“Aurora”, Zero Pressure Balloon Project at Iowa State University

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High altitude ballooning is one of the best resources for collecting data from near space at a reasonable cost. However, a typical latex balloon flight is only 2 to 3 hours, which limits the amount of data collected. The undergraduate group of students at Iowa State University called HABET has begun experimenting with various methods for a long duration flight including zero pressure latex and plastic balloons. The HABET team has also constructed a plastic balloon for this purpose. Within this paper the need, experiences and equipment will be discussed and why it was needed to complete this mission.

Nomenclature

A = Area
BPSK = Binary Phase Shift Keying
C = Celsius
D = Density
EOSS = Edge of Space Sciences
FCC = Federal Communications Commission
GPS = Global Positioning System
HAB = High Altitude Balloon
HABET = High Altitude Balloon Experiments in Technology
HF = High Frequency (3 - 30 MHz)
ISU = Iowa State University
LDB = Long Duration Balloon
M = Mass
m = meter
n = number of moles of gas
NASA = National Aeronautics and Space Administration
P = Pressure
Pa = Pascal
QPSK = Quadrature Phase Shift Keying
R = Universal Gas Constant (Joules per kilogram per Kelvin)
r = Radius
T = Temperature
t = thickness
UHF = Ultra High Frequency (300 MHz - 3 GHz)
VHF = Very High Frequency (30 - 300 MHz)
V = Volume
ZP = Zero Pressure

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I. Introduction

According to EOSS, a zero pressure balloon is, “made from very thin (7.5 micron) plastic sheet, like a laundry bag. It is filled with helium through a tube connected to the upper portion, and it has a vent to the atmosphere at the very bottom.”[9] There are two common names for this type of balloon, ZP balloon and LDB. For the purpose of this paper, the group will be referring to this as a ZP balloon. The group named the ZP balloon project Aurora after the Latin word for dawn. This name was chosen with the hope that the balloon will be at altitude long enough to see the dawn. These balloons are extremely useful in providing a stable platform for scientific tests to be carried out over a long duration, at fairly constant altitudes. This provides both student and amateur groups the ability to test equipment and take samples over time periods that would otherwise require the launch of a satellite. However, this method does not come without problems that need to be overcome.

II. Long Duration Considerations

When it comes to choosing a long duration platform, there are many different conditions that must be taken into account. These variables range from launch location to float altitude.

A. Payload

The first component that must be considered before the zero pressure balloon itself can even be thought of is the payload it will be carrying. This is extremely important because all future calculations will be based off the payload. An ideal payload for a self-created ZP balloon is as lightweight as possible. The HABET group at Iowa State have concluded that for the first test flight the equipment flown will be a battery pack, open tracker, radio board and GPS unit. This will be housed within a blue foam box to cut down on weight and maximize thermal protection of the components. The total payload package will weigh around 0.7 kg.

B. Atmospheric Conditions

Unlike a typical flight with a latex balloon that is up in the air for two hours, a long duration flight is much more reliant on the surrounding atmospheric conditions. When calculating what balloon attributes will need to be addressed the atmosphere plays a great deal. If a long duration flight is carried out correctly it can be flying for up to 36 hours. This means that the balloon has experienced at least one cycle of direct sunlight and two cycles of no sunlight. This change in exposure has had a great influence on the helium within the balloon and on the balloon itself. The temperature range that can be experienced at altitude can range from 25 deg Celsius during the day to -65 deg Celsius during the night. According to the Ideal Gas Law as shown in Eq.(1),[2]

$$PV = nRT \tag{1}$$

as the temperature of the gas increases, so does the pressure. This means that as the helium is warmed by the exposure to sunlight, the pressure of the gas on the inside of the balloon will also increase. This causes the helium within the balloon to be released through the bottom vent to accommodate for the pressure being created. This in turn reduces the amount of helium still present within the balloon. When a dark cycle is then experienced, there is less helium within the balloon and therefore the balloon cannot lift what it could previous to the light cycle.

As can be seen in Fig. (1),[7] this causes the balloon to lift higher during the second light cycle which means it will drop lower during the following dark cycle. To counter this occurrence, ballast can be added to the payload that can be released at time to keep the balloon at a fairly constant altitude, but once the ballast is used up heating and cooling would once again be a factor in altitude. The HABET group concluded that one night cycle and one day cycle would be considered a successful mission so no ballast was added and change in altitude is to be expected.

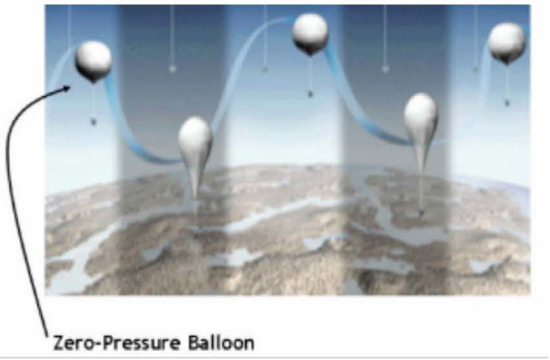

Figure 1. Zero Pressure balloon light and dark cycles.

C. Tracking

As with all HAB missions, it is important to be able to track and receive information from the spacecraft as it travels. A typical HAB flight is expected to last 2 to 3 hours and usually land within 200 miles from the launch site. In a ZP flight however, flight times can be measured in days and these balloons have the ability to travel halfway around the world. Therefore, the communication requirements become increasingly more complicated to handle these longer durations. These communication requirements will also impact both the mass of the spacecraft and the power requirements for the spacecraft as well.

A typical HAB payload will use a VHF or UHF transmitter to send data to a ground station. Often times this is done via a direct link between the ground station and the balloon system itself. In most cases, the balloon is within line of sight of the ground station and the distance between the ground station and spacecraft can be done with 1 watt or less on the transmitter power output. However, with a ZP balloon, the distance increases dramatically and the balloon may be beyond line of sight of the ground station due to the curvature of the Earth. This required the group to rethink on how the communications are handled on this type of balloon flight.

One method for communication between the balloon and ground station is to take advantage of the APRS network. The Automatic Packet Reporting System is a system that has been used by amateur radio operators for many years to report information including position and telemetry. This network in the United States operates on the amateur radio frequency of 144.390 MHz and has a very large footprint covering most of the United States. The advantage with this system is that while the spacecraft is over the United States it should be able to communicate on this network. It also has the advantage that information carried on the RF side is being transported to the Internet through what are called I-gates. This allows for tracking of the balloon from any web browser.

The disadvantage with using this system is that it is widely used by many amateur radio operators across the country. The system was not specifically designed with HABs in mind, and it is possible to cause unnecessary and harmful interference to the system. This is due to the fact that the spacecraft is able to communicate with multiple nodes or digipeaters on the network. To help alleviate this issue and in order to be good stewards of the network, several things can be done. First, it is recommended that balloons either use no relays in their configuration or use a WIDE1-1 configuration. This reduces or eliminates the network from repeating the information multiple times causing redundant information and added congestion to the network. The second thing is to reduce the transmission times to 1 minute or greater. Most tracking system on HAB spacecrafts do not listen to the channel they are using. If a tracking system sends information faster than 1 minute this can cause additional congestion and block information from other users of the system.

Another system that has been successfully used in other ZP flights is an HF transmitter. HF frequencies behave differently than VHF and UHF frequencies. VHF and above frequencies operate on line of sight, which means things like the curvature of the Earth will effectively block the signal. HF signals however can be refracted or even be completely bounced back to the Earth as they propagate into the ionosphere. This happens at altitudes of 50 km or greater, so HAB flights are still under these layers and can benefit from this affect. In addition to the fact that the signal can propagate farther, HF transmitters are able to use more efficient amplifiers, which results in less power required for the transmitter.

HF transmissions in the amateur radio band are allowed to use digital codes. However, the FCC does limit the data transmission rate to a maximum of 300 bps. This is due to the fact that the HF bands used for amateur radio are much smaller and have less bandwidth than the VHF, UHF and higher frequencies. There are several digital modes that have been used by amateur radio operators for years and recently have been used on HAB flights. These digital modes are PSK31 and the Hellschreiber mode. However, ISU is planning to use the Hellschreiber mode due to its' simplicity to implement. The Hellschreiber mode operates very much like morse code which can greatly simplify the radio transmitter design. It is also a very bandwidth efficient mode and has shown to work in very noisy HF frequencies.

While the HF system can certainly help in maintaining communication with the spacecraft during flight, it too has some drawbacks. HF propagation is highly dependent on several factors including the time of the day, atmospheric conditions and solar sunspot activity. This can result in communication blackouts with the HF system or during long duration events like solar sunspot activity a lack of communication with the payload. One way to mitigate this is to have multiple transmitters that operate in different bands. However, this adds weight and complexity to the system. Another method is to use higher HF frequencies such as the 20-meter band (14 MHz), which tend to have fewer fluctuations due to these effects then the lower bands. This will be the approach the ISU ZP flight will use.

It should be noted that both systems described in this paper require an amateur radio license, and for using the HF system described a General class or higher license is required. Today, obtaining these licenses are not difficult to do. The FCC has eliminated the morse code requirement and only the multiple choice exams are being required. Many HAB flights have used low power transceivers such as the Digi xTend radio modems for their communication needs. However, these devices are not well suited for ZP flights as they can quickly get out of range of the ground station. Another option that has been used on some ZP flights is use of satellite radios. These radios can be operated from practically any point on the globe. However, they often have a cost associated with them and this cost may be out of reach for some HAB groups.

The Aurora Project will actually incorporate both the APRS tracker and a Hellschreiber mode on HF. This combination should allow the group to maintain communication with the spacecraft throughout the flight. This type of configuration has also been used on other ZP flights and has been shown to work. Aurora will use a standard APRS tracker using the Argent Data OpenTracker, Garmin 18x GPS and a 2-meter transmitter. The HF system will actually be designed and built by electrical and computer engineering students at ISU. This will give the group control of the radio and allow a lightweight and efficient system to be built. The APRS tracker will use the standard APRS format for the data sent, where the HF system will use a data format that will have less information due to the restricted bandwidth available.

D. Recovery

For a mission like the one being attempted at Iowa State University, recovery of the electronics must be considered. The HABET group decided that for this mission, cheaper electronics would be utilized and a team would not be put together to go and retrieve the payload. This was decided due to predictions being run for a three-hour flight, the balloon was predicted to travel outside the feasible recovery zone. This zone was decided upon considering the cost of renting a vehicle along with the cost of gas compared to the cost of the electronics onboard the payload. The group will be okay with the electronics being deemed lost; however a label will be placed on the box. This will allow for someone to perhaps find the box and contact HABET about possible recovery of the payload. The label information being used is a best possible scenario.

III. Calculations for a Zero Pressure Balloon

With all of the above factors considered, the size of the balloon and how to construct the balloon may be calculated.

A. Material

For constructing a ZP balloon, the material used is a large factor. This material must be very lightweight but strong enough to hold the pressure that will be exerted on the seal lines. Even though this is a ZP balloon some stresses will be exerted on the seam lines, which are the weakest part of the balloon system. From research done on companies who build scientific payload sized balloons for NASA, it was found that companies prefer to use polyethylene sheeting. This is the same material that is used for sandwich bags. The average thickness of this material is about 0.0008 inches thick.[6] The group was then tasked with finding a fairly inexpensive similar thickness polyethylene sheeting. It was found that painter's plastic was the right type of material and was thinner than what was used by NASA balloons. The material found was .3100 mil or $7.874e^{-6}$ m thick. The next task that was presented was what shape was the balloon going to be.

B. Calculating Shape and Volume

Using the parameters that were specified by the weight of the payload and the weight of the balloon material, the volume needed to lift the balloon to a specific altitude can be calculated. For this flight, the altitude of 60,000 feet was decided upon due to the very limited flight traffic at this altitude. Along with the fact that even if the balloon were to lose 20,000 feet during the duration of the flight, the payload and balloon are still above most commercial airspace. Finally the calculation for needed volume could be done.

First air density was calculated using Eq. (2),[2]

$$D = \frac{P}{RT} \tag{2}$$

with the pressure of air at 60,000 feet being equal to 7200 Pa, temperature of -60 deg C and R equaling 287.05. This provided the density of air to be 0.1177 kg/m^3. The same was done to find the density of helium at the same altitude. The values are the same except for the R being equal to 2077. This yielded a density of 0.0163 kg/m^3. The film density was averaged and found to be 950 kg/m^3. With the mass of the payload calculated to be 0.7 kg. To simplify this problem, the shape of a sphere was chosen. Though the final balloon would not be a sphere, the following calculations allowed for the group to set minimum values that the balloon would need to have. The volume of a sphere was found using Eq. (3) ,

$$V_{sphere} = \frac{m_{payload}}{D_{air} - D_{He}} \tag{3}$$

providing the value of sphere volume to out to be 6.901 m^3. From the volume, the radius of the sphere could be calculated using Eq. (4).

$$r_{sphere} = \frac{3 * V_{sphere}}{\sqrt[3]{4\pi}} \tag{4}$$

Giving the balloon a minimum radius of 1.181 m. The final calculation with the sphere was to find the area. Using Eq. (5),

$$A_{sphere} = 4\pi * r_{sphere} \tag{5}$$

the area of the sphere was found to be 17.53 m^2. Next the film was taken into account. The film volume was found using Eq. (6)

$$V_{film} = A_{sphere} * t_{film} \tag{6}$$

yielding $1.380e^{-4}$ m^3. This value was then used to find the mass of the film using Eq. (7).

$$M_{film} = V_{film} * D_{film} \tag{7}$$

The mass of the film was found to be 0.1311kg. These equations were then iterated to find the weight of the film as the volume changed. The first iteration assumed that the film had no mass. The next iteration took into account the weight of the film calculated by the previous iteration and so on. When the values of the volume converged, the group knew the values that needed to be used. The final values that were the minimum needed became $V_{sphere} = 8.371 m^3$, $r_{sphere} = 1.260$ m, $A_{sphere} = 19.94$ m^2, $V_{film} = 0.0002$ m^3, $M_{film} = 0.1491$ kg.

C. Choosing Gore Pattern

After researching the ZP balloon it was clear that these balloon used multiple panels called gores that were sealed together to create the balloon shape. Once all the values above were found the size of the balloon could be found. For the first attempt at making a balloon of this type, the group decided to make a premade gore patterned balloon. The pattern found was for a make at home hot air balloon eight feet long, see Table (1). The overall shape was similar to both the shape wanted and the top could be assumed to be circular. From pre-calculated values it was assumed that the 8-foot pattern was very close to the minimum values. For this first attempt, the group wanted to have more room to play with. It was decided to double the gore values creating a 16 feet long balloon with a maximum circumference of 8.889 m using 8 gores. After this flight, the group has plans to create a natural balloon shape that will be closer to the minimum needed values and will have 16 gores within the shape.

IV. Building a Zero Pressure Balloon

Since this was the first attempt at building a balloon to launch, many lessons were learned along the way to be able to completely build a zero pressure balloon.

A. First Attempt

The first attempt at building a ZP balloon was undertaken in 2010. At the time, it was to be used as a test platform for the CySat team at Iowa State who were building in house CubeSat components to be launched on a NASA rocket. The CubeSat specifications limit the payload to 1.2 kg plus some extra weight for box and possible side experiment pushed the estimated weight to about 2.5 kg. It was also decided that the balloon would reach a hold altitude of 80,000 feet. Using the previous calculations the balloon came to consist of 16 gores that were 60 feet long. Since this was a new endeavor, it was to be built as inexpensively as could be done. And Itouchless bag re-sealer was purchased, Fig. (2).[5] This seemed to create a seal that would allow two gores to be sealed together. Painter's Plastic Sheeting

Figure 2. Itouchless heat sealers

was purchased and the only place that could be found to assemble the balloon was on the floor of the Howe Hall Atrium. A piece of cheap fabric was bought that was 60 feet long to create a gore pattern from. After 6 hours of bending over and moving the sealer along the plastic it was deemed that something needed to change. Within that time 16 gores were cut out, however, only half were sealed together into 8 pairs of gores. Along with the strenuous effort to seal the balloon, the sealers did not allow for the sealer to stop half way. It would create a stress concentration within the seal and if it were inflated would have been the first place to fail. Due to all these factors this balloon has remained incomplete.

B. Second Attempt

After all the lessons learned from the first attempt at building a ZP balloon, the mission parameters were changed so that a more manageable balloon could be produced. The Painter's Plastic had worked well so the group was confident to use this material again. The heat sealers from before did not meet the requirements for the balloons so a new heat sealer was purchased as shown in Fig. (3). The gore pattern was printed out on an 8.5” x11” piece of paper. This smaller pattern was used to calibrate the new heat sealer to the proper temperature for the plastic. This is shown in Fig. (4). It was soon found that it did not take a lot of heat from this sealer to seal the plastic together without melting large holes into the seam. The length was then scaled from 60 to 16 feet which was much more manageable and able to be constructed on worktables. The gore pattern was cut out of wrapping paper and taped to the workspace allowing for the gores to be fairly consistent throughout the construction process. The plastic sheet was then folded in half and placed over this pattern allowing for two gores to be sealed together at a time. This is shown in Fig. (5).

Figure 3. New roller for seam sealing.

Figure 4. Pre-determined setting for proper seam sealing.

Figure 5. Two layers of sheeting over gore pattern.

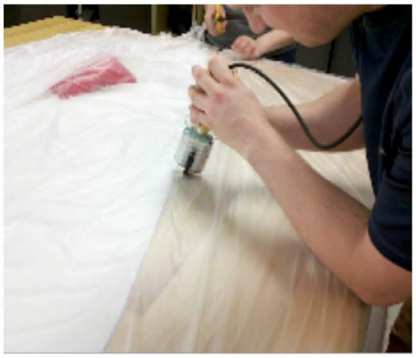

Figure 6. Final gores being sealed.

Within the course of an hour, 4 sets of gores had been sealed and were ready to be sealed to the other pairs. The previously sealed seams were lined up with the pattern on the table and then sealed together on the opposite side, as shown in Fig. (6). This allowed for all eight gores to be sealed together with relative ease. For this first attempt as sealing pairs together, the group was not extremely concerned about the gores being inside the balloon or outside the balloon. However, most of the seals ended up on the inside of the balloon.

The next major problem that needed to be addressed was how to seal the top of the balloon. While a cap was going to be used, it was found that simply zip-tying the top of the balloon together solved the problem and required much less effort. A cap would have required extra plastic and a seal around the top of the balloon where the majority of stress will occur. The zip-tie solution eliminates the need for another seam. Once the gores were sealed and the top closed, it was time to fill the balloon. This was done to check the overall shape and see if there were holes see Fig. (7). Once the balloon was inflated it was seen that some small holes had occurred on the seam. This was remedied with very cheap, thin and light Scotch tape, as seen in Fig. (8). The most

Figure 7. Beginning to inflate balloon.

important holes to find and fill are located at the top of the balloon since this is where the helium will be accumulating. The final step was how to vent the bottom of the balloon while allowing for a payload to be attached. This was remedied by using a three inch diameter PVC pipe. This pipe allows for the balloon to vent while allowing a more secure attachment point for the payload.

C. Testing

Before constructing the second balloon the HABET group wanted to see if it was possible to get a latex balloon to mimic a long duration flight. It had been done by other groups preceding the attempt by the HABET group. Since it was known that the built balloon would be larger than any balloon that the group possessed, a 3000 g balloon was used. A similar payload was constructed for the latex flight and the neck was kept open at the bottom also mimicking how the ZP balloon is going to be constructed. It was launched at roughly the same time that the built ZP balloon was to be launched. This was in the evening to give the balloon the best chance at lasting 24 hours. However, during the flight the balloon did not reach the intended altitude. It is believed that we hit a thermal boundary layer and due to the slow ascent rate of the balloon we lacked the momentum to break through this layer. This resulted in the balloon floating at around 8,000 feet. It did, however, end up floating for around twelve hours. This was a proof of concept that a balloon, even latex, with this construction would be able to fly for longer than the typical two to four hour flights. This balloon eventually came down in a tree near Green Bay, Wisconsin. This was outside the recovery zone so the payload was not recovered.

Figure 8. Fully inflated balloon.

At the time of this paper, the second attempt at a zero pressure flight has not been completed. It is scheduled to be flown on or around June 12, 2012. A successful mission would be keeping the balloon aloft for a 24-hour period. A successful flight would be making it over 14 hours of flight time. If this flight proves successful, the group hopes to take this knowledge and be able to construct a balloon pattern from a natural balloon shape that will be calculated by the group. It is also hoped that the pattern will be larger and allow for the possibility of more hardware or an experiment in the future.

V. Conclusion

Zero Pressure balloons offer a platform for long duration testing that cannot be achieved any other way at such a relatively low cost. The HABET group at Iowa State University has gained vast amounts of knowledge through trial and error within this project. It is hoped that the previous flights along with the upcoming flight are just stepping stones for Aurora to further this project and build balloons that allow for more equipment and experiments in the future.

Appendix

Length (feet)	Width (feet)	Width (inches)	Width (meters)
1	0.7917	9.5	0.2413
2	1.583	19	0.4826
3	2.292	27.5	0.6985
4	2.917	35	0.8889
5	3.333	40	1.016
6	3.583	43	1.092
7	3.646	43.75	1.111
8	3.583	43	1.092
9	3.458	41.5	1.054
10	3.167	38	0.9652
11	2.813	33.75	0.8572
12	2.375	28.5	0.7239
13	1.917	23	0.5842
14	1.458	17.5	0.4445
15	1.042	21.5	0.3175
16	0.6667	8	0.2032

Table 1. Gore pattern dimensions.

Acknowledgments

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