Santa Cruz Institute for Particle Physics

BaBAR: Balloon and Barometer Atmospheric Research Project

By Marshall Rogers

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Acknowledgments

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Abstract

This report studies the usage of barometers manufactured by Vernier Software and Technology as altimeters, and the accuracy of those readings.

It is very common for pressure readings used with reference to sea level pressure readings to be used to calculate relative altitudes. Other technologies commonly used in altimetry include radar and GPS.

In order to use Vernier barometers as altimeters, one must have two pressure readings. First, one must have some reference reading(such as sea-level pressure) and the actual reading at the point where the altitude needs to be known. There are several formulas that can be used to utilize these measurements in order to determine altitude measurements, and they will be discussed in detail in the background.

A general experiment I performed was, after warming up the barometers for half an hour, taking one reference and one altitude measurement with the barometers, and then using the exponential pressure formula, calculating the altitude from the barometric readings, and then comparing that with the actual known altitude.

After multiple tests, it became obvious that the barometers readings were both largely erroneous and effected by temperature. I have written a basic formula in attempt to account for these temperature changes, although it does not account for them completely.

Introduction

This report will walk you through the ideology behind my experiment, the step by step methodology to my experiment, and the analysis and formulas created before and after I conducted my experiments.

This experiment was performed in order to find more accurate methods to determine altitude using Vernier barometers in order to use them as altimeters during the balloon flight experiment at the end of the SCIPP High School internship program. During that experiment, a scintillator panel with two photo multiplier tubes will be sent up on a tethered weather balloon to determine muon count rates at different elevations. Knowing precise as possible altitude measurements during that experiment is important to finding trends in muon count rates at different elevations in the atmosphere. Although the elevation of the balloon will be quite low (below 600m), there is still a possibility of discovering differences in count rates at different elevations.

Current problems with Vernier barometers have been documented by myself in my report entitled "Temperature and Vernier Barometers" and Mr. Steve Kliewer in his 2006 unpublished report entitled "Barometeric Altimetry Using the Vernier LabPro". Kliewer's paper provides insight to the accuracy of Vernier barometers as basic altimeter equipment, but does not provide a standard model to correct for error produced by the barometers. My paper provides insight onto the correlation between temperature and the barometers, but does not provide a model for error correction.

The purpose of this experiment was to determine if the correlation between temperature and pressure that I found in Vernier barometers was factual or false, and also to determine the caliber of the effects of temperature on pressure readings produced by the barometers. Although I had seen what seemed to be a correlation between temperature and pressure in the barometers, I had to run experiments to precisely define that correlation.

Background

Vernier barometers are an inexpensive way to measure pressure in a learning environment. The technology at the core of the Vernier Barometers is the Honeywell SenSym SDX15A4 Sensing Element(figure 1). The SenSym SDX15A4 uses a membrane that flexes as pressure changes. On one side of the membrane is a vacuum, and on the other side is the outside pressure(figure 2). As this membrane flexes, it creates an output voltage which is related linearly to the outside pressure. This signal is then converted by the computer application, *Logger Pro* to humanly quantifiable units of pressure (in this study I used kilopascals) that provide the end user with usable data.

Honeywell (the manufacturer of the SenSym SDX15A4) claims that the SenSym SDX15A4 is able to compensate for differences in temperature, to provide for more accurate pressure readings. This technology is supposed to work between 0 degrees centigrade to 50 degrees centigrade. While some minor compensation might be happening within the sensing element, it became obvious through testing that the SDX15A4 does not completely compensate for temperature.
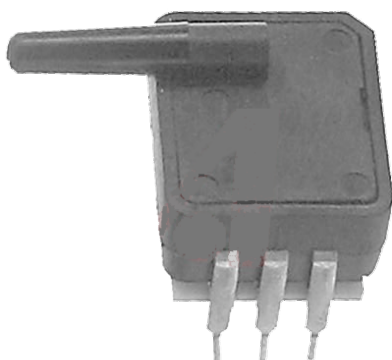

Figure 1

Outside Air

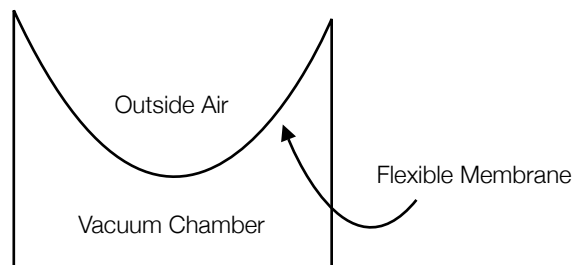Flexible Membrane

Vacuum Chamber

Figure 2

In order to use barometric measurements to correlate to relative altitudes, we must have access to a number of formulas.

$$\frac{P}{T} = \frac{P_\circ}{T_\circ} \quad \text{in any gas}$$

Also, we must know the exponential pressure model:

$$P = P_\circ e^{\frac{-h}{a}}$$

To derive the exponential pressure model, we must first create a system consisting of an infinitely thin disc, with even mass distribution, located some distance h above a reference point in a fluid(Figure 1).
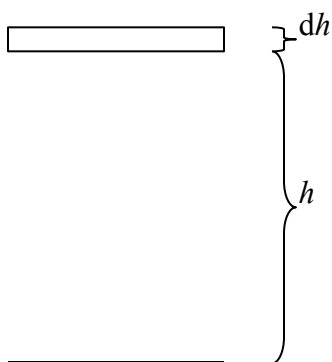
Because the disc is infinitely thin, it must also have an infinitely small mass, dm. Thus, the weight of the disc, or downward force of gravity on the disc is (dm)g. Also, since the disc is of uniform density, we can rewrite dm as $gA\rho \times dh$, where A is the cross sectional area of the disc, dh is the thickness of the disc, and ρ is the density of the disc.

The formal definition of pressure is defined as $F = PA$, that is, force equals pressure multiplied by the area. Given this definition, the force due to pressure on the lower face would be PA and the force due to pressure on the upper face would be $(P + dP)A$. Making a free body diagram out of the system gives us:

P2
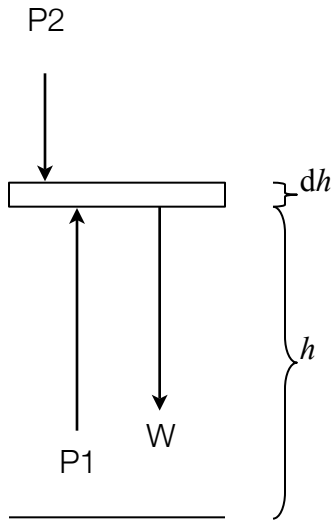
Using Newton's Third law, we will write a sum for all of the forces in the system, such that:

$$\sum F = PA - (P + dP)A - gA\rho \times dh = 0$$

To begin solving this system, we will isolate the two pairs of forces:

$$PA = (P + dP)A + gA\rho \times dh$$

Then, we will divide both sides by A:

$$P = (P + dP) + g\rho \times dh$$

Then, we will take away the parenthesis, so that:

$$P = P + dP + g\rho \times dh$$

Notice how both sides of the equation now contain P. We will subtract P from both sides to get us:

$$0 = dP + g\rho \times dh$$

Moving dP to the other side gets us:

$$-dP = g\rho \times dh$$

Dividing both sides by dh gives us:

$$\frac{dP}{dh} = -g\rho$$

(Equation 1)

Since our experiment requires us to use the barometers as altimeters between two different points, we must have some way to include an initial and final pressure. Because pressure and density are directly proportional, we can say:

$$\frac{P}{P_\circ} = \frac{\rho}{\rho_\circ}$$

Isolating for ρ , we get:

$$\rho = \frac{P}{P_\circ} \times \rho_\circ$$

Using this new definition of ρ , we can substitute it back into Equation 1:

$$\frac{dP}{dh} = -g\frac{P}{P_\circ} \times \rho_\circ$$

Now, we must isolate both sides so the differential operators are paired with the correct variables:

$$\frac{dP}{P} \times P_\circ = -g\rho_\circ \times dh$$

If we integrate both sides between (1) the initial and final pressures, and (2) the initial and final(unknown) altitudes.

$$\int_{P_\circ}^{P} P_\circ \times \frac{dP}{P} = \int_{0}^{h} -g\rho_\circ \times dh$$

Then, we can separate the constants out of the integration areas to make our work cleaner and easier:

$$P_\circ \int_{P_\circ}^{P} \frac{dP}{P} = -g\rho_\circ \int_{0}^{h} dh$$

Now, integrating both sides will give us:

$$P_\circ\left[\ln P - \ln P_\circ\right] = -g\rho_\circ\left[h - 0\right]$$

This is equal to:

$$P_\circ \ln \frac{P}{P_\circ} = -g\rho_\circ h$$

Then, moving $P_\circ$ to the other side:

$$\ln \frac{P}{P_\circ} = \frac{-g\rho_\circ h}{P_\circ}$$

Then raising each side as a power of e:

$$e^{\ln\frac{P}{P_\circ}} = e^{\frac{-g\rho_\circ h}{P_\circ}}$$

This gives us:

$$\frac{P}{P_\circ} = e^{\frac{-g\rho_\circ h}{P_\circ}}$$

Moving $P_\circ$ to the other side gives us:

$$P = P_\circ e^{\frac{-g\rho_\circ h}{P_\circ}}$$

To simplify the equation and make it easier to work with, we will call $\dfrac{-g\rho_\circ h}{P_\circ} = a$.

This then gives us our final product:

$$P = P_\circ e^{\frac{-h}{a}}$$

Materials And Method

Materials- Fridge & Lamp Test

- 1 Computer (PC or Mac) with Vernier Logger Pro installed

- 1 Vernier LabPro sensor hub

- 1 USB Cable

- 1 AC Adapter (output 6V DC)

- 3 Vernier Barometers

- 1 Vernier Temperature Probe

- 4 AA Batteries

- 1 Silver Sharpie

- 1 Heat Producing Lamp

- 1 Fridge or Freezer

Method- Fridge & Lamp Test

1. I Label each barometer 1 through 3; it is important to differentiate between each barometer in case one produces extremely different output.

2. Plug the barometer labeled 1 into the port labeled "CH 1" on the Vernier LabPro, and barometer 2 into "CH 2" and barometer 3 into "CH 3". Plug the temperature probe into "CH 4". All channels should be full now.

3. After all the sensors are plugged into the LabPro hub, the batteries should be placed into the back.

4. Plug the USB cable into the LabPro hub, and then into the computer. Open up Logger Pro, and wait for the program to initialize and detect the sensors.

5. If a new project is not open, open one by going to "File" and selecting "New".

6. Once the new file is open, go to "Experiment" then to "Data Collection...". In the window set the mode to "Time Based". In the box below enter "3000" and in the drop down menu next to the box, select seconds.

7. Make sure the sampling rate is set to 1 sample/second and 1 second/sample. Once you have verified this, click "Done".

8. Then, go to "Experiment", "Remote", "Setup", "LabPro: 1". A window will open displaying information about the LabPro[1]. In the "Collection Settings" window, make sure that three barometers are plugged into channels 1-3 and that the temperature probe is plugged into channel 4. Click "OK".

9. The program will process for a few moments, then a window titled "Please Disconnect" will ask you to disconnect the LabPro. Disconnect the LabPro from the computer.

10. A light on the front of the LabPro will be Orange, which signifies the LabPro is ready to record data. Press the "Start/Stop" button. The light on the front of the LabPro will now be green and flashing, meaning that it is recording data.

11. Let all the sensors record data for 5 minutes in the environment where you plan to run the first test.

12. After they have recorded data for 5 minutes in the same environment, place Barometer 1 and the temperature probe into the fridge or freezer.[2][3] Place barometers 2 and 3 outside of the fridge or freezer (Figure 3). Let the instruments record data for the remaining 2700 seconds.

13. After the sensors have finished recording data, plug the LabPro back into the computer. A dialogue box will appear saying "Remote Data Available" asking you if you would like to retrieve the data from the LabPro. Select "Yes".

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[1] Make sure the battery status says OK, or else change the batteries on the LabPro

[2] Make sure that the fridge or freezer door is open, so that the sensors are at the same pressure as the sensor outside of the fridge. The temperature probe should not tough any metal surfaces inside of the freezer, but rather be recording the ambient temperature around Barometer 1.

[3] The temperature cannot go below zero degrees centigrade

14. Another window will appear asking you where you want to save your data. Select the the first option, to "Retrieve remote data into the current file." Select "OK". The computer will process for several moments, and then display 2 graphs plotting the pressure readings versus time and temperature reading versus time. Logger Pro will also display a table of all the data points.

15. On the graph, Barometer 1 should show a rapid decline in pressure as it acclimates to the colder temperature around it.(figure 4)
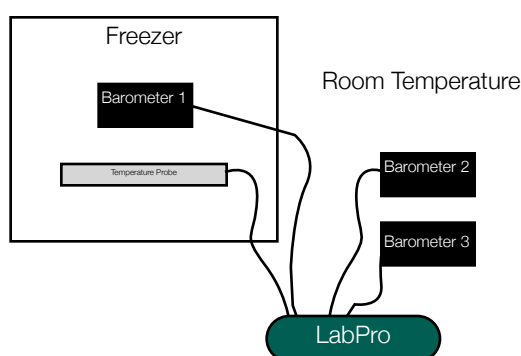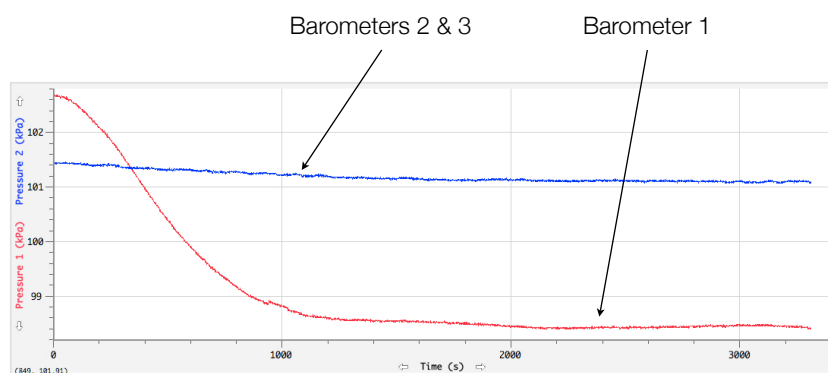

Figure 3

Figure 4

16. Repeat steps 5-11 after all the sensors have come back to room temperature(wait several hours or overnight).

17. While the sensors are recording the first 5 minutes of data, turn on the lamp so it is warmed up.

18. After the sensors have recorded data for 5 minutes, place Barometer 1 and the temperature probe under the heated lamp, and keep the other 2 barometers in the outside conditions (Figure 5).

19. Repeat steps 13-14.

20. This next graph should display barometer 1 going above barometers 2 and 3 as barometer 1 becomes acclimated to the warmer temperatures around it (Figure 6).
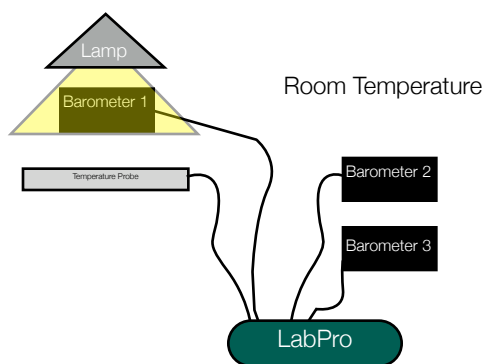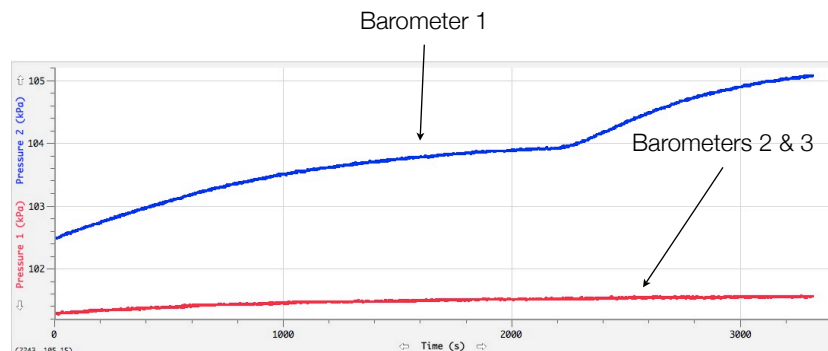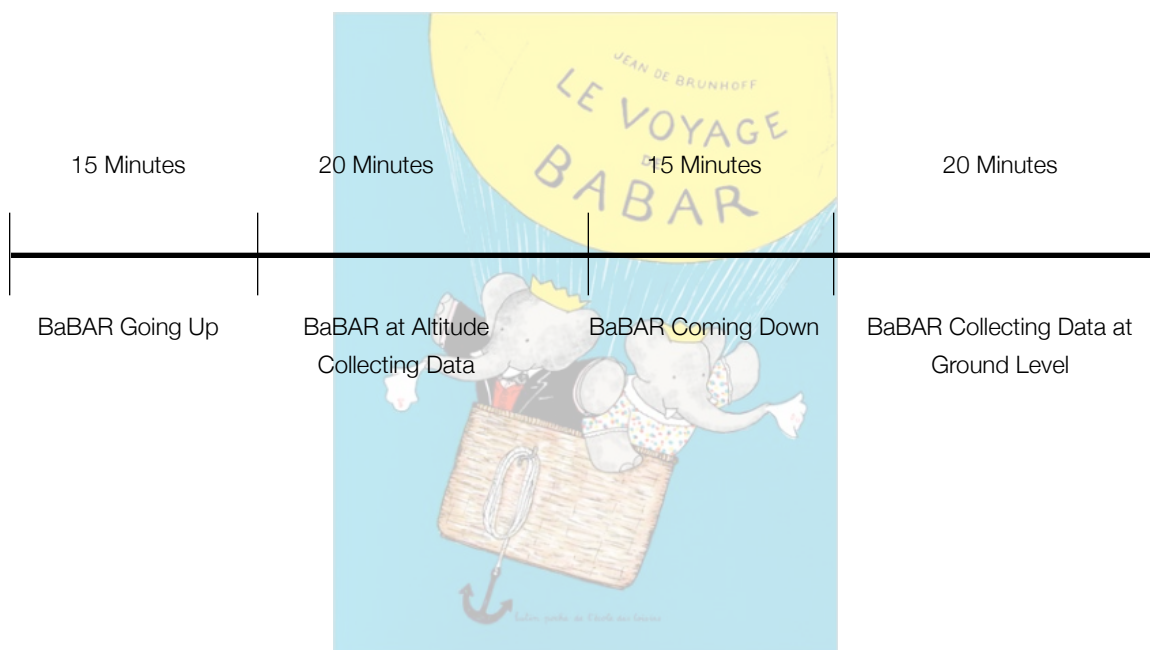
Figure 5

Figure 6

Materials- BaBAR Balloon Launch

• 1 Latex Balloon- 7 feet in diameter

• 1 K-Tank of Helium (approximately 270 cubic feet)

• 1 Cardboard box

• 4 feet of nylon cord

• 1000 feet of nylon cord

• 1 Vernier LabPro hub

• 3 Vernier Barometers

• 1 Vernier Temperature Probe

• Tape

• Twine

Method- BaBAR Balloon Launch

1. Using the cardboard box, twine, and tape, construct a small container that will attach to the balloon to carry the barometers, temperature probe, and Vernier LabPro.

2. In the morning, somewhere between 8-11 am, do the balloon launch; winds are softest at this time.

3. Fill the balloon up so it can carry the box containing the barometric equipment, and about 1.5 kg of additional weight (for 1,000 ft cord).

4. Attach BaBAR to the balloon, and start collecting data from Vernier LabPro. Note time.

5. Begin raising BaBAR up to 1,000 ft altitude.

6. When BaBAR reaches the top, leave static in position for about 20 minutes, then begin to take down.

7. When BaBAR has reached the ground level again, let run for 20 minutes as well. Note time.

8. Stop LabPro from taking more data.

9. Import data into Logger Pro. Correct for any pressure readings out of the 15-25 degrees celsius range.

15 Minutes	20 Minutes	15 Minutes	20 Minutes
BaBAR Going Up	BaBAR at Altitude Collecting Data	BaBAR Coming Down	BaBAR Collecting Data at Ground Level

Results

From this experiment I discovered that Vernier barometers are not very accurate and are extremely temperature dependent. During the fridge/freezer test, the greatest difference between the barometer inside of the fridge and the average pressure of the barometers outside of the fridge was 2.7 kPa over a temperature difference of 22 degrees centigrade(colder). The greatest difference between the barometer under the lamp and the average pressure of the barometers at room temperature was 3.6 kPa over a temperature difference of 8.27 degrees centigrade(warmer).

After running my tests, I found out that the problem with the pressure readings were the fault of the Honeywell SenSym SDX15A4's membrane-vacuum system. The membrane that covers the vacuum in the SDX15A4 is a flexible polymer that stretches and contracts as temperature changes. The SDX15A4 has built in technology that is supposed to take into account for this flexibility, but the technology is not perfect.

As a result, when temperatures surrounding the barometer become colder, the membrane contracts, becoming tighter, and thus making the barometer read as if it is under less pressure than it really is. The opposite is true for when the barometer is in a hotter environment. As temperature increases, the barometer stretches more and more into the vacuum space, thus giving a reading that is higher than it actually is.

Also, from my fridge/lamp experiments, I was able to use Excel to come up with a formula for data that is out of the 10 degree centigrade range. The formula is as follows:

$$P(T) = 0.0013T^3 - 0.0725T^2 + 1.2656T + 94.068$$

Where P(T) is the recorded pressure from the Vernier Barometers as a function of temperature, T. In order to make use of this formula, we must first look at the following graph, which contains a plot of collected data and also the cubic function, P(T).

Pressure vs Temperature

$y = 0.0013x^3 - 0.0725x^2 + 1.2656x +$
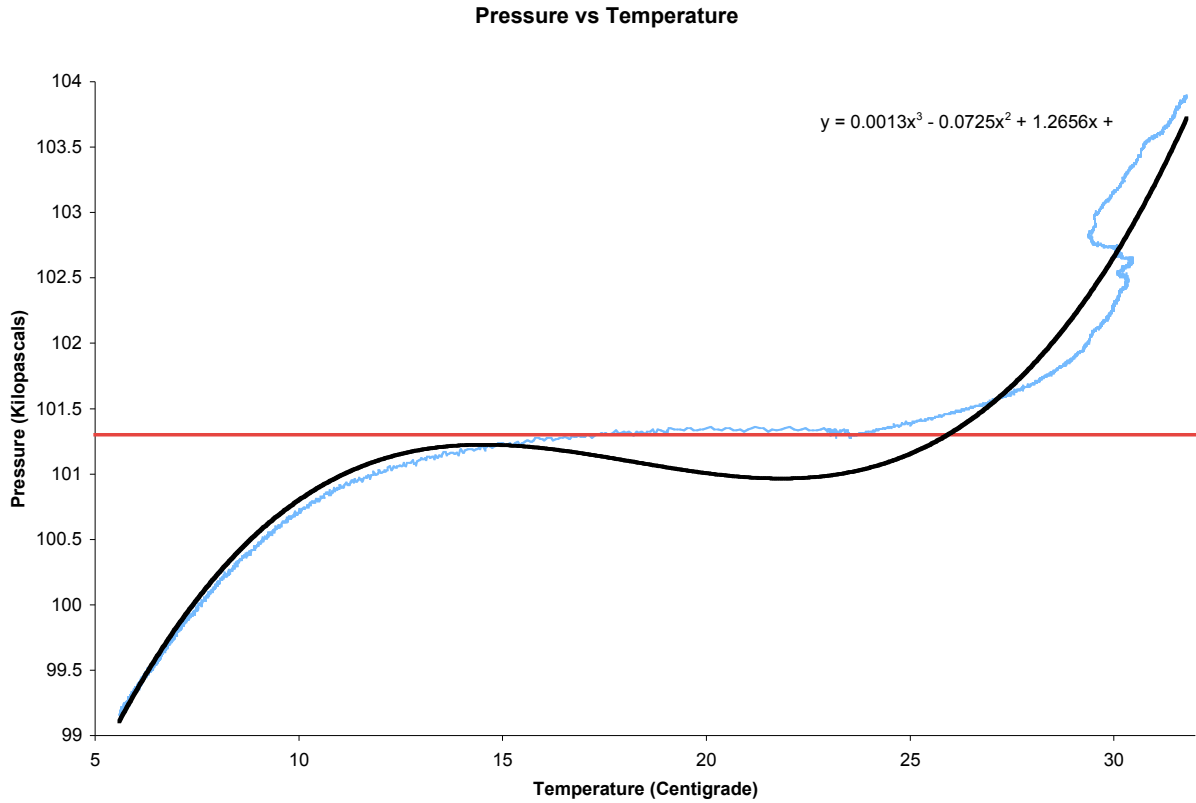
In this graph, the black line is P(T), the blue line is collected data, and the red line is the static, actual pressure(this graph assumes the pressure was static during data collection). As is visible from looking at this graph, the black line varies quite a bit from the collected data on the intervals between [15,25] degrees celsius. Because of this variation, we cannot use this formula for data correction on that interval. This is ok though, because on the interval [15,25], pressure readings are fairly accurate.

In order to make use of this function, P(T), we really want to find the height h, or the distance between the black line (P(T)), and the red line (101.3). To do this, we simply subtract 101.3 from P(T), which gets us:

$$P(T) = 0.0013T^3 - 0.0725T^2 + 1.2656T + 94.068 - 101.3$$

This gives us:

$$h = 0.0013T^3 - 0.0725T^2 + 1.2656T - 7.232$$

So now that we know the distance h, we can simply plug in our collected data like this:

$$[\text{BaBAR Readings}]-h= \text{Actual Pressure}$$

Which is equal to:

$$[\text{BaBAR Readings}]- 0.0013T^3 + 0.0725T^2 - 1.2656T + 7.232 = \text{Actual Pressure, on the interval } [0,15] \cup [25,50]$$

Using this formula and Excel, we can convert large amounts of inaccurate pressure readings into more accurate measurements. With these more precise pressure readings, we can then use the exponential pressure model to obtain relative altitudes.

Note on Collected Data

While performing these experiments I noticed that the barometers had consistent curves (meaning that they had the same bumps and dips), but they had some certain offset.

In Logger Pro, there is a way to calibrate the barometers. To do this, you go to the Experiment menu, then click "Calibrate", and follow the onscreen instructions from there. All Logger Pro does is move the outputs so they start at the same point. You can do the same thing after data has been collected too.

In order to calibrate the barometers(using either method), you must have some accurate pressure reading for the location at which the barometers are at. At UCSC I had a difficult time finding a weather station on campus, but eventually found one at the beach in Santa Cruz that had a live feed online. Using the exponential pressure model, coupled with the known altitude of the Natural Sciences II building, I was able to have a fairly accurate pressure reading for where I was at.

Once data had been collected, I would use the weather station's feed to find out the pressure when I started my experiment. I would then use the exponential pressure model to find the pressure at the location where the experiment was performed. After doing so, I added or subtracted a certain value from each barometer to find out the actual pressure readings.

Because all the barometers follow the same shape, once calibrated, the readouts should follow the same line.

Using the Exponential Pressure Model with BaBAR Readings

In order to determine the altitude of BaBAR, we must use the exponential pressure model that was derived in the Background Section. Here I will outline how to use the exponential pressure model:

To use the EPM, you must have two important pieces of information:

1. An initial pressure

2. An ending pressure

With those two pieces of information, you can calculate the altitude of BaBAR.

The initial pressure for the Summer 2007 BaBAR launch was ~ 98.15 kPa at ground level.

The ending pressure for the Summer 2007 BaBAR launch was ~ 94.15 kPa at maximum altitude.

Plugging those into the exponential pressure model, we get:

$$94.15 = 98.15 \bullet e^{-h/8550}$$

$$94.15/98.15 = e^{-h/8550}$$

$$0.95924605196 = e^{-h/8550}$$

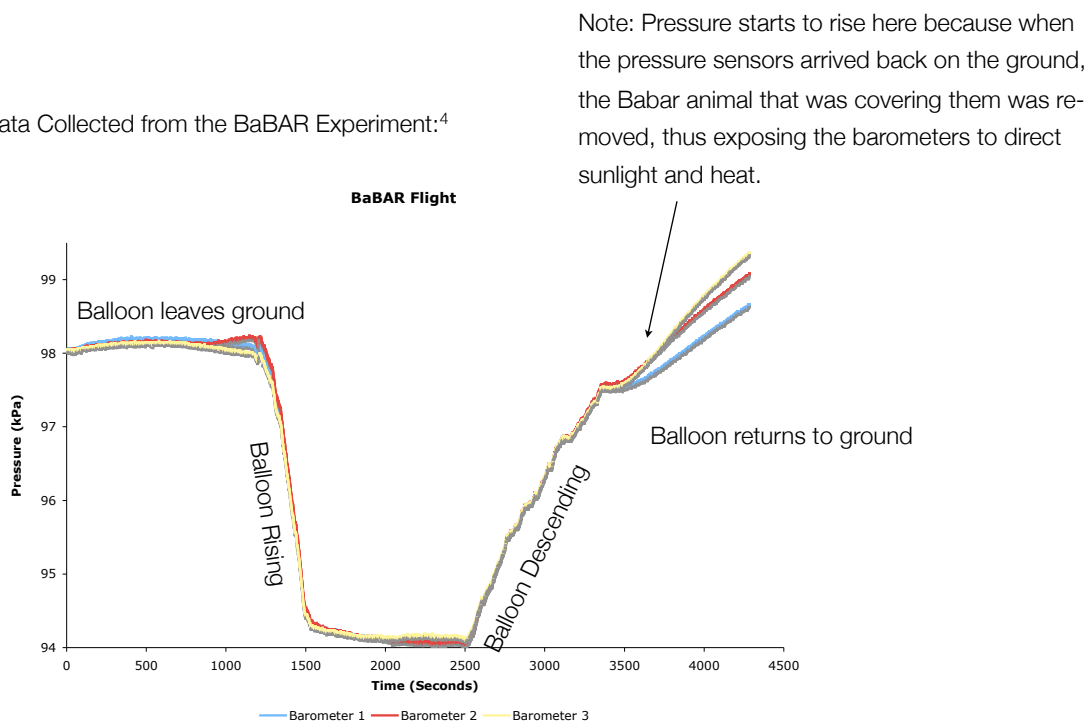$$\ln|0.95924605196| = -h/8550$$

$$-0.04160766562 = -h/8550$$

$$\Rightarrow h \approx 350m$$

$$350m = 1148 \text{ ft}$$

Considering the lack of sophistication of the BaBAR equipment, and imperfections of the correction formula, 350m is a fairly reasonable altitude estimate. The actual reading was probably more somewhere around 305m.
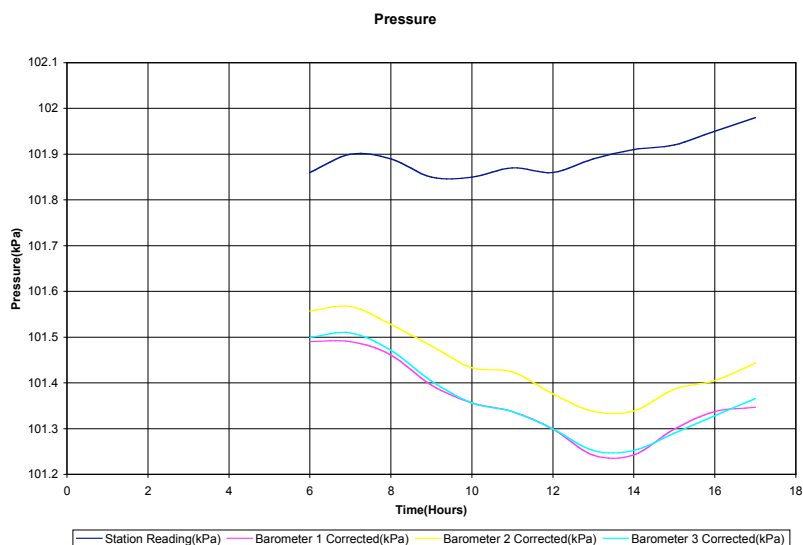
Appendix

Graph of Pressure Data Collected from the BaBAR Experiment:[4]

Note: Pressure starts to rise here because when the pressure sensors arrived back on the ground, the Babar animal that was covering them was removed, thus exposing the barometers to direct sunlight and heat.

BaBAR Flight

Balloon leaves ground

Balloon Rising

Balloon Descending

Balloon returns to ground

Pressure (kPa)

Time (Seconds)

Barometer 1   Barometer 2   Barometer 3

T=1500-2500; Balloon at maximum altitude

Graph of Vernier Barometer Readings vs Weather Station Readings:[5]

Pressure

Pressure(kPa)

Time(Hours)

Station Reading(kPa)   Barometer 1 Corrected(kPa)   Barometer 2 Corrected(kPa)   Barometer 3 Corrected(kPa)

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[4] This graph shows the various readings from the BaBAR experiment after they had been adjusted to all have the same starting point.

[5] During this test, the temperature surrounding the Vernier barometers was decreasing, therefore, the equipment gave a decreasing pressure reading. If examined closely, certain bumps in pressure are correlated though.

Warm Up Period in Vernier Barometers:[6]

Barometer 1

Barometer 1 vs Barometer 2
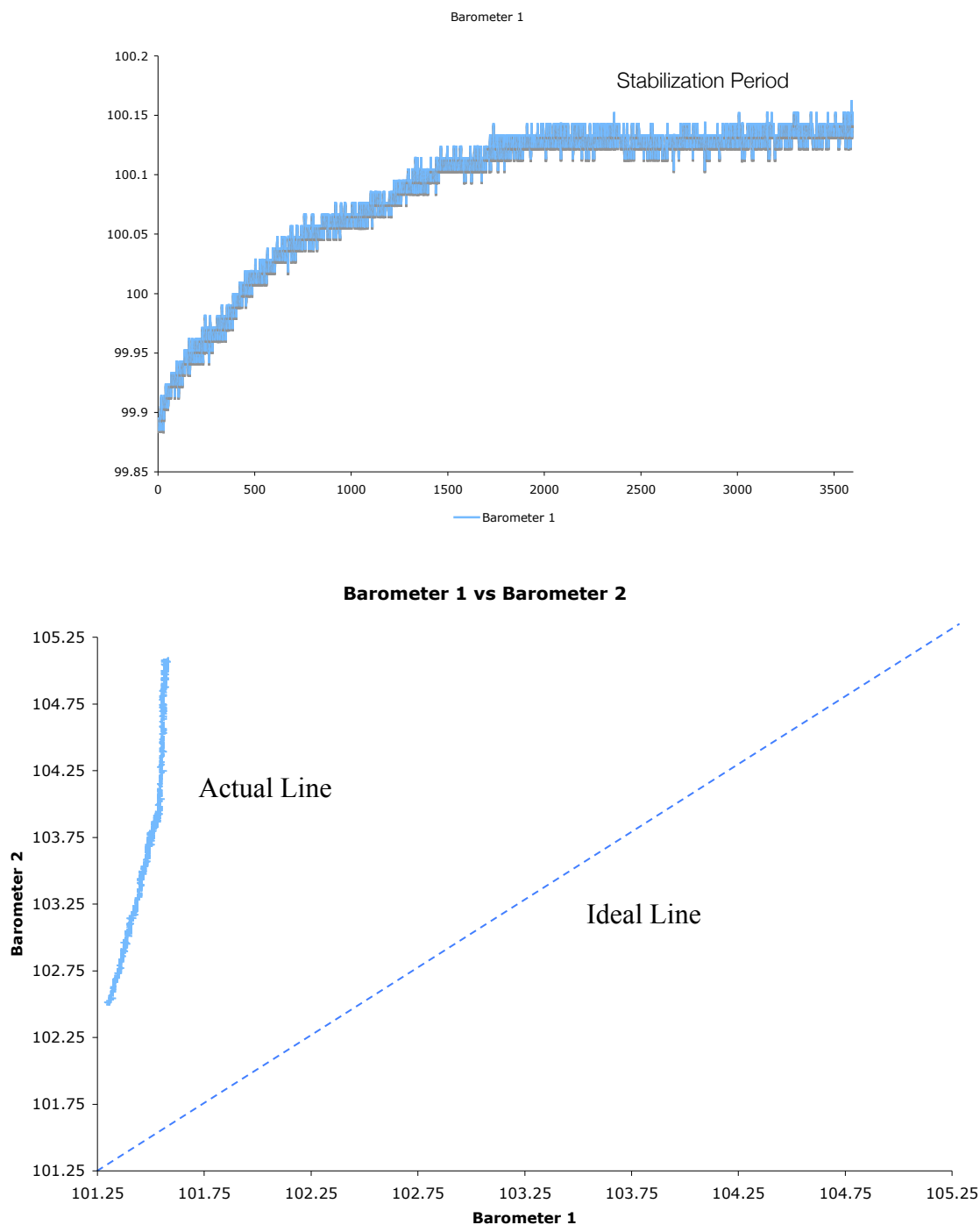
This graph shows a plot of Barometer 1 vs Barometer 2. One of the Barometers(Barometer 2) was under a heat lamp, while Barometer 1 was at room temperature

[6] There is about a .3 kPa difference in pressure during the warm up period. This correlates to about 2.5 m or 8 ft in elevation change.

Graph of Temperature Data Collected from BaBAR Flight:
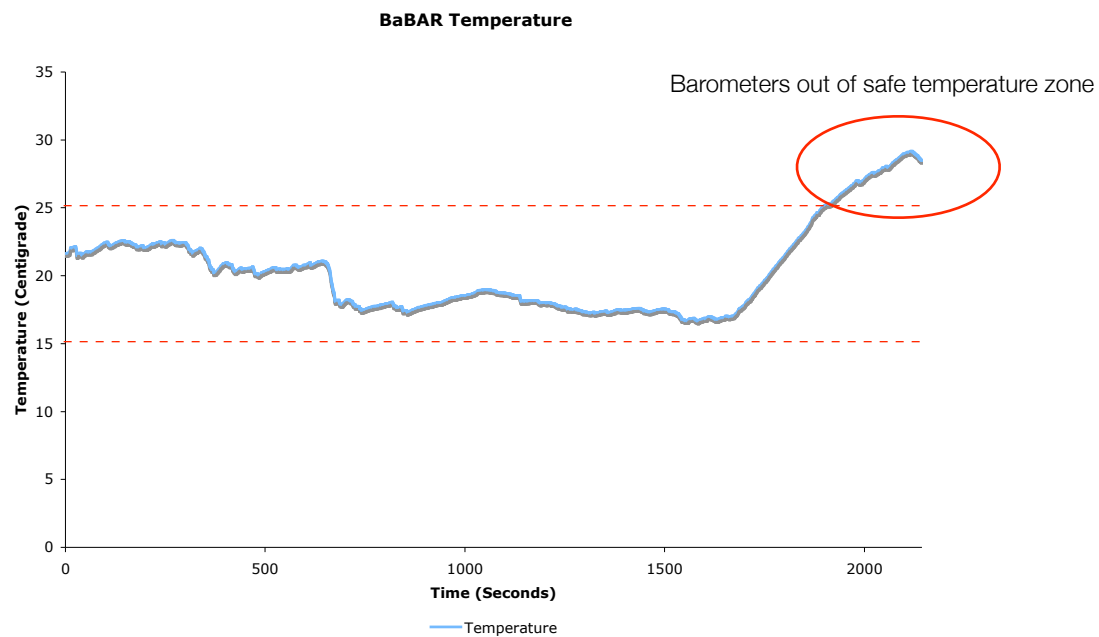
BaBAR Temperature

Temperature over Pressure: