Scripta

Fall 2023, Vol. 2, No. 3, 15-18
ISSN: 2769-9242

High Altitude Weather Balloons: Development and Data Collection

Matthew Patkowski *

ABSTRACT

A High Altitude Weather Balloon (HAB) was developed, which can be used to measure various atmospheric parameters at a variety of conditions. We employ tracking devices along with simulations to predict the landing location of the balloon payload, facilitating payload recovery. Additional tracking methods are proposed to improve the chance of recovery. Furthermore, payload sensors allow us to examine various atmospheric parameters, including temperature and pressure as a function of height. These datasets can be used to extrapolate the adiabatic lapse rate, as well as the heat capacity ratio. Further studies with the HAB data can translate these measurements into more detailed weather and atmospheric predictions, and offer more research opportunities. Efforts are being made to improve the HAB design to be able to launch it in any weather, as well as test satellite components onboard.

Introduction

High-altitude balloons (HABs) offer a simple and cost-effective method of transporting scientific instrumentation into the troposphere and stratosphere [1]. They are generally uncrewed, and can reach altitudes between around 18 to 37 km, although some have reached altitudes of above 50 km [2]. They are often lifted by a latex balloon filled with helium [3] (or some other gas less dense than the atmosphere at sea level), and are commonly used to study these lower atmospheric layers, alongside weather patterns. More recently, hobbyists and high schoolers have utilized these balloons for learning experiences and easy research on the lower atmosphere [4].

In addition to the balloon itself, a payload is often attached below, carrying various sensors, an onboard computer, and a GPS unit. Some payloads include a camera either pointed downwards looking at the Earth or horizontally at the horizon. Payloads typically range from 0.5-5 kg, though the FSA HAB sets a limit of 1.5 kg on the payload to meet the balloon lift capabilities, as well as follow FAA regulations. Temperatures at such altitudes can drop to around -100 degrees Celsius, necessitating thermal

---

*Senior Student, Fulton Science Academy.
Contact: mpatkowski@fultonscienceacademy.org

protection of onboard components, as well as decreasing the battery life of the power supplies.

Several launches have been conducted in the past year. FSA's HAB development began in the summer of 2022, using an Eagle Flight Computer [1], as well as a basic HAB kit. These allowed a couple of launches and data collection throughout the 2022-2023 year. However, many flights and data were lost due to GPS failures, as well as weather conditions. Since the beginning of the 2023 school year, more work has been put into the HAB project, focusing on developing the payload structure, communications, and sensors.

This study will highlight the steps taken in designing, constructing, and improving the HAB, as well as an analysis of some of the data collected.

Methods

The essential components of a HAB include the weather balloon, providing the lift force; the recovery parachute, facilitating the safe recovery of the payload; and the payload, containing the sensors and tracking devices.

Payload

The HAB payload connects to the parachute-balloon system through a series of ropes. The payload is encased in a 3D-printed enclosure to protect it from wind, minor moisture, as well as to keep all of the components secure.

Structure

The HAB payload structure was modeled in a CAD software and 3D-printed. It consists of 3 major layers: the sensor layer, the On-Board Computer (OBC) layer, and the power layer.

The sensor layer is designed as an enclosure for the sensors. It is not isolated from the atmosphere to allow air to reach the pressure, temperature, and air-composition sensors. The layer also contains attachment points for tracking devices (see Tracking).

The power layer holds the power bank used to power all onboard components: the OBC, sensors, and the tracking devices. Additionally, at the bottom of this layer, the payload antenna (see Tracking) is attached.

The OBC layer holds the onboard computer(s). In the most recent model of the HAB, both a Raspberry Pi zero and an Arduino nano (a small form factor microcontroller) [5] are used. The Raspberry Pi zero is equipped with a GPS-tracking hat, while the Arduino controls the sensors. Additional side ports may be uncapped to allow attachment points for cameras, strobes, or additional sensors that require alternative mounting points compared to the sensor layer.

Tracking

At all three stages of a successful HAB mission—before the launch, during the flight, and after the landing—various tracking and prediction methods exist to ensure the highest chance of recovery.

Before a flight begins, it is important to verify the distance and direction the weather balloon will travel. Depending on the burst height, payload weight, parachute strength, and, chiefly, the atmospheric conditions, the balloon travel distance may vary drastically. We use the HAB-HUB website [6] to approximate the landing location before launch, allowing us to anticipate driving time and direction. However, given the complex nature of the atmosphere, as well as the large amount of ambiguity in the inputs to the HABHUB predictor, the landing locations are often 10-20 km off from the prediction. Therefore, it should not be used for locating the landed balloon.

During and after the flight, we have developed three methods for staying in touch with the HAB. First, we use the SPOT tracker, which is a commercially available GPS tracker. This system consists of a tracker that one attaches on the payload, as well as an app, that informs the user of the most recent location every 2.5 minutes. However, the SPOT is often unreliable, because after landing, it does not send the most recent location. Thus, there is an ambiguity of 0-2.5 minutes after receiving the last location of where the balloon landed. Additionally, the height of the balloon is not transmitted, which complicates the recovery process. Furthermore, the SPOT tracker cuts off above a certain altitude, making it impossible to track until the payload falls below a certain altitude again. Therefore, during the 1-2 hour ”blackout” period, one must rely on simulations conducted before the launch to estimate the landing location. Unfortunately, once the balloon lands, the SPOT will most likely be obstructed by small twigs or branches, or even tall grass. Most of our unrecovered missions are not located due to this issue, and the one recovered months later (see FSA HAB Launches), only was found during the winter when the leaves cleared, allowing the SPOT to reconnect with GPS satellites.

The next redundancy supplied with new missions is the Apple AirTag, which provides extremely accurate positioning when nearby. However, the AirTag relies on being within 50 meters of some Apple products; therefore, when the balloon lands in remote areas, the AirTag data is often not received.

The most recent, and most promising method, is LoRa communication. Although the common range on LoRa is placed at 20 km, recent launches have shown great results, maintaining relatively secure contact throughout the entire flight. With improvements to the ground-station antenna, this data could be reliable throughout the entire launch. In addition to sending data at intervals of time one can decide, the LoRa option also provides real-time altitude data, further facilitating landing location and time prediction. However, the LoRa method is often unreliable once the balloon lands. This is because the transmission antenna (mounted on the bottom of the power layer), is extremely delicate. Once the balloon lands, the antenna is deformed, thus losing most of its transmission power.

Unfortunately, there are some missions in which the payload is lost, not due to communication errors, but due to the balloon landing in a body of water or in the branches of a tall tree. In this case, strobe lights attached to the side ports of the OBC layer (Structure) can be used to aid in finding the stuck balloon.

Launch Date	Spot Tracker	Air Tag	LORA	Status
August, 2022	Functional	n/a	n/a	Successfully Recovered
September 3, 2022	Unreliable	n/a	n/a	Recovered After Months
November 18, 2022	n/a	n/a	Unreliable	Unrecovered
August 18, 2023	Unreliable	Recovery Method	n/a	Successfully Recovered
September 18, 2023	Unreliable	No signal	Successful Signal	Recovered
October 11, 2023	Unreliable	No signal	No signal	Unrecovered

Table 1: FSA HAB Launches

Sensors

The first three balloon launches used the Eagle Flight Computer to collect various atmospheric data, supporting the connection of sensors. However, this method is quite unreliable, and the sensor data often cuts out for periods of time. These sensors included temperature, pressure, accelerometer, as well as altitude data.

Further launches have used a Raspberry Pi or, most recently, an Arduino to interface the sensors and store data. This has allowed for additional sensors to be implemented, as well as software-side redundancies ensuring a constant stream of data is recorded. These new sensors include the BME680, which has temperature, humidity, barometric pressure, and VOC gas sensing capabilities. Additionally, we employ the L3GD20H triple-axis gyrometer, and the MQ2 gas sensors. Further improvements may include a triple-axis magnetometer or a Geiger counter.

Various cameras have been employed to collect photo and video data from the Pi. As of now, we are using GoPro cameras, and other similar cameras to obtain video both looking down and looking to the side. The side camera allows us to see the curvature of the earth. These cameras can be mounted on the additional attachment ports on the OBC layer of the structure Structure. These additional cameras allow us to discern the weather conditions, such as cloud density and precipitation, for reference to the sensor data.

Atmospheric Models

We now present two theoretical models of the atmosphere that we will use to calculate various parameters: the isothermal (constant temperature) model, and the adiabatic atmosphere model. As will be seen by the collected temperature data, the temperature of the atmosphere is not constant with height. However, using the isothermal model will provide us with a value of T that is approximately the average along the path. On the other hand, the adiabatic atmospheric model assumes air packets move adiabatically (without loss of heat), and can predict the temperature (and thereby pressure) with much more accuracy.

We begin by deriving the isothermal atmosphere model. Consider a slice of the atmosphere of thickness $\mathrm{d}z$ with area A will have mass $\rho A\mathrm{d}z$. The weight of this slice will be compensated for by a decrease of pressure with height, where a pressure gradient of $\mathrm{d}P$ will change over this height. Thus we can equate

$$\rho A\mathrm{d}zg = -A\mathrm{d}P,$$

which can be written as

$$\frac{\mathrm{d}P}{\mathrm{d}z} = -\rho g. \tag{1}$$

By the ideal gas equation, we may write $PV = Nk_bT$, which can be solved for the density (assuming the average air molecule has mass m:

$$\rho = \frac{Nm}{V} = \frac{Pm}{k_bT}.$$

Now this equation can be substituted back into equation 1. Then this provides

$$\frac{\mathrm{d}P}{\mathrm{d}z} = -\frac{Pm}{k_bT}g, \tag{2}$$

a seperable diff. eq. Assuming $P = P_0$ at ground level, we may integrate to find (and here we must assume isothermality):

$$\int_{P_0}^{P} \frac{\mathrm{d}P}{P} = \int_{z_0}^{z} -\frac{mg}{k_bT}\,\mathrm{d}z. \tag{3}$$

Standard procedures yield

$$P(z) = P_0 \exp\left(-\frac{mg}{k_bT}(z - z_0)\right). \tag{4}$$

The quantity $\frac{mg}{k_bT}$ is called the *isothermal scale height* [7].

As we will see later, the assumption of an isothermal atmosphere is poor, but the collected HAB data is surprisingly still valid to the isothermal equation.

We will now present the adiabatic atmosphere formula, which assumes an adiabatic transfer and motion in the atmosphere, giving the adiabatic constant γ. After a lengthy derivation, one arrives at the formula

$$\frac{\mathrm{d}T}{\mathrm{d}z} = -\left(\frac{\gamma - 1}{\gamma}\right)\frac{mg}{k_b}. \tag{5}$$

The quantity given by $\left(\frac{\gamma-1}{\gamma}\right)\frac{mg}{k_b}$ is called the *adiabatic lapse rate* [8].

Further atmospheric models predict the troposphere (approximately the lower 10 km of the atmosphere) to follow the adiabatic atmosphere model. On the other hand, at the tropopause, and throughout the stratosphere (the transition between the troposphere and stratosphere), the temperature will flatten out to give $\frac{\mathrm{d}T}{\mathrm{d}z} \approx 0$ [9].

The two quantities will be found and evaluated for the collected HAB data. Furthermore, the overall shape of the temperature gradient will be evaluated in terms of its adherence to the model described above.

Results

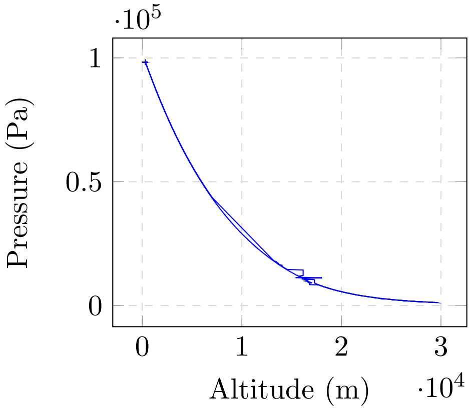

Figure 1: Pressure Distribution

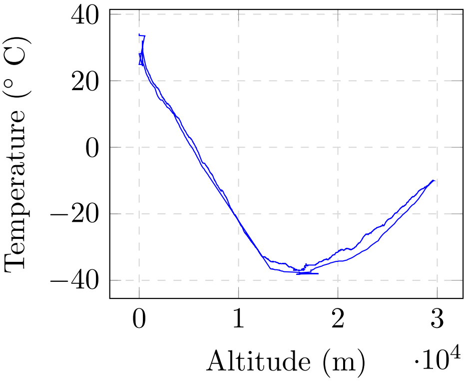

Figure 2: Temperature Distribution

As mentioned in ‘Sensors’, we collected the temperature and pressure as a function of altitude. Other measurements, such as velocity, and gas parameters were also taken but lost in failed missions. Shown in ‘Pressure Distribution’ and ‘Temperature Distribution’, the left figure shows the pressure gradient, while the right figure shows the temperature gradient in the atmosphere. The data in the graphs and subsequent analysis only include data from the first launch, as further launches contained poorly recorded data, with many downtime periods.

Discussion

Fitting the isothermal pressure curves to the data, we approximate the values $P_0 = 98000\,\mathrm{Pa}$ and $z_0 = 350\,\mathrm{m}$. These are common values associated with the altitude above sea level of Alpharetta, obtained by reading $P(0)$ from the collected data. Applying a curve fit with these parameters, we find the isothermal scale height to be $\frac{mg}{k_b T} = 0.00012834\,\mathrm{N\,J^{-1}}$. If we assume m to be $\frac{1}{N_A} \cdot 28.96\,\mathrm{g}$, and $g = 9.81\,\mathrm{m\,s^{-2}}$. We find $T = 266.2\,\mathrm{K} = -6.95°\,\mathrm{C}$, which, as discussed before, could be a value for the average temperature in the atmosphere.

There are several important conclusions we can draw from the results. First, from ‘Temperature Distribution’ above, we can see that the isothermal atmosphere is a relatively good approximation, especially for the lower atmosphere as shown. As we chose P_0 and z_0 from commonly known data, the lower range of this fit, near z_0 and P_0 will be very near the data.

Next, we fit to the adiabatic equation. As previously stated, the adiabatic equation generally applies to altitudes below 10 km. Thus, we apply a linear fit to this region. The fit gives $\frac{\mathrm{d}T}{\mathrm{d}z} = -5.0001\,\mathrm{K\,km^{-1}}$. Typical values of this rate are around 6 to 10 $\mathrm{K\,km^{-1}}$. Therefore, the decrease in height recorded by our HAB is a bit less quick than most other experiments. However, this difference could be attributed to a different time of day or weather conditions.

The FSA HAB project continues, as the development of the satellite and more atmospheric parameter sensors. The HAB project offers various avenues of future work. First, we may add control to the balloon using servo motors to alter the lengths of the parachute lines, controlling the balloon's direction of travel. This would involve using a special type of parachute called a parasail, specifically crafted to provide the most maneuverability. Additional studies will need to be conducted to determine the extent to which various motors and lines will affect the balloon's descent. After determining this, a program to guide the HAB to the desired location will be implemented. Additional challenges may arise in implementing the deployment mechanism for the parasail. With a more complex connection to the various servo motors of the payload, the parasail will have to stay inside an enclosure until after the balloon pops, to prevent tangling. Furthermore, a balloon release mechanism will be developed to control the maximum height and reduce line clutter before deploying a parasail.

Another avenue of work is sensor development and interpretation. Many other sensors exist, as previously discussed; however, they are often unreliable. Future work focus on studying the composition of the lower layers of the atmosphere. Additionally, various aspects of the FSA Satellite project will be tested on the HAB. Satellites share many similarities with HAB payloads, such as communications, power, sensors, and an OBC. The current plan for the satellite project involves using spectrometer data alongside ionospheric data measured in-situ to determine the effects of solar and cosmic background radiation on the upper ionosphere. Although the HAB will not reach even the lowest layers of the ionosphere, the various sensors including ionosondes, radiation sensors, magnetic field sensors, and spectrometers, can be tested on these launches.

Finally, the HAB will be launched in a variety of other weather conditions. At the moment, we have limited the launches to fair-weather days, with relatively low winds. However, different values of the isothermal scale height and adiabatic lapse rate may be recorded in other weather conditions. Time of day also impacts the reading. Different processes supply heat to the atmosphere at different times of day. Therefore, launching early in the morning, as opposed to late in the afternoon, will be studied to observe any changes during the day.

References

1. Price, A. An apparatus for personalized atmospheric and flight data collection aboard high altitude weather balloons. *HardwareX* **6,** e00077 (2019).
2. Pacheco, L. E. *Japan sets new balloon altitude record: 53.7 kms* `https://web.archive.org/web/20160322234357/http://stratocat.com.ar/news0913e.htm`.
3. Science, H. A. *Weather Balloon 600 g* `https://www.highaltitudescience.com/products/600-g-near-space-balloon`.
4. Coleman, J. S. & Mitchell, M. Active learning in the atmospheric science classroom and beyond through high-altitude ballooning. *Journal of College Science Teaching* **44,** 26–30 (2014).
5. Arduino. *What is Arduino?* `https://www.arduino.cc/en/Guide/Introduction`.
6. Jessop, P. P. *Habhub* `https://habhub.org/`.
7. Fitzpatrick, R. *The isothermal atmosphere* `https://farside.ph.utexas.edu/teaching/sm1/lectures/node55.html`.
8. Blundell, S. J. & Blundell, K. M. *Concepts in thermal physics* (Oup Oxford, 2010).
9. Ramaswamy, V. *et al.* Stratospheric temperature trends: Observations and model simulations. *Reviews of Geophysics* **39,** 71–122 (2001).