the tracking is lost on ascent, it is likely true that the greatest altitude of that flight is not the actual burst altitude. Therefore, the Lost on Ascent values have been removed from the Manufacturer and Day vs. Night categories it appears in so as to try and minimize the effect.

As always, human error potentially can affect the outcome of the study. If mistakes were made during the categorization process, it is possible that data belonging to one category would end up in another. This would cause skewed data and would decrease the significance of the study. Additionally, it is possible that datum was handled incorrectly. When processing the raw data exports from APRS.fi, all times are given in the Universal Standard Time model. For each flight, the time had to be readjusted into the local time of the launch,



and then analyzed to determine if the flight took place during the day or night. Mainly, flights took place squarely within the day or in the middle of the night, leaving little room for misinterpretation. However, it is possible that errors were made. If this is the case the day and night flight data might have become skewed.

Unfortunately, the parameters studied here are not the only things that affect balloon performance. Structural weaknesses in the balloon can cause it to burst earlier than predicted. These weaknesses can arise from flaws in the manufacturer process, or from mistakes in the inflation stage of a launch. The latex of the material can be damaged by contact with the oils found on human hands, so if the launchers forgo gloves, they can potentially lower the performance of the balloon. Additionally, incorrect storage or contact with sharp objects can weaken the integrity of the balloon.<sup>16</sup>

Inclement weather can also affect balloon performance. When condensing the data, we did not check the weather for the day of each launch in the launch location. While balloonists typically prefer to launch on days that are not stormy or windy, there are valid reasons that one might choose to go against that convention. Certain meteorological studies might call for launches in inclement weather, or perhaps a need for data would constitute launch. If researchers choose to do so, it could introduce another parameter not accounted for in this study.

## V. Conclusion and Future Work

Two different parameters were studied with respect to balloon burst altitude. Time of day was found to be statistically significant by a  $t$ -test, indicating that there are differences between balloon performance during day and night conditions. Balloon manufacturer was also found to have a large impact on balloon burst altitude, and we found manufacturers to have varying levels of accuracy about the predicted altitude of their balloons. Additionally, APRS performed well more than half of the time.

The significant differences between day and night flights indicates that there are key physical differences in the troposphere and stratosphere throughout the day. However, pinpointing which variables have the greatest effect on balloon burst altitude is beyond the reach of this study. More research in diurnal variations of temperature and pressure would be necessary, as would further investigations on the interaction of UV radiation, pressure and temperature and how they affect the material properties of latex.

Further research would also need to be done in order to clarify the relation between balloon manufacturer and balloon burst altitude. The methods each manufacturer uses to test the quality of their product would need to be verified, and the chemical composition

and molding methods of each would need to be compared. As stated above, these variables would greatly affect the performance of the balloon, and it would be worthy of further study.

We would also need to do more research in order to clarify the potential relationship between the change in the volume of the last ten minutes before burst and the burst altitude. This information should include more precise measurements of the pressure experienced by the balloon, which would lead to better estimations of the ratio of the final volume to the volume ten minutes before burst.

Continuing onward, this study will delve into the physical aspects of this problem, including the different manufacturing processes and the affects of conditions for day or night flights on the latex of the balloons. In future studies, APRS will be tested for its reliability and reasons for its failures will be examined.

## VI. Acknowledgments

Professor Erick Agrimson	St. Catherine University	Project Advisor and Data Contributor
Dr. Jessie Lenarz	St. Catherine University	Project Advisor
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