High Altitude Weather Balloon Venting and Balloon Dynamics

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When testing experiments on high altitude weather balloons, it is often desirable to conduct experiments at high altitudes for extended periods of time. However, standard latex weather balloons (as opposed to more expensive zero pressure balloons) rise at a near constant velocity that limits the amount of time any experiment can operate in certain atmospheric conditions. The expansion of the balloon also limits the peak altitude reached. Both of these properties are fixed at launch by the amount of helium in the balloon and the weight of the payload string. This paper describes progress towards developing a balloon valve that could remove helium midflight, and thereby change these properties as desired. This paper details both expected and unexpected challenges faced during construction, testing, and flight of the balloon valve on launches to maximum altitudes between 80,000 and 95,000 feet. Two versions of the valve have been constructed and flown to date with each flight providing incremental progress, and revealing surprising balloon dynamics involving internal temperature, pressure, ascent rate, and burst. Flight tests have confirmed the viability of the system, but leave many possibilities for improvement. Flight termination functionality must also be tested before attempting a neutrally buoyant flight. An overview of essential procedures is also provided along with plans for a third version and upcoming flights.

I. Introduction

A. Background

A high altitude latex weather balloon, the standard for university balloon groups, operates by expanding as it ascends such that the internal pressure matches the sum of elastic pressure and ambient pressure. This causes the balloon to rise at a nearly constant velocity, and then burst once the stretching of the walls exceeds the tensile strength of the latex. As a result, the maximum duration of flight and the maximum distance over which to conduct experiments are limited, and the flight path is effectively fixed as soon as the balloon is launched. One alternative to achieve longer flight durations is to use zero pressure balloons, which do not expand and therefore can be made to hover at a maximum altitude at which the balloon payload is neutrally buoyant. As a result, the experiments flown can be tested for long durations with limited control over the maximum altitude. However, these balloons are often too expensive for university groups.

This ongoing project seeks to develop a balloon valve capable of releasing an amount of helium midflight to dynamically alter the flight trajectory. Such a valve could theoretically control the ascent rate and burst altitude of the balloon. The valve could also make the balloon neutrally buoyant near a specified altitude for several hours up to the natural lifetime of the balloon, allowing extended duration and distance over which to perform experiments. With adequate knowledge of the wind directions at various altitudes, the valve would also have limited control over the balloon groundtrack and final descent location.

B. Payload

To date, two valve prototypes, internally designated "Helios 1" and "Helios 2," have been flown by the University of Maryland (UMD) Nearspace Program. The first valve attempted to prove the viability and safety of the concept, and revealed several concerns. With these concerns in mind, a second valve was flown

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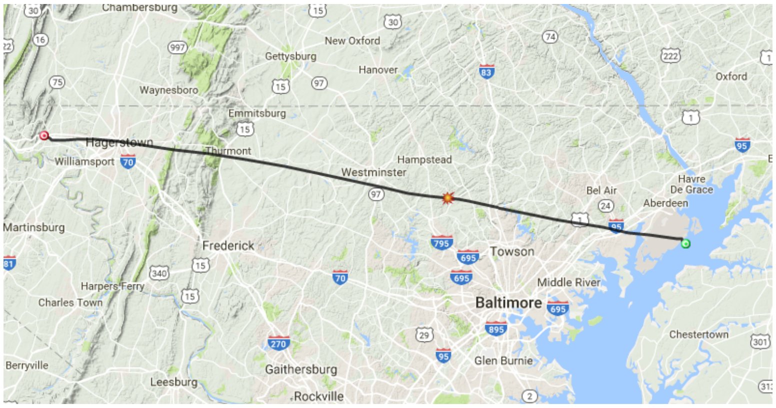

Figure 1. A sample groundtrack with a water landing.

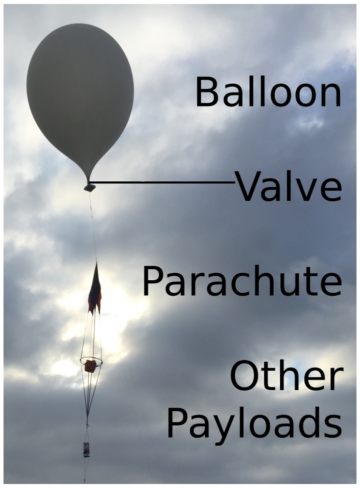

Figure 2. The balloon flight configuration.

the following year with the goal of demonstrating the capability to alter the balloon ascent rate imprecisely. This valve also demonstrated unexpected operations and additional concerns, explained below.

C. Launch Considerations

The UMD Nearspace Program launches most balloons, including all flights testing Helios, from Clear Spring, MD, about 150 km west of the Chesapeake Bay with winds to the east at most altitudes. To avoid substantially extending the balloon flight and drifting into the water, the valve operation routines have focused on causing the minimum measurable difference in balloon ascent rate as the criterion for success. Additionally, balloons can only be flown when the jet stream occurs sufficiently north of the launch site, around April to October, as to not risk landing in the water regardless of the valve presence. Figure 1 shows a sample groundtrack simulation made in late November 2016.[1] A prediction like this would have resulted in postponement of the launch or a change in launch location.

Additionally, the valve has always flown mounted directly inside or immediately below the balloon neck, above the parachute (see figure 2), to avoid the additional mass of tubing required to place it elsewhere on the payload string, and the associated tangling risk. However, one resultant concern was whether the valve would compromise the parachute upon descent. As such, the mass had to be as small as possible.

II. Helios 1 Construction

To achieve high flow at low pressure, a custom aluminum valve was constructed using a 10 mm linear actuator moving a plug inside an aluminum tube with 12 radial vents sized to utilize the full actuator range of motion as shown in the left part of figure 3. In total, the vents provide half the total cross sectional area of the tube used for balloon inflation. The aluminum valve was housed inside an electronics box just below the balloon and connected with 30 cm of tubing to an aluminum disc in the balloon neck that stretched and sealed the balloon, as well as to a hand valve that served as the inflation port, as shown in the right part of figure 3. The actuator was held relative to the aluminum tube in a custom 3D printed structure, shown in pink in figure 3.

The aluminum disc was installed in the balloon neck at the launch site and secured with a hoseclamp around a 3D printed ninjaflex band to avoid tearing the balloon. The hoseclamp was then wrapped in duct tape to avoid sharp edges. The payload box was attached below the disc via the tubing. The balloon was then inflated through the tubing at the launch site as shown in figure 4. The string carrying the other payloads was then routed through the electronics box and tied to the disc in the balloon neck.

The payload also contained a Parallax MS5607 pressure and temperature sensor both inside and outside the balloon, an Adafruit BNO055 recording temperature inside the electronics box, and an Adafruit MTK3339 GPS receiver. The valve flew in a 1600 g balloon on 14 November 2015 and opened for 60 s at an altitude of 18 km (as measured by the GPS). The measure of success for Helios was whether it could fly above the parachute without negatively impacting other payloads and whether opening the valve made a detectable difference in the balloon ascent rate.

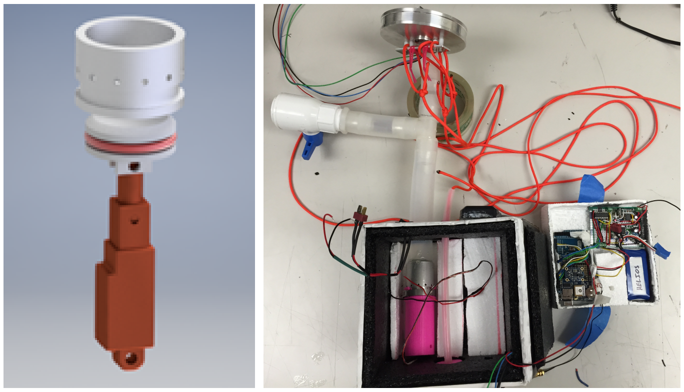

Figure 3. Left: Actuator configuration taken apart. Right: Tubing setup

Figure 4. Balloon inflation process with valve.

III. Helios 1 Results

The altitude versus time plot in figure 5 indicates a nearly linear ascent rate. The ascent rate appears constant, then appears to decrease when the valve is opened, and then recovers after the valve is closed. A linear regression indicates slopes of 6.15 m/s over the total region before opening and 5.84 m/s over the remaining ascent after closing with an average ascent velocity of 6.10 m/s. The valve opening and closing are indicated with red dashed lines in figure 5, but the data in that region is too noisy to reasonably define a slope. However, a closer analysis of several subintervals on both sides of the valve opening shows that the ascent velocity varies considerably and was consistently increasing over the period before the valve was opened. The ascent velocity over 500 points shortly before the valve opened had reached 6.37 m/s (first solid line to first dashed line), while the velocity just after closing was 6.31 m/s (second dashed line to second solid line), before abruptly falling again approximately 500 data points after the valve closed.

Comparing the descent rate, a representative launch from one month prior to the first valve launch had an average velocity during the last 2400 m of 8.0 m/s, while with the valve above the parachute, the balloon had an average descent velocity of 9.1 m/s in the same region.

Pressure data inside and outside the balloon are shown in figure 6. Temperature data inside and outside the balloon and inside the electronics box are shown in figure 7. Values are plotted against time instead of altitude to prevent propagation of the noise in the altitude data.

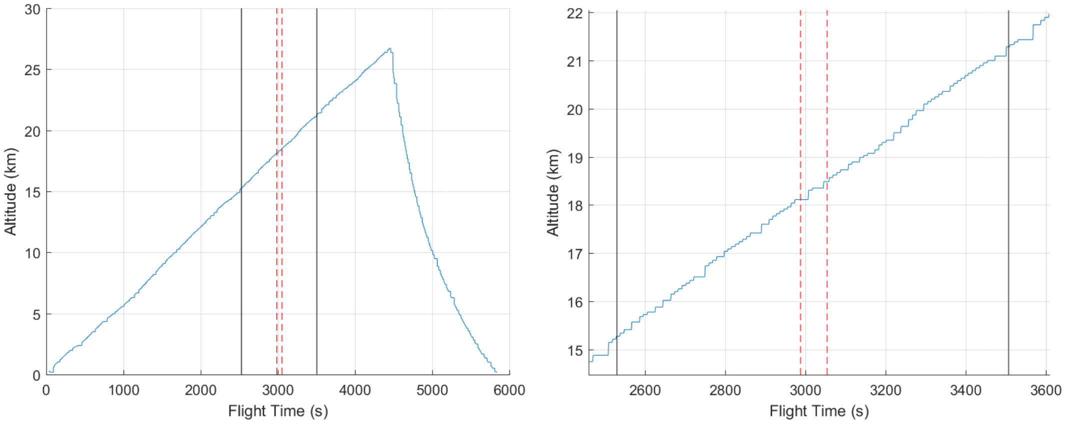

Figure 5. Altitude versus Time during first flight

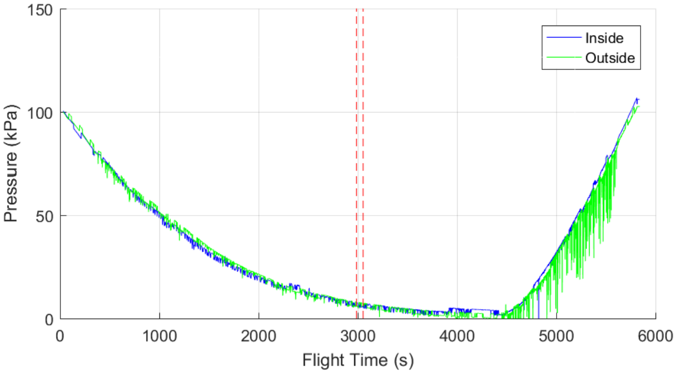

Figure 6. Pressure versus Time during first flight

IV. Helios 1 Interpretation

Helios 1 verified that the lab could fly a payload above the parachute without significantly affecting the other payloads. However, the descent velocity was higher than usual, indicating that the payload above

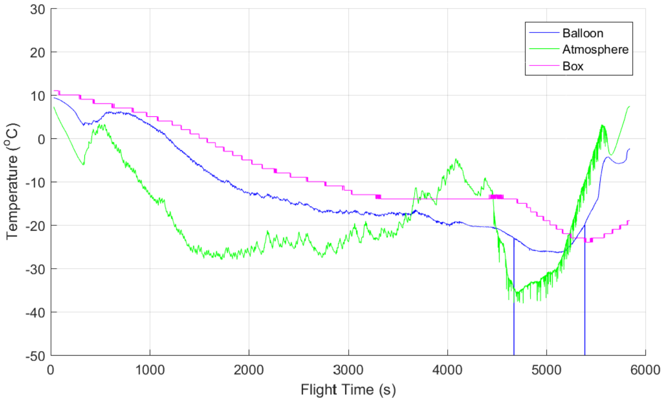

Figure 7. Temperature versus Time during first flight.

the parachute likely had some adverse effect on parachute performance. As such, minimizing weight was a priority for Helios 2.

The valve had no statistically significant impact on the balloon flight dynamics. Looking at the long term velocities, the valve appeared to have a small impact, but the more thorough analysis of smaller intervals revealed that the difference in ascent velocity was negligible. Furthermore, the ascent velocity changes substantially throughout the flight. The goal of altering the ascent velocity was therefore retested in Helios 2.

The pressure inside and outside the balloon are nearly identical throughout the flight within the accuracy of the sensors. We had hypothesized that the internal pressure would be larger due to the elastic tension of the latex, but this tensile pressure appeared negligible. This could have contributed to the failure of the valve, which relied on a positive pressure difference to force gas out. Without this pressure difference, minimal helium would escape through the bottom of the balloon. The temperature graph shows that the inside of the balloon is a remarkably stable environment, suggesting the possibility of housing electronics above the alumnium disc instead of inside a separate insulated box.

V. Helios 2 Modifications

To reduce mass, the new valve was made much more compact. The valve was built into the disc inside the balloon to eliminate the substantial tubing mass, and the disc was shrunk to accommodate a thicker, tighter balloon neck. The new aluminum disc and payload are shown in figure 8. The same actuator configuration was maintained, and the payload electronics box was placed immediately below the actuator housing.

Due to the substantial variation in the pressure data, the Parallax pressure sensors were replaced with higher resolution Honeywell SSC sensors. The GPS receiver was also reprogrammed to reduce noise.

Most importantly, a fan was added just above the disc to force a pressure difference across the valve, and the valve was tested with a potential flight balloon to determine an adequate release time instead of the overly conservative 60 seconds used for Helios 1. An experiment with an inflated 300 g balloon took 90 s with the fan on until the balloon skin wrinkled, indicating substantial reduction in air volume. The valve was set to open for 90 s at 20 km with the assumption that the fan would be much less effective at higher altitudes with reduced pressures. The balloon was filled through the aluminum tube stem before installing the plug with attached actuator this time, complicating the fill procedure in order to reduce weight. The valve flew in a 3000 g balloon on 17 September 2016.

VI. Helios 2 Results

With the improved GPS setup, it was also possible to measure the ascent velocity while the valve was open. The average ascent velocities were 6.50 m/s before opening the valve, 5.47 m/s while open, and 5.89 m/s after closing with an average ascent velocity of 6.24 m/s. If one considers narrower subintervals, the ascent velocity initially increases with altitude as with Helios 1, except the balloon then decelerated shortly

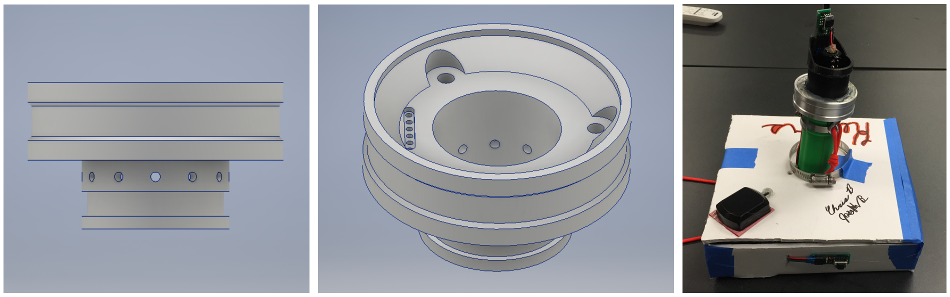

Figure 8. Helios 2

before opening, and then accelerated again well after closing. The lowest velocities in the entire flight were measured both immediately before and after the valve was opened, whereas this region exhibited the peak ascent velocity for Helios 1. The ascent velocity just before the valve opened was 5.71 m/s, and the velocity just after closing was 5.67 m/s, shown in figure 9. The GPS and pressure sensor inside the balloon appear to have been covered by latex on the descent, causing both sensors to fail then.

A GPS unit in a different payload flying at the same time indicated a descent velocity of 7.8 m/s during the final 2400 m. Pressure and temperature graphs are shown in figures 10 and 11 respectively. The singularities are pressure sensor failures, presumably caused by the fan turning on and the balloon bursting.

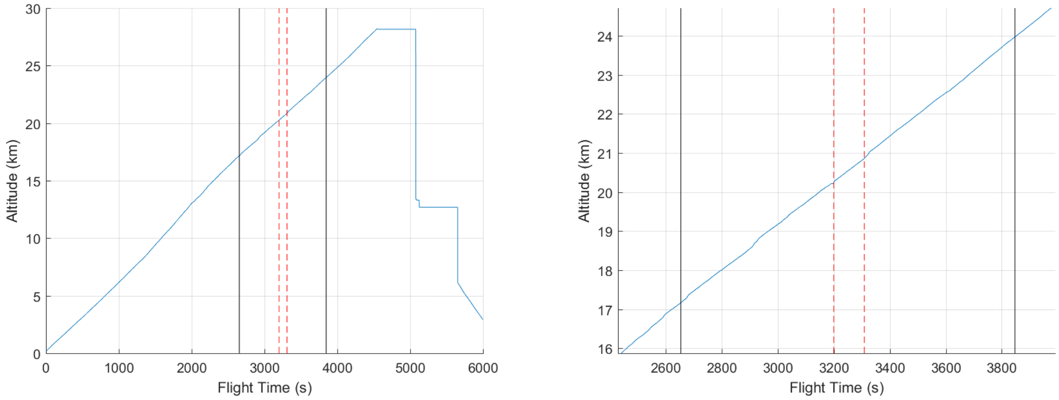

Figure 9. Altitude versus Time during second flight

VII. Helios 2 Interpretation

Much smoother altitude data was collected, but the ascent rate was still barely measurably smaller while the valve was open, though not afterwards, suggesting that the balloon might recover partially after the valve is closed. The GPS data for this launch is remarkably smooth, and the sharp bump that looks like noise near the first red dashed line in figure 9 is the only variation of that size in the entire data set. While still too small to be conclusive, this suggests that some event occurred when the valve was opened that altered the original data progression. The altitude graph at that time during the first launch is similarly noisier than at all other times. While a change in ascent velocity was detected, it is statistically doubtful even with smoother data.

The new configuration made the payload substantially smaller and decreased the mass from 1050 g to 800 g. This change was followed by a decrease in the descent velocity, building further confidence in the safety of flying the system above the balloon parachute.

The temperature graph confirmed that the inside of the balloon is more stable than the outside atmosphere. The pressure curves were far less noisy, but still support the prior conclusion that the elastic pressure from the latex is negligible.

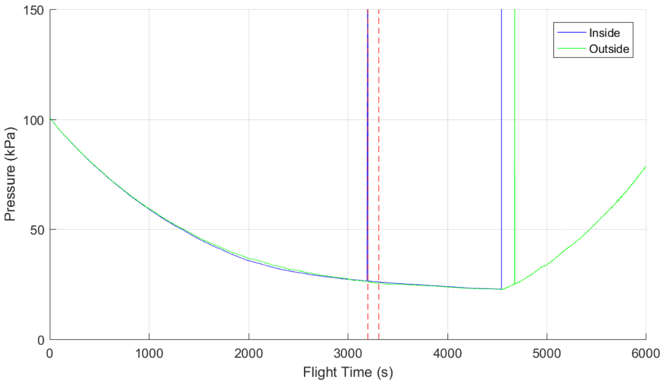

Figure 10. Pressure versus Time during second flight

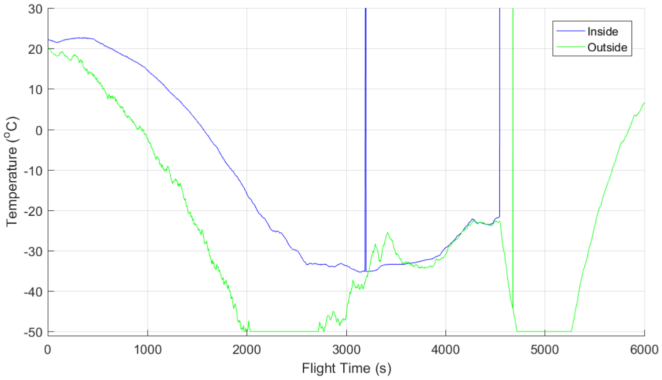

Figure 11. Temperature versus Time during second flight

A. Failed August Launch

The removal of the tubing now required that the balloon fill hose be inserted directly into the bottom of the valve, and sealed in place with duct tape. The fill hose was then quickly removed and replaced by the valve plug and actuator which were attached to the electronics box. This posed a considerable leak risk, which was examined more thoroughly after an August launch carrying Helios 2 failed to exceed 2000 ft altitude.

During the following launch, soap bubbles were placed around the duct tape seal to search for leaks. Instead of watching the bubbles expand, observers found that the soap was suctioned into the balloon. Considering this, launch supervisors hypothesized that the previous launch could have failed in part because the balloon had contained a large quantity of air as well as helium. The flights have proven that there is not a positive pressure difference inside the balloon, so it is not surprising that helium did not leak out. Additionally, the entire filling apparatus also becomes very cold, which could explain why air was actively pulled into the balloon.

VIII. Conclusion

Neither launch can confirm definitively that the valve succeeded at its objective of changing the ascent velocity, so more testing is required to prove the concept. This also requires riskier long duration flights that can only be completed during periods in which the winds are blowing west, away from bodies of water. We hope to fly again in late spring 2017 to test a much longer helium release under suitable conditions for a long duration flight. Future flights will continue to examine the balloon dynamics to explain why the ascent velocity fluctuates and any other phenomena in the temperature and pressure curves. The valve will continue to be shrunk to decrease risk and increase payload capacity, and more components will be housed inside the balloon itself to avoid an external insulated box.

Long term, the lab hopes to use the valve to develop a general flight control system to dynamically make crude adjustments to balloon trajectory, while extending flight duration and altitude limits. The final valve will then require vacuum chamber experiments to measure its flow rate, which will then need to be corroborated against several flight tests in the real flight configuration to make a precise controller. The payload never flies without an additional payload string, so the safety of those payloads is essential, though this limits the pace at which new valve test programs can be attempted. A flight termination system is also being developed for neutrally buoyant flights, as is a remote command system for upcoming flights. Thus, the payload focus is still on making a safe and effective valve, though sensor results have suggested other topics for exploration as well.

Acknowledgments

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[1] "Predictor," *habhub*, URL: https://predict.habhub.org/ [cited 20 November 2016]