Statistical Tests Exploring a Subset of Variables Related to Balloon Burst Altitude

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The ability to accurately estimate balloon burst altitude is important when modeling flight paths in preparation for a high altitude balloon launch. Variables considered for the study of burst altitude include the manufacturer of the balloon, the time of day of the flight, and the ascent rate of the balloon during the last ten minutes before burst. To study these variables, we ran statistical tests on data collected from more than sixty balloon flights carried out by researchers across America.

Nomenclature

α Significance level for statistical tests

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ANOVA	Analysis of Variance, a statistical test
P	Pressure (mb)
$p-$value	Conditional probability
$t-$test	A statistical test
Tukey test	A statistical test to determine the difference in multiple means
V	Volume (m^3)

I. Introduction

High Altitude Ballooning (HAB) provides a reliable method with which to reach "near space." HAB researchers rely upon successful retrieval of downed payloads, in many instances to collect stored data. Researchers need reliable parameters in order to more accurately calculate 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.[1] 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.

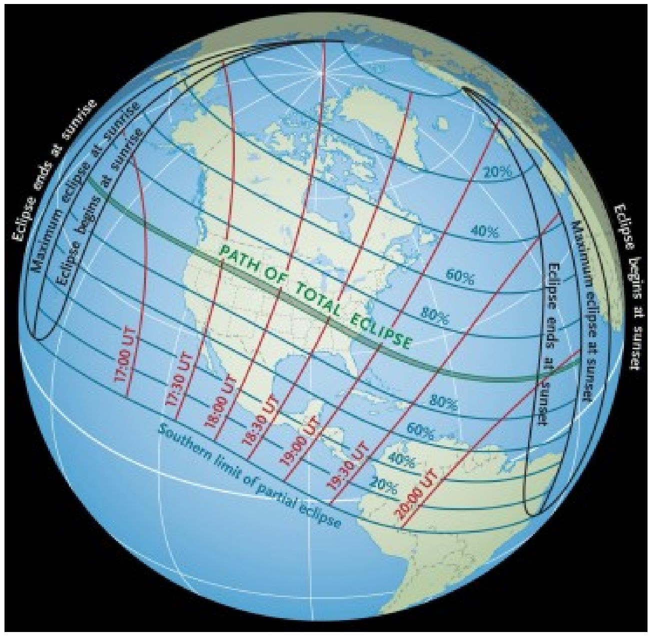

Figure 1. The path of the upcoming 2017 solar eclipse.[1]

II. Background

A. Variables Under Investigation

1. Manufacturer

This study focuses on the following variables: balloon manufacturer, size, time of day of the launch, and final ascent velocity. Balloons produced by Kaymont Consolidated Industries (Kaymont), Zhuzhou Rubber Research and Design Institute Company, Ltd. (Hwoyee), and Aether Industries (Aether) were used by researchers who contributed data. Table 1 summarizes the balloon sizes and manufacturer specifications included in our analysis.

Manufacturer	Balloon Weight (g)	Burst Altitude (m)
Kaymont	200	21336
	1200	33223
	1500	34137
Aether	1200	35000
Hwoyee	1600	36000

Table 1. Balloon Manufacturer Specifications.[2–4]

2. Day or Night

Speculating that time of day would have an impact on the burst altitude, we classified each observation as either a 'Day' or 'Night' flight. The impact on the burst altitude might happen indirectly, through the change in ambient temperature and therefore volume, or directly, by the degradation of latex caused by ultraviolet radiation. Tertiary effects might include the changing behaviour of latex at low temperatures; see Section V.

3. Volume Ratio Near End of Ascent

The vertical velocity of the balloon near the end of the flight will impact the rate at which the volume changes. We surmise the rate of change of volume may create more stress and strain in the material, thus producing failure of the material inducing a burst. This is to say, if the balloon is "going up hot," ascending fast through the atmosphere, the likelihood of an early burst is greater than had the balloon had a more gentle ascent.

III. Methods

A. Data Collection

In order to analyze the variables which affect balloon burst height, we collected data from a variety of balloon researchers; a list of contributors can be seen in Section VII. 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, and rate of ascent.

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 and did not document the manufacturer were not included.

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. A typical flight for this study can be seen in Figure 2. In contrast, the researcher who collected the data shown in Figure 3 had 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.

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 to look at the ratio between the volume at burst and the volume ten minutes before burst.

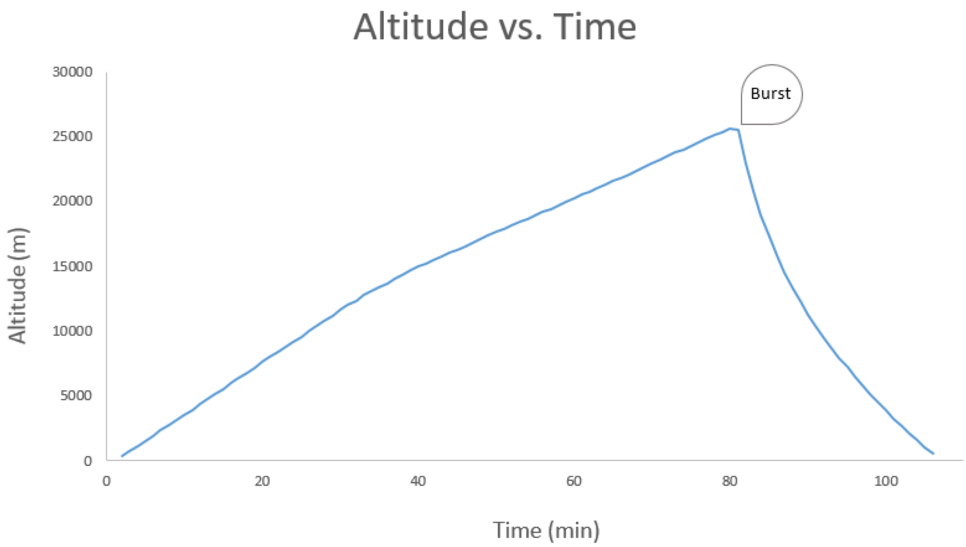

Figure 2. A typical flight path, with burst at approximately 90 minutes; courtesy of Professor Michael Davis of Truman College in Missouri.

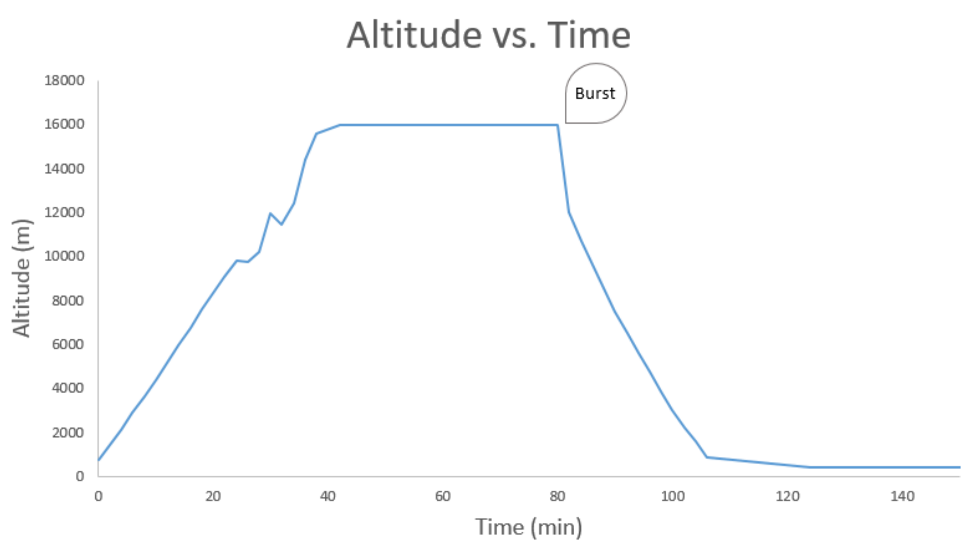

Figure 3. An unusual flight path displays a constant altitude for approximately forty minutes. The APRS information was courtesy of Dr. Kendra Sibbernsen of Metropolitan Community College in Nebraska.

B. Data Analysis

Observations were separated into different classes based on the balloon manufacturer used and the time of the flight. This separation into classes allowed for the statistical examination of altitudes with respect to manufacturer and day vs. night. Final velocity was also calculated and studied for those observations where the necessary measurements were available. R Project for Statistical Computing (R) was used to conduct all statistical analyses in this study.

1. Manufacturer Analysis

The data consists of balloons with varying sizes across each manufacturer, therefore we will consider the ratio of burst altitude to the stated manufacturer altitude shown in Table 2. A balloon that bursts at a height equal to the stated manufacturer altitude will have a ratio of exactly 1.

First, a one-sample $t-$test was performed. To conduct this test, we assume that our sample is random and normally distributed. The null hypothesis states that the mean burst ratio is equal to 1, while the alternative hypothesis states the ratio is significantly smaller or larger than 1. A $p-$value less than the significance level of $\alpha = 0.05$ indicates the null hypothesis will be rejected.

The manufacturer data splits the observations into five different classes; 'Kaymont 200 g', 'Kaymont 1200 g', 'Kaymont 1500 g', 'Hwoyee 1600 g', and 'Project Aether 1200 g'. To examine this data, an Analysis of Variance (ANOVA) test was performed. An ANOVA is used for random, independent samples with normal distributions and similar variances.[5] The null hypothesis for this test will assume an equal mean burst ratio for each class. The alternative hypothesis is that at least one of the classes has a significantly different mean burst ratio. Again, a significance level of $\alpha = 0.05$ was used and the null hypothesis will be rejected should the $p-$value be less than this level. A rejection of the null hypothesis would lead us to conclude that at least one of the classes has a significantly different mean than the others. In this event, a Tukey pairwise comparison can be conducted to determine which groups have different mean burst ratios.

2. Day vs. Night Analysis

For the time of day data, a two-sample $t-$test was performed. This test is used for small, random samples that are normally distributed.[5] The null hypothesis assumes that there is no statistical difference between the means of each sample group, while the alternative hypothesis states that there is a difference between the means of the sample groups. The null hypothesis will be rejected if the $p-$value is less than the significance level $\alpha = 0.05$.

3. Final Velocity Analysis

To evaluate final velocity, we graphed the data to try and see if there was any discernable correlation or patterns. 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 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 6.

IV. Results and Analysis

A. Manufacturer Results

Manufacturer	Average Burst Altitude (m)	Manufacturer Altitude (m)	Number of Flights	Average Burst Ratio
Kaymont - 200 g	12875.16	21336	6	0.6034476
Aether - 1200 g	19655.13	35000	5	0.5615753
Kaymont - 1200 g	27828.70	33223	16	0.8376284
Kaymont - 1500 g	26172.33	34137	30	0.7666717
Hwoyee - 1600 g	27719.26	36000	9	0.7699794

Table 2. Analysis of Manufacturer Altitude with actual burst altitude.

Table 2 shows a comparison of manufacturer specifications and experimental data. Manufacturers predicted the burst altitudes of their balloons with varying levels of precision. The mean burst ratio for our sample was 0.7682 with a standard deviation of 0.1934. This indicates that on average the balloons analyzed burst after reaching an altitude that is 76.82% of the stated manufacturer altitude.

The one-sample t-test performed to determine if the mean burst ratio was significantly different than 1 resulted in a $p-$value of less than 0.0001. We reject the null hypothesis since this value is less than the significance level of $\alpha = 0.05$. We are confident from our sample in saying the average burst ratio is significantly less than 1, and balloons are not reaching their stated manufacturer altitudes. Some possible explanations for this result are the size of the payloads, conditions during flight, or unexpected events leading to a premature burst. More detailed data will be necessary to examine these factors and may lead to further research; see Section V.

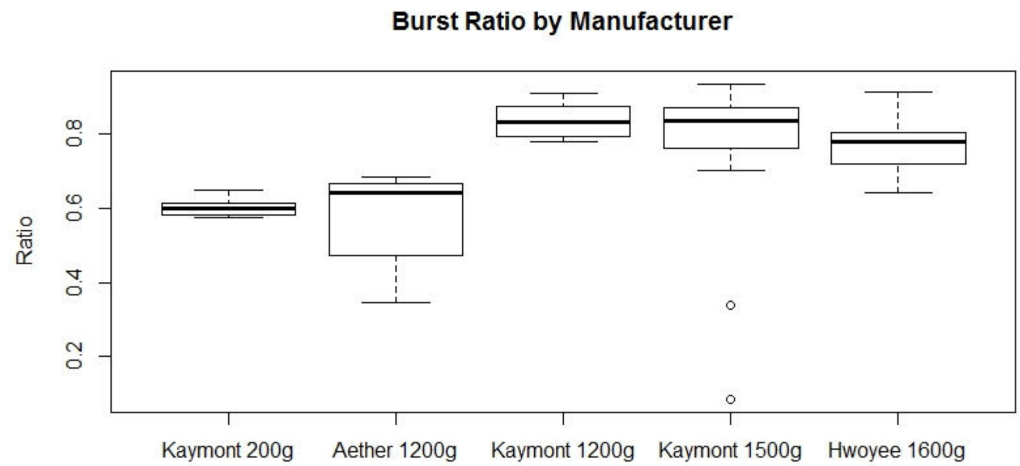

Figure 4. The burst altitudes of Hwoyee, Kaymont, and Project Aether balloons.

Manufacturer performance can be seen in Figure 4. Sample sizes of the manufacturer categories ranged from 5 to 28 flights, with Aether being the most underrepresented and Kaymont the most plentiful. Outliers were present within the Kaymont 1500 g class and point to burst ratios that were more than 1.5 times the interquartile range (IQR) less than the first quartile. A test for normality and equal variance among the classes showed our data do not violate the assumptions for the chosen statistical method. The results of the ANOVA performed can be seen in Table 3.

Source of Variation	dof	Sum Sq	Mean Sq	F Value	$p-$Value
Treatments	4	0.4401	0.11004	4.484	0.00305
Error	61	1.4969	0.02454		

Table 3. ANOVA Table for Comparing Manufacturer Values.

The ANOVA test yielded a $p-$ value of 0.00305, as can be seen in Table 3. Since the $p-$ value is less than 0.05, we reject the null hypothesis. There is strong enough evidence from our sample to show a difference in the mean burst ratio between the manufacturers, at least one of the classes has a significantly different mean burst ratio than the others. The Tukey pairwise comparison reveals that the burst ratio for Kaymont 1200 g is significantly different from Kaymont 200 g and Aether 1200 g. Specifically, the Kaymont 200 g and Aether 1200 g balloons are having an even harder time reaching the stated manufacturer altitude. The differences between the average burst ratios of all other possible pairs of classes are close enough that they can be attributed to sample variation.

B. Day vs. Night Results

A comparison of day and night flight performance can be seen in Figure 5. The figure seems to suggest that there is no statistically significant difference in day and night flights. The two-sample $t-$test performed to determine if the mean burst altitude for day flights differed from the mean burst altitude for night flights resulted in a $p-$value of 0.3587. Since this value is greater than the significance level of $\alpha = 0.05$, we fail to reject the null hypothesis, and the differences in night and day launch altitudes are not found to be statistically significant. Outliers identified for the day flights were more than 1.5 times the interquartile range (IQR) less than the first quartile or more than the third quartile. 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. Additionally, night flights were very underrepresented, with a sample size of four out of sixty-five flights. We would recommend increasing the sample size for night flights before drawing any conclusions.

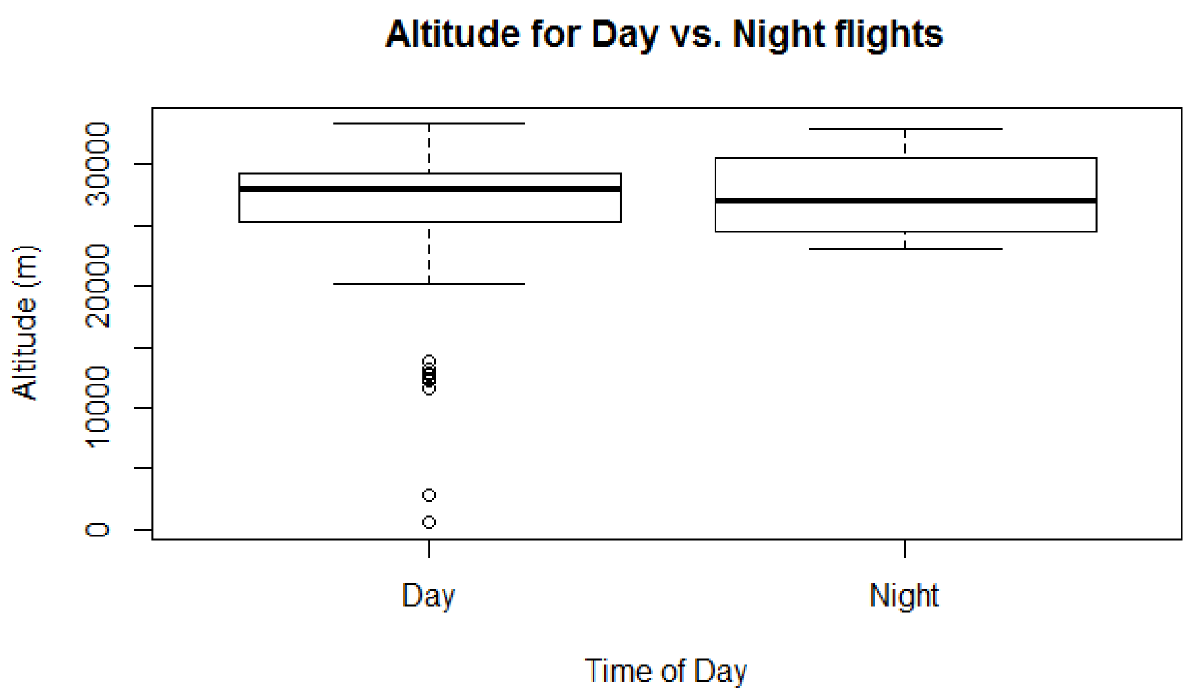

Figure 5. The burst altitudes for day and night flights

C. Volume Ratio Analysis

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^3 ten minutes before, it would be 14 m^3 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.

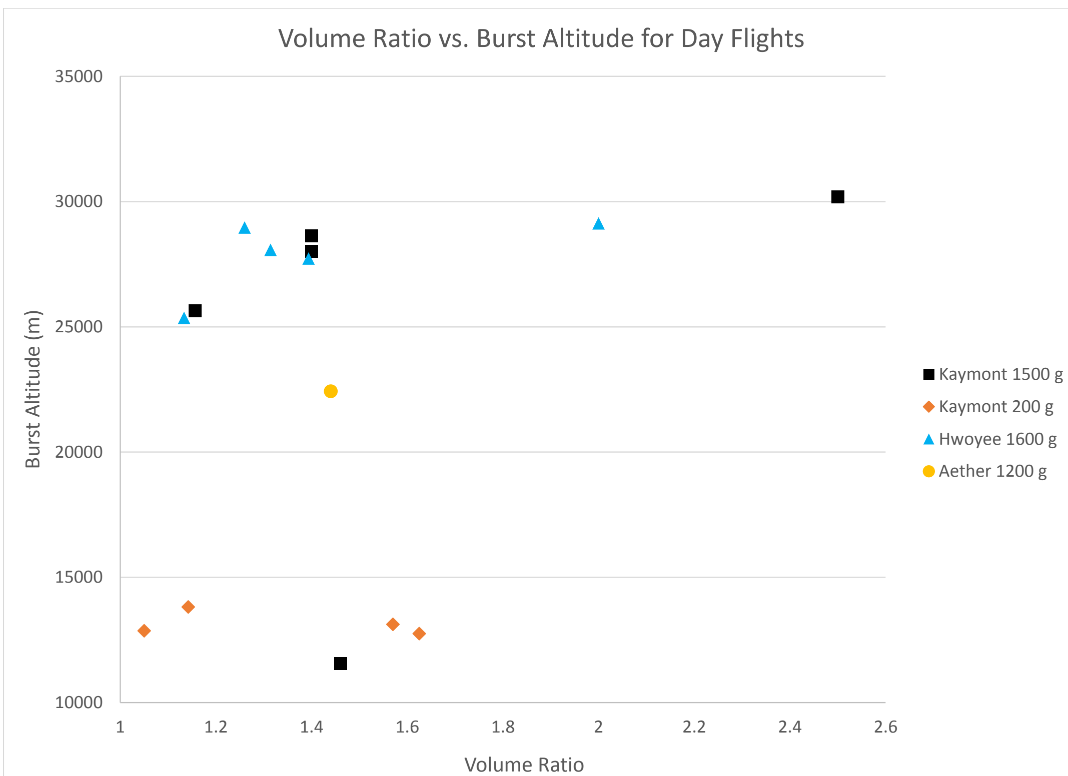

Figure 6. The ratio of the volume at burst to the volume ten minutes before burst, compared to the burst altitude of the balloon.

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.

D. Discussion

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.

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.

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. Questions for Further Consideration

A. How do structural weaknesses in the balloon affect burst altitude?

1. What are possible sources of weakness as a result of the manufacturing process?

2. How much variance exists from one batch of balloons to another?

3. How does mishandling of the balloon i.e. non use of gloves imparting oils from the hands onto the latex influence burst altitude?

4. To what extent does storage of the balloon have a role in future flight performance?

5. What will occur as balloons reach the glass transition temperature?

B. How does ambient weather on the day of launch affect burst altitude?

1. Does relative humidity have any influence on overall performance?

2. What role does wind (additional stress and strain while filling balloon in moderate wind) play?

VI. 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.

A. Suggested Documentation for Ballooning Teams

1. Manufacturer brand and mass
2. Launch Date
3. Purchase Date of balloon
4. Payload Weight
5. UT of launch
6. Ground conditions i.e. RH, wind, temp
7. time elapsed from fill to release of balloon
8. Lift gas used
9. APRS tracking file
10. Alternate tracking file i.e. 900MHz Stratostar etc.

VII. Acknowledgments

Dr. Bernhard Beck-Winchatz	DePaul University	Data Contributor
Dr. Howard Brooks	DePauw University	Data Contributor
Professor Michael Davis	Truman College	Data Contributor
Dr. Ronald Fevig	University of North Dakota	Data Contributor
Jason Krueger	Stratostar	Data Contributor
Dr. Chris Schaben	Omaha Public Schools	Data Contributor
Dr. Kendra Sibbernsen	Metropolitan Community College	Data Contributor

We would like to thank the Minnesota Space Grant Consortium for financial support for student research and supplies for ballooning research at both the University of Minnesota and Saint Catherine University since the fall of 2007.

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