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Solar High Altitude Balloons (SHAB) as a Long Duration Controllable Aerial Platform

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Solar balloons are a simple and lightweight option for aerial exploration and meteorological data collection both terrestrially and on other planets. By using a lightweight material that absorbs visual light and emits low levels of thermal radiation, solar balloons behave similarly to hot air balloons but are capable of ascending to much higher altitudes. Unlike hot air balloons, which use an onboard heat source to raise the temperature of the internal air, solar balloons generate heat by absorbing solar radiation, providing a free source of lift and eliminating the need for carrying an extra tank of lighter than air gas or fuel. Recently, solar balloons have gone through many technological advancements, ranging from design to material selection to controllability. This paper discusses the results and progress of new experimental solar balloon designs that explore various envelope sizes and material selection well as a novel mechanical vent design on the top of the balloon to store and release hot air. By including a mechanical vent, the balloons can adjust altitude to enter regions of the atmosphere with different wind flows, which can lead to limited horizontal controllability of the platform.

I. Introduction

Weather balloons, also known as sounding balloons, are the most common type of high-altitude balloon. The envelope material for weather balloons is typically made from an elastic latex and filled with helium. These types of balloons are also used for radiosondes, which are released from over 1000 locations worldwide daily. Radiosondes ascend to altitudes of up to 40km and carry a payload which includes sensors that measure temperature, humidity, pressure, and wind speeds [1]. Radiosondes are instrumental in providing data for predicting weather forecasts.

There are two types of long duration high altitude balloons with altitude adjustment capabilities. Super pressure and zero pressure balloons are usually filled with helium or hydrogen and the envelopes are made out of a lightweight linear low-density polyethylene (LLDPE) film. Zero pressure balloons are typically inflated with helium, and when the balloon reaches a desired float altitude, excess helium is released out of a valve at the bottom of the balloon. These balloons typically last for 1-2 weeks [2]. Super pressure balloons on the other hand are inflated with a lower amount of helium than needed for full inflation and the gas pressurizes and inflates the balloon once the desired float altitude is reached. Super pressure balloons, also known as pumpkin balloons or ultra long duration balloons (ULDBs), can fly for up to 100 days. Figure 1 shows a side-by-side comparison of a zero pressure and a super pressure balloon.

Solar high-altitude balloons (SHABs) are a special type of hot air balloon that incorporates a lightweight envelope that absorbs solar radiation to heat internal air and generate lift. These balloons can climb to the lower stratosphere on

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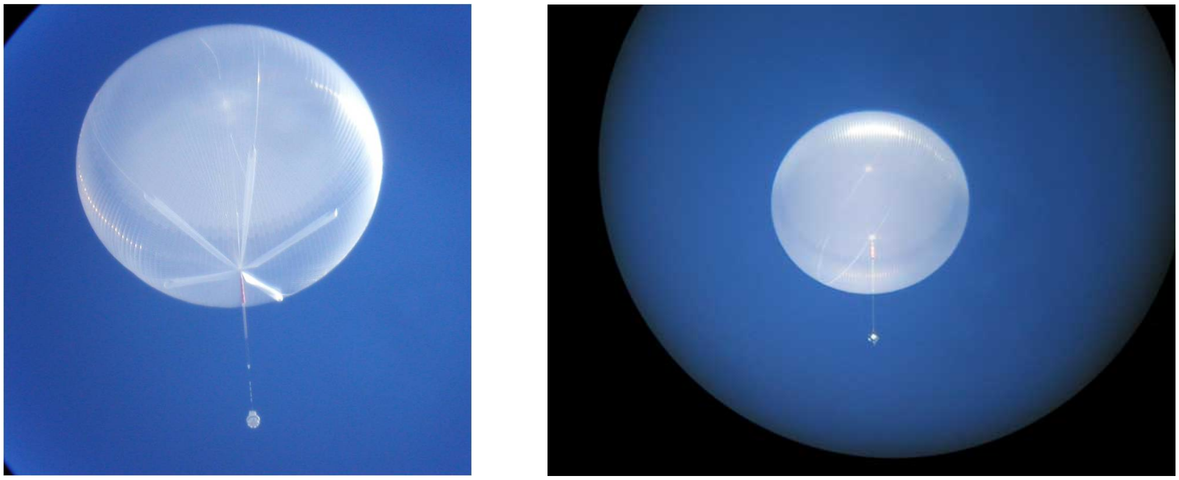


Fig. 1 Zero Pressure Balloon (left) and Super Pressure Balloon (right) at float altitude

Earth and will fly as long as the sun is above the horizon. Dozens of solar balloon flights are conducted every year [3], carrying scientific payloads investigating low frequency sound transmission in the stratosphere [4, 5] and capturing aerosol levels above the tropopause. They have been used here on Earth to validate means of detecting seismic activity on Venus using sound [6], and have been proposed as flight systems in their own right for both Mars and Venus due to their simplicity and lack of lift gas [7–9].

This research expands upon Bowman et al.'s solar balloon research and development testing new materials and sizes, as well as introducing a vent to the system for altitude control [3]. Some of these results were published in Schuler's thesis on solar balloons in 2020 [10]. The vent system consists of a mechanical structure and 2 simple flaps (actuated by a servo motor) that swing open and closed to release or retain air. Vented solar balloons open the opportunity for limited horizontal control, depending on wind flows, which can lead to waypoint navigation and station keeping maneuvers. Google Loon proved high altitude balloons are capable of autonomous navigation by using specially modified super pressure balloons from Raven Aerostar (Thunderhead) with an internal bladder for adjusting altitude [11]. Vented solar balloons can offer similar capabilities, but on a much smaller scale and payload size. Standard solar balloons are 6 m in diameter (spherical) and lift payloads up to 3 kg whereas the larger Thunderhead balloons lift payloads up to 50 kg.

II. Solar Balloon Envelope Construction

The solar balloon envelopes were constructed from the heliotrope design by Sandia National Laboratories [3]. The initial solar balloon envelopes were constructed from 0.31 mil, 400 x 12 ft. rolls of clear high density plastic sheeting. The sheets were then cut into 30 ft. long sections, folded, and a curve following equation (1) was used to cut out the gore pattern of the balloon in the material.

$$w = \frac{c}{2n} cos(2\pi \frac{l}{c}) \tag{1}$$

where w is the width measured from the fold axis along the center of the gore, c is the circumference of the balloon envelope, n is the number of gores desired, and l ranges from 0 (the center of the gore) to c/4.

After the gores were cut, they were sealed together using strips of Scotch shipping tape until a giant spherical ball was constructed, sealed on both ends. Next, a hole was cut on one of the "ends" of the ball and reinforced with paracord, creating the intake hole for solar balloon. Next, guy lines were tied around the paracord at each seam of the balloon and connected to a main line that would later connect to the gondola. Figure 2 shows several steps of the manufacturing process for several of these SHAB envelopes and vent.

Prior to darkening the envelope, the balloon is inflated and inspected for small holes. During the construction process, and because of defects in the plastic as manufactured, dozens of small holes can form in the material and are sealed from the inside of the envelope with small pieces of scotch tape. While inflated the temperature probes can also be mounted and hung from the top of the balloon or the vent. For all vented solar balloons after SHAB3-V, two safety

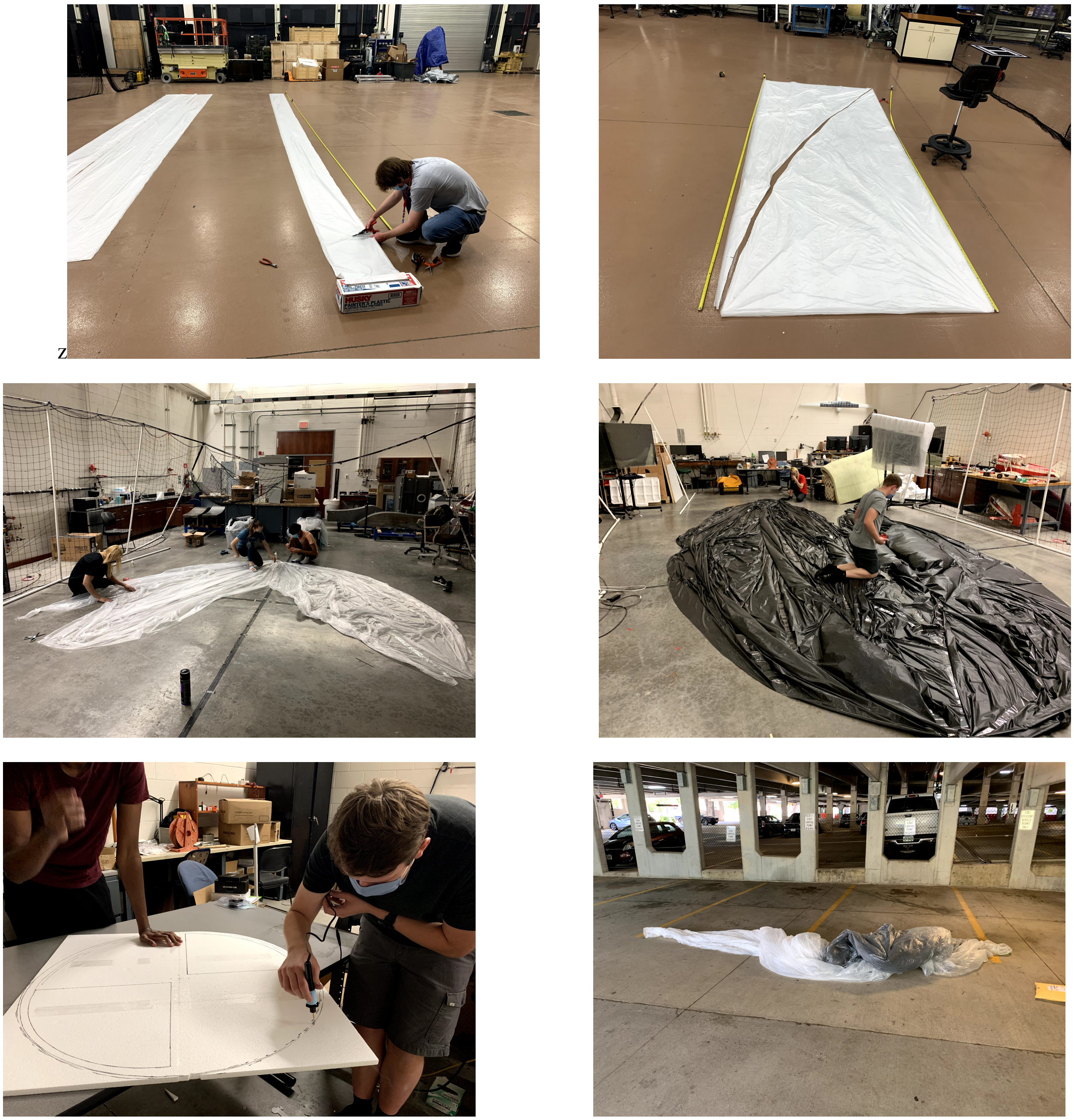


Fig. 2 Images of Envelope Construction, Vent Construction, and Charcoal Coating of several SHAB missions

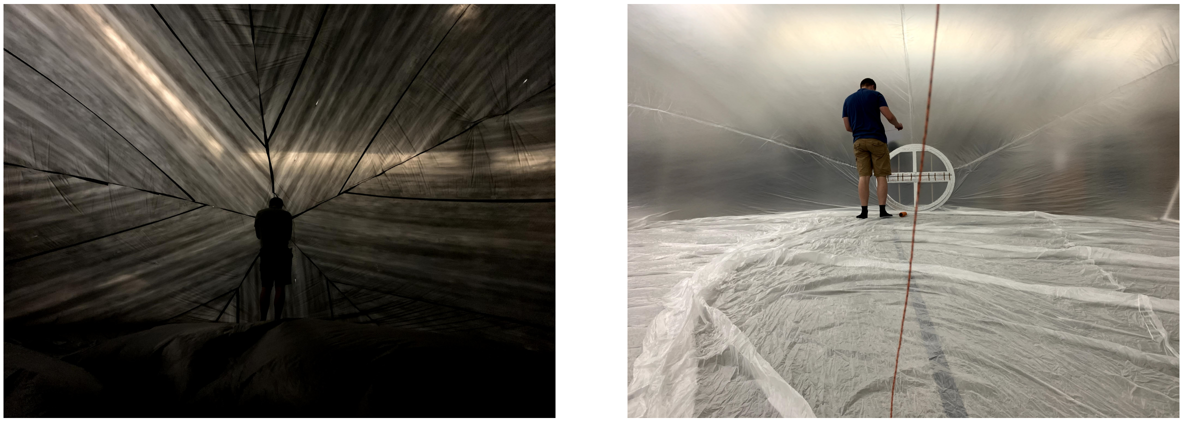


Fig. 3 Internal Inspection of BlackSHAB and SHAB4-V Envelopes

lines were connected from the vent to the parachute guy lines using 10 m of nylon cord in case of a gore seam tape failure, which happened on the SHAB3-V mission and is discussed in Section IV. Figure 4 shows inspection of the SHAB3-V and BlackSHAB envelopes.

The final step of envelope construction was to darken the clear plastic material. This was done using pyrotechnic grade air float charcoal powder; the fine powder sticks to the inside of the envelope without the need for adhesives. This step can be very messy and was also performed outside in areas where there was a wind block to prevent unwanted inflation of the solar balloon. The reason the charcoal coated plastic balloons are used for the standard design instead of using black polyethylene is due to the scarcity of lightweight black plastic in large rolls. Because one of the key ingredients of charcoal powder is carbon, the fine powder coats and darkens the material, improving the solar absorption properties. If the entire envelope could be coated with an ultra-fine layer of these carbon nanoparticles, the hypothesis is that the balloon would have superior solar absorption properties compared with the clear and black polyethylene plastics as well as the germanium aluminum alloy coating JPL proposed. Similarly, carbon nanoparticles have been proposed as a method for producing solar thermal steam propulsion for interplanetary travel [12, 13].

Unfortunately, the exact optical properties of the 2 different envelope materials have not been measured at this time. However, estimates can be made from experiments conducted by NASA and the Naval Research Laboratory for common materials. In the experiments the solar absorptance of the material was measured with a spectrometer with an integrating sphere attachment, and the normal infrared emittance of the materials was measured using an infrared spectrometer with an attached heated cavity (Holhraum) [14]. Black polyethylene had a solar absorptivity of 0.93 and an emissivity of 0.92. Clear polyethylene has an absorptivity of 0.835 and emissivity of 0.165 [15]. Therefore, the charcoal coated material has optical properties somewhere between the clear and black polyethylene. An ideal balloon envelope material would have an absorptivity of 1 and emissivity of 0, converting all incident solar irradiation to heat without losing any energy to the environment.

Fig. 4 SHAB Styrofoam Gondola with Internally Mounted Electronics

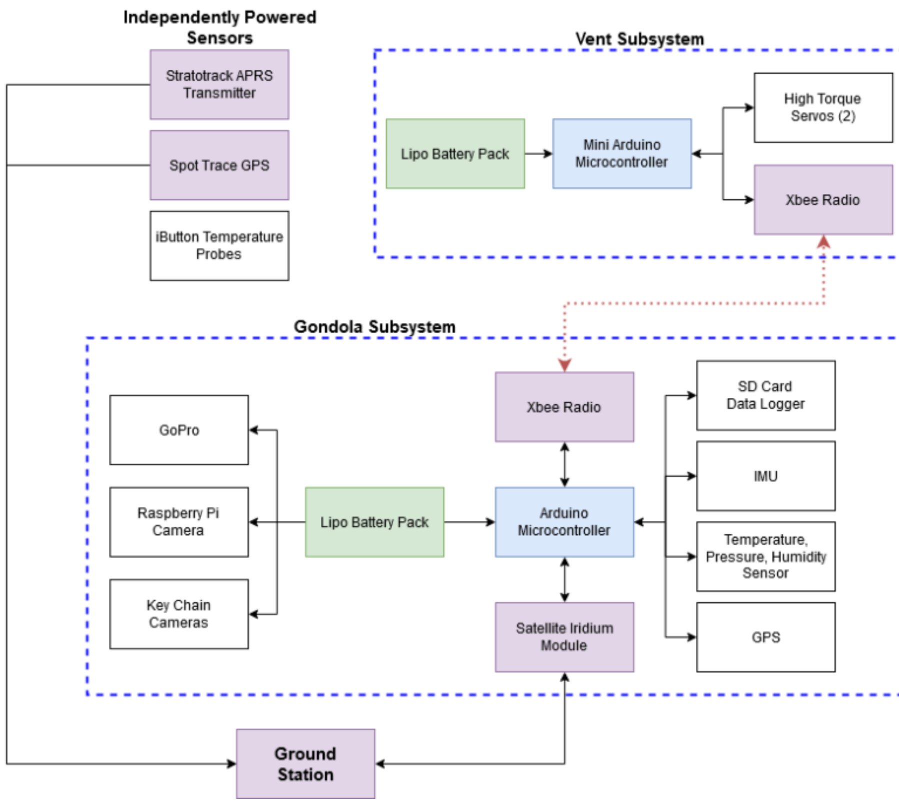


Fig. 5 Block Diagram of SHAB Gondola and Vent Electronics Architecture

III. Gondola

For terrestrial flight experiments, the bare minimum payload required for tracking is a satellite GPS tracker and an Automatic Packet Reporting System (APRS) transmitter. APRS is a protocol within the amateur radio community (ham) that allows for real-time GPS tracking over 1-minute intervals at 144.39 MHz in the U.S. (different countries have different frequencies reserved for APRS traffic). APRS transmitters for high altitude balloon flights require longer antennas than typical APRS transmitters to communicate with the ground networks from high altitudes. These solar balloons used the StratoTrack APRS transmitter from High Altitude Science which is specifically designed for high altitude balloons. The tracker records atmospheric temperature, pressure, and device voltage, and includes an unlocked GPS for tracking at high altitudes; many commercial GPS modules do not work above 18km, above which solar balloons can fly. The StratoTracker relies on line-of-sight (LOS) communication with nearby ground radio towers, while the APRS transmitters are unreliable near the Earth's surface. Real-time tracking dropped out a few kilometers in elevation above the landing location on each solar balloon flight. Therefore, a satellite GPS tracker was also necessary, with the primary use being for retrieval of the balloons after landing.

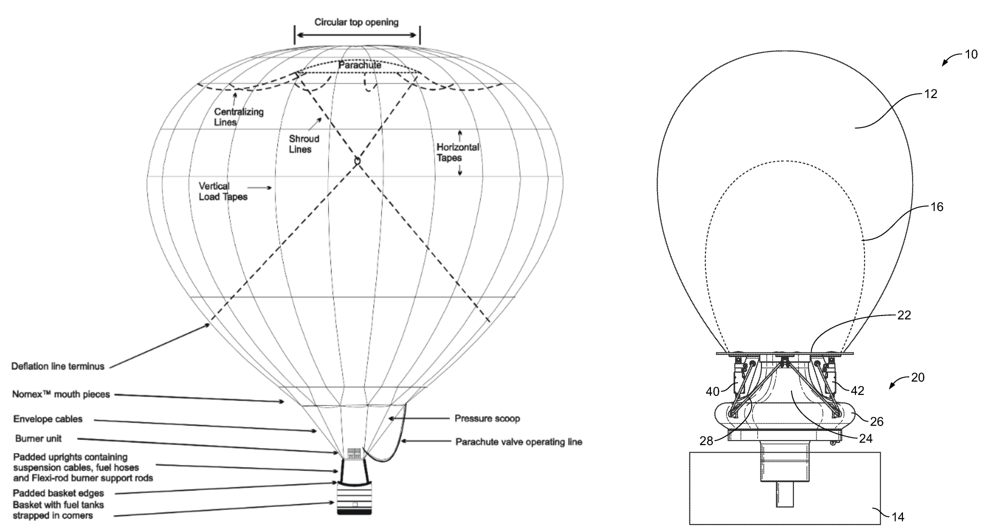
The Spot Trace is a popular GPS tracker in the high-altitude balloon community for locating weather balloons after they land. They can also be used as a real time tracker but can be unreliable and do not update as often as APRS transmitters. On one flight the Spot Trace did not update for the duration of the flight until the balloon landed. Also, it's very important to use lithium-ion batteries for any powered systems on the balloon due to the extreme temperatures (a lesson learned the hard way after the first flight).

For heavier payloads Styrofoam coolers were used to mount all the electronics as well as keep them insulated. The main gondola setup consisted of an Arduino Mega, IMU, altimeter, temperature sensors, GPS, XBee radio, Spot Trace, and Iridium satellite module. Cameras in the gondola and small temperature probes inside the envelope were also included on a few flights (the temperature probes were never recovered). Figure 5 shows a block diagram of the standard electronics architecture for the SHAB missions. The IMU, GPS, and meteorological sensors can be used for control algorithms and the Iridium satellite module can be used for remotely controlling the balloons or manual override of the autonomous balloons. The Iridium satellite module used was the RockBlock 9607 which works from anywhere in the world, at any altitude, and requires both a line rental to activate and credits for sending and receiving 50-byte messages. An XBee pair was used for controlling the vent at the top of the balloon over 2.4GHz radio.

IV. Balloon Control Methods

There are 3 main methods balloons used in industry to adjust the altitude of balloons (not including blimps or zeppelins which use propellers and a weight shifting keel-like structure). High altitude balloons use two different methods depending on if it is a zero-pressure or super-pressure balloon. Zero-pressure balloons don't necessarily control their altitude, but they have a vent at the bottom of the balloon to let out excess gas and prevent the balloon from bursting when rising to higher altitudes. However, zero-pressure balloons can only descend once the highest altitude is reached as the material degrades and gas starts leaking.

Zero-pressure balloons (ultra-long duration balloons, or ULDBs), are completely sealed and filled with a pre-calculated amount of helium to provide positive lift. Because the balloon is sealed, as the balloon rises, the internal pressure of the balloon expands and displaces more ambient air, eventually realizing a float altitude. Up until recently these ULDBs have been used as free-flying balloons to perform science missions on the edge of space, but several companies have modified the design to incorporate controllability.



(a) Hot Air Balloon Vent (b) Google Loon Umbrella Valve [16]

Fig. 6 Balloon Altitude Control Mechanisms

Table 1 Potential Structural Vent Material Properties

Material	Density (kg/m^3)	Tensile Strength (MPa)	Melting Temperature (k)
Expanded Polystyrene (EPS)	50	46-60	380
Low-Density Polyethylene (LDPE)	940	10-20	350
Balsa Wood	250	7-30	380
Carbon Fiber	1930	500000	3925

Both Google Loon and Worldview are developing high altitude balloon systems that loiter in place. Google is designing these balloons to provide cell coverage all over the world, whereas Worldview is more interested in capturing high quality imagery. Both companies have similar patents that involve using a pump to add or remove air into the system, thus changing the amount of buoyancy. Google's patent has the bladder inside of the super-pressure balloon whereas Worldview uses a combination of zero-pressure and super-pressure balloons and pumps air in and out of the super-pressure balloon [17, 18]. Since the solar balloon has an opening at the bottom to allow for ram-inflation and natural degassing, these pumping devices won't work without a method for sealing and unsealing the bottom valve.

Hot air balloon pilots use a parachute valve to adjust altitude while in flight, as well as for rapidly deflating the balloon while grounded. The parachute consists of a large circular piece of fabric at the top of the balloon, and a pulley system that connects the vent to the upper walls of the balloon envelope as well as a control line down to the pilot's basket as shown in Figure 6. The vent is opened by the pilot pulling the control line, which compresses the upper walls of the envelope and allows the vent to drop into the balloon, thus letting hot air to escape out of the top of the balloon.

V. Vent Design

Designing a vent for a solar balloon is somewhat uncharted territory. One of the only records of a vented solar balloon is from NASA's Jet Propulsion Laboratory in the 1990s; however, they provided no documentation or patents revealing how the vent was constructed [7]. Due to the complex nature of flexible inflated envelope materials, as well as the many unknown atmospheric variables the balloons can experience while in flight, an agile prototyping process was used to design a successful vent for solar balloon applications.

A. Parachute Vent Feasibility Experiment

For larger solar balloons with a more durable material, the parachute vent could be a good option. However, with a more durable material also comes added weight, and therefore less lifting force. Before installing a parachute vent in a solar balloon, a tethered balloon test was conducted to test the feasibility of a typical vent design on a fragile material.

For the tethered test, a solar balloon was filled manually with air and allowed time for the internal air to heat up and produce lift. The five guy lines connected to the balloon's intake hoop were then tied to a main line and attached to a counterweight on the ground. Within minutes, three of the five guy lines ripped the envelope material due to the high lift force as shown in Figure 7. After this experiment, the polyethylene was deemed too fragile to incorporate a miniaturized parachute vent system for solar balloon prototypes.

B. Vent Prototyping

All the vent prototypes used a structural vent at the top of the balloon rather than the parachute vent. Minimizing weight while maximizing air flow was the driving force of the design. Expanded polystyrene (EPS) was the obvious material to use after comparing the mechanical properties of several lightweight structural materials as shown in Table 1. EPS is the lightest material, and while not as strong as carbon fiber, the vent experiences minimal forces from the internal air pressure of the balloon. The melting point of EPS is right on the maximum temperature the solar balloons' reach; however, by coating the EPS with aluminum foil this issue is avoided.

The first vent prototype consisted of a butterfly vent design using two large circular pieces of EPS that rotate on the same axis as shown in Figure 8a. Depending on the orientation of the two panels, the mass flow rate could be adjusted. The axial motion of this vent was ideal because external forces such as wind or turbulence wouldn't be able to rip the vent apart if instead a flap design was used. The coefficient of friction of EPS was not considered when designing the initial prototype, which turned out to be a major design flaw. EPS has a coefficient of friction between 0.6-0.8. Several

Fig. 7 Ripped Envelope During Tethered Solar Balloon Experiment

(a) Butteryfly Valve (b) 1-Flap-1-Servo Vent (c) 2-Flap-2-Servo Vent

Fig. 8 EPS Vent Prototypes for Solar Balloon Applications

Fig. 9 Flapping Vent in Closed and Open Configuration (Top-Down View)

techniques were tried to combat the high friction coefficient between the 2 panels.

First, the servo was upgraded to a one with a higher stall torque of 8 kg-cm, compared to the initial micro servo with a stall torque of 2.5 kg-cm. Second, several materials were tested to reduce friction, including Ultra High Molecular Weight Polyethylene (UHMW) tape, Teflon tape, graphite, and dry lube. Out of all these materials, the UHMW reduced the most friction and the graphite and dry lube had no effect. While the UHMW tape and high-torque servo did improve the mechanics, the butterfly vent still did not open and close reliably enough to include for a vented SHAB flight experiment.

The next two vent prototypes were inspired by a butterfly valve. The first prototype had only one half of the circular area available to open as seen in Figure 8b. The flap was actuated into the balloon to prevent the flap being exposed to external forces such as wind and turbulence. Additionally, by having the vent actuate into the balloon, the internal pressure inside the balloon assists in keeping the vent sealed while in the closed position. This vent had a diameter of 0.6 m, and a trapezoidal outflow area of 0.12 m^2. The vent only ended up dropping the balloon 1km when fully opened so the next flapping vent included several modifications.

The final flapping prototype, flown on SHAB 5-V, depicted in Figure 9 has 1m diameter, and 2 downward actuated flaps that increased the outflow area 5 times compared with the first vent. To save weight, lightening holes were added and replaced with the balloon envelope material, reducing weight by 25 percent; this was also attempted with the first prototype, but the weight of the tape and plastic equaled the weight of the Styrofoam since the vent was much smaller. Two wooden balsa wood rods were also added across the top of the balloon to add additional support to the structure when the flaps are in the open position. This vent also only uses one servo for 2 flaps instead of the vent flown on SHAB4-V depicted in Figure 8b.

Vents for SHAB flights 3V and 4V include electronics payload on the vent housed within a box constructed of the same EPS material to keep the system insulated from the extreme temperatures, as shown in Figure 8c. The electronics payload includes the high torque servo, a 3.7 V, 2000 mAh battery, DC/DC boost converter, Arduino Nano, and an XBee Radio. The DC/DC boost converter is used to efficiently convert the input voltage to a higher voltage for the high torque servo to use. Also, the XBee Radio has a line of sight (LOS) range of up to 100 m. SHAB 5-7v, which switched to the one servo design removed the radio controlled vent, and instead have cables deployed through the inflated envelope, down to the Gondola.

VI. Flight Experiments and Results

Launching a solar balloon can be a challenging endeavor. Low surface wind speeds (<5mph) are extremely helpful for launching balloons. Wind speeds on Earth are usually at their lowest in early mornings just after sunrise. Low stratospheric wind speeds are also desirable to have a shorter retrieval distance. For the later balloon launches, a battery powered fan was used to inflate the balloon, making the launching process significantly easier. Due to the fragile envelope material, grass fields or asphalt are desired; most of the balloons were launched on public baseball fields. All six balloons were launched in Arizona and five of the six solar balloons were mostly recovered. Figure 10 shows the first four non-vented balloons being launched.

(a) 6m Charcoal Coated Clear Plastic (b) 3 m Charcoal Coated Clear Plastic (c) 6 m Black Plastic

Fig. 10 Various SHAB Envelope Designs

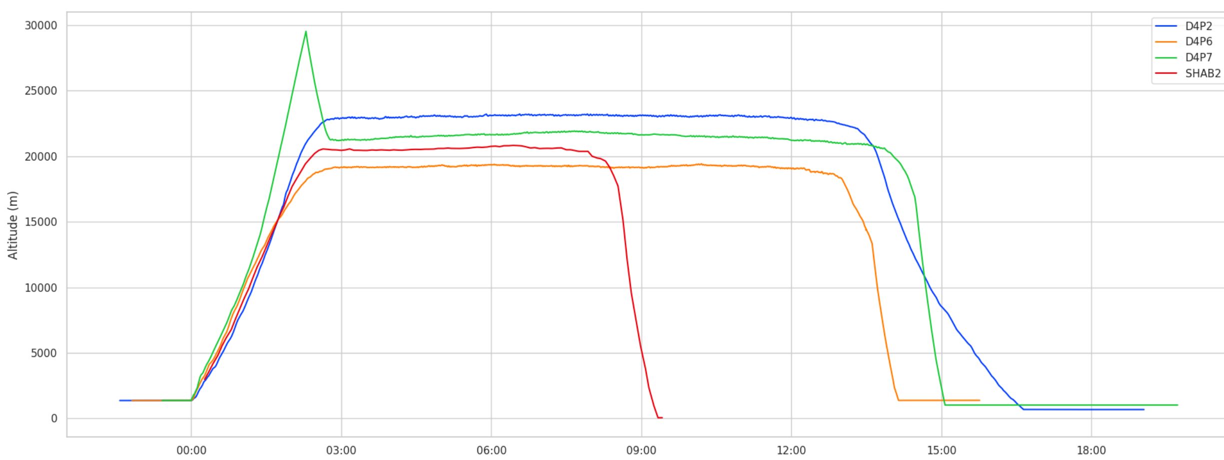


Fig. 11 Standard 6m Spherical Charcoal Coated Clear Plastic SHAB Envelope Altitude Profiles. Note that balloon D4P7 was towed aloft using a weather balloon, then released and allowed to sink to its neutral buoyancy altitude.

A. Standard 6m spherical SHAB Flights

Figure 11 shows the altitude profiles of a sample of standard 6m charcoal coated spherical SHAB envelopes, including a "grand slam" solar balloon flight. The grand slam design features a standard solar balloon that is attached to a weather balloon and released when the weather balloon bursts, showing the feasibility of ram-inflating solar balloons from a higher altitude, which could help with solar balloon missions on Mars or Venus [8, 9].

On average, the standard SHAB designs have ascent rates between 1-3 m/s and descent velocities between -3 to -8 m/s. These standard solar balloons usually float between 19 km and 23 km depending on the payload weight which has ranged between 0.5 and 3kg. The float duration also ranges depending on the season when the balloon is deployed; SHAB2 was launched in Fall 2020 whereas the other 3 balloons were launched in summer 2020. Once a float altitude is reached, the balloons can oscillate between a few hundred meters. These oscillations have been recorded with high altitude weather balloons as well and have been hypothesized to be caused by gravity waves [19]. Additionally, the intake hoop at the bottom of the solar balloon could contribute to the oscillations due to complex heat transfer and fluid flow that can occur in that region of the balloon.

B. Scaled size SHAB Flights

In addition to the standard 6 m diameter SHAB Envelopes, experiments were also conducted with 3 m diameter SHAB envelopes, dubbed MiniSHAB envelopes. These envelopes were constructed with the same methods as the standard SHAB envelopes, with the measurements scaled to result in a half-sized envelope. In flight, the MiniSHAB envelopes had slower times to climb to float altitude, taking about 4 hours to reach float. They also tended to float slightly lower than the standard SHAB envelopes, floating between 17500 m and 20000 m. Both these effects can be attributed to the smaller size of the envelope, which directly impacts the amount of buoyant lift the envelope can produce in comparison to its surface area. With 1/8th the lifting volume of a standard SHAB envelope, the balloons have a much smaller payload capacity. The advantage of the MiniSHAB envelopes is the ease of construction, using 1/3rd the construction time and 1/4 the material of a standard SHAB envelope.

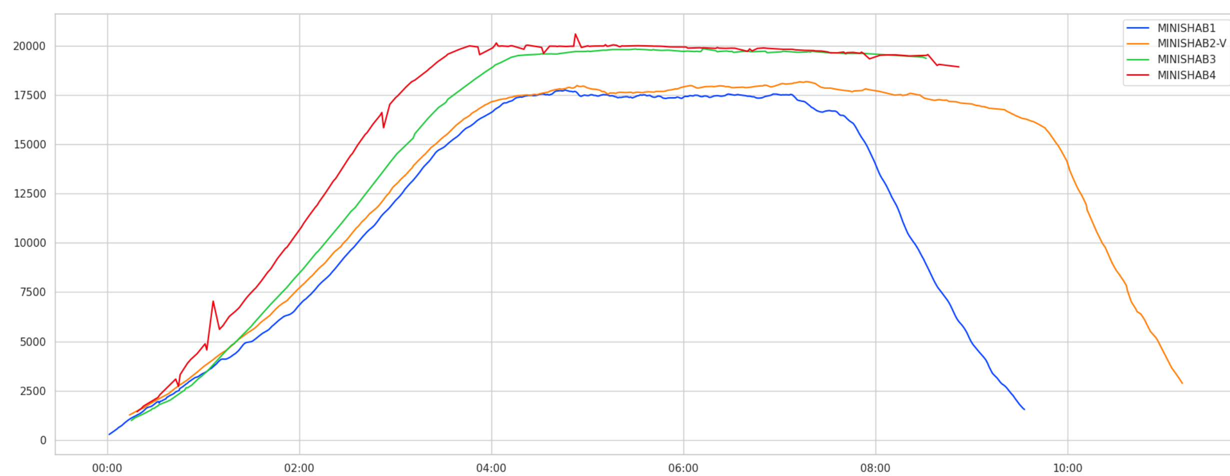


Fig. 12 3m Charcoal Coated Clear Plastic SHAB Envelope Altitude Profiles

There were 4 MiniSHAB flights flown. MiniSHAB 1 was a proof of concept, flown to show that a smaller solar balloon can fly with a light enough payload. The balloon reached a float altitude of only 17500 m, less than the standard balloons. MiniSHAB 2V was a MiniSHAB envelope flown with a scaled vent, to experiment with using a vent on 3 m envelopes. The balloon flew successfully, however no significant vent action was noted. This was most likely due to the small size of the vent, which was unable to release enough heated air to significantly change the altitude of the balloon. The small size of the vent was necessary to keep the system mass low enough to fly; therefore vented MiniSHABs with the current mechanical vent design are unfeasible.

MiniSHAB 3 and 4 were experiments to test the concept of the infrared balloons [20]. MiniSHAB 3 was a standard charcoal coated 3 m envelope as a base case to compare against MiniSHAB 4. MiniSHAB 4 was an adaptation of the Infrared Montgolfier, with the bottom half of the balloon coated in charcoal, and the top half coated in aluminum powder to mimic the metalized mylar used in the Infrared Montgolfier. By capturing IR radiation emitted by the ground, and using this energy to heat the internal air, the balloon can theoretically stay aloft at night, without direct solar radiation. Both MiniSHAB 3 and 4 used an extremely light solar powered tracker payload, to maximize their float altitude and likelihood of success for the infrared balloon envelope. The balloons were launched on the same day, within a half hour of each other, to ensure that the best possible comparison between the standard MiniSHAB and infrared MiniSHAB. The two balloons both reached a very similar float altitude at 20000 m and maintained this altitude for the entire day. However, once the sun set, both balloons quickly descended to the ground. This does not invalidate the concept of the infrared balloon; however, it shows that the MiniSHAB is likely too small to fly at night using IR radiation. Additionally, the metal powder did not adhere well to the polyethylene envelope like activated charcoal powder does, which is another likely factor for not staying afloat at night. For future work, we plan to test the same concept on larger balloons, also exploring other materials and powders.

Sandia National Laboratories conducted a series of test flights using 10 m diameter balloons, but found that they were very unreliable - either terminating before level flight was achieved (Figure **10 m time/alt**), or floating lower than expected. The cause was determined to be excessive stress on the balloon envelope, which opened longitudinal tears along the lower half of the balloon, as seen in the upward camera footage in Figure 13. In most cases, these tears then propagated upward, resulting in catastrophic failure at altitudes between about 8 and 14 km. In some instances the tears did not terminate the flight, but the excessive hot air loss through them resulted in low float altitudes. Efforts are underway to redesign these larger envelopes to better accommodate the higher stress levels.

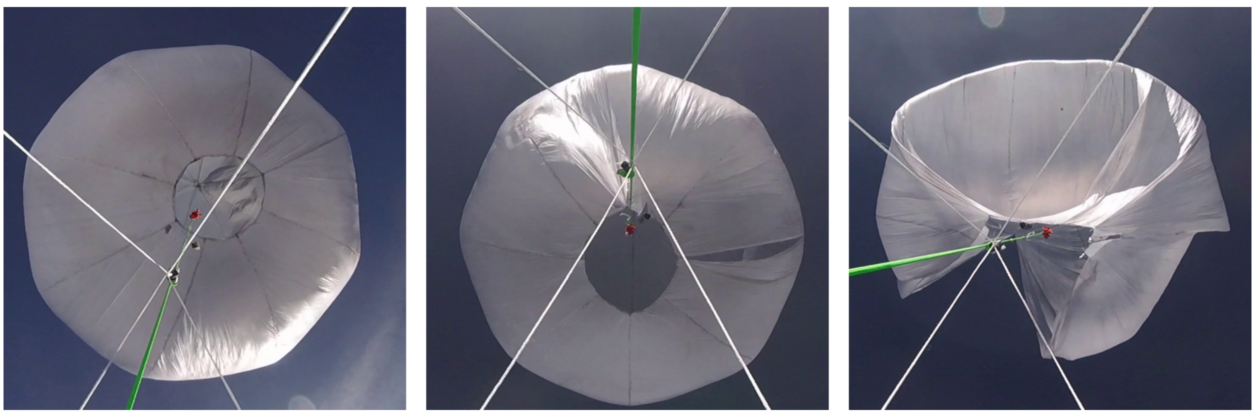


Fig. 13 Progressive failure of 10 m prototype due to excessive stress on the envelope.

C. Black Plastic SHAB Flights

BlackSHAB1 was constructed out of 1 mil black polyethylene and manufactured into the same 6m sphere heliotrope design mentioned in Section VI.A. The black balloon envelope weighed 3kg due to the thicker material instead of 1.25 kg like the same sized charcoal coated clear polyethylene balloons. Due to the heavier envelope, a stripped payload including only 2 GPS trackers was flown.

During the flight, the balloon experienced a strange phenomenon where a float altitude was never achieved as seen in 14; instead, the balloon rose and fell several kilometers 3 times throughout the flight. Unfortunately, this balloon landed in the mountains of New Mexico and could not be recovered to inspect the envelope. We hypothesize that the balloon may have rolled upside down during flight, allowing solar balloon opening to release hot air at a faster rate. Another hypothesis is that the tape lost and regained adhesion during the flight; both SHAB 3V and SHAB 4V discussed in the next section had missing gore seaming tape upon recovery.

Sandia National Laboratories also conducted a series of test flights with 0.7 mil photodegradable black plastic envelopes, with sizes ranging from 6 m to 9 m in diameter. Flight performance was variable, with most balloons landing of their own accord before sunset, but one remaining aloft until terminated via geofence. All of the Sandia test balloons balloons showed signs of the black plastic melting during the flight, as shown in Figure 15. However, this doesn't explain how the BlackSHAB1 balloon regained lift twice instead of leading to an early landing. In any case, more testing is needed to determine whether solar balloons constructed from commercially-available black plastic can sustain nominal, level flight in the lower stratosphere.

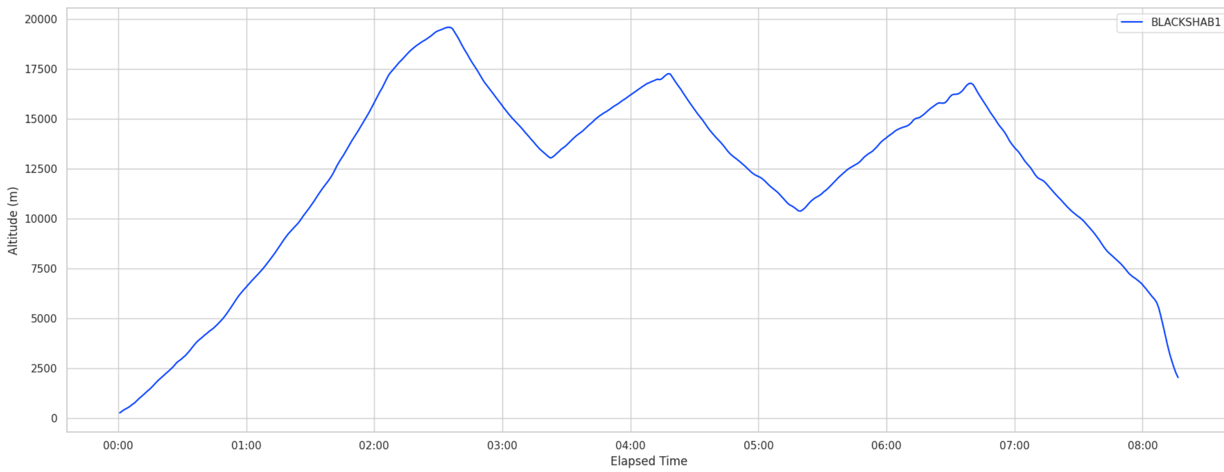


Fig. 14 6m Black Plastic SHAB Envelope Altitude Profiles

Fig. 15 Recovered Melted BlackSHAB Envelope After a Flight

D. Vented SHAB Flights

Figure 16 shows the trajectories of the three vented SHAB flights. SHAB3-V used the smaller single flap prototype discussed in Section IV and SHAB4-V used the larger double flap design. The goal of both vents was demonstrated commanding the SHAB to new altitudes. SHAB3-V was successful in remotely commanding an altitude change. However, the small vent only allowed a 1km variance in float altitude with the vent fully open. SHAB4-V included a larger vent which unfortunately failed after its initial opening. On this experiment, the vent was commanded to open instantaneously which resulted in the balloon falling apart, most likely due to the rapid change in temperature and buoyancy. Subsequent vented SHAB flights corrected this issue by opening the vent at a reduced rate.

Neither of these first two vents were recovered for post analysis (the first vent fell off during ascent, and the second vent got stuck high in a tree) but the balloon envelopes were able to be examined and showed gore seaming tape missing. There were no signs of rips or stretches in the envelope material. The hypothesis for why the balloons experienced this phenomenon was that the tape fell off after sunset when the balloon experienced sudden cold temperatures followed by record high wind speeds of over 100 mph. The most likely explanation for these instances is inadequate construction methods. Future vented balloon flights used stronger tape and better quality control during construction, preventing the issue from recurring. Future development will also consider alternative gore seaming techniques besides tape, possibly glue or heat sealing.

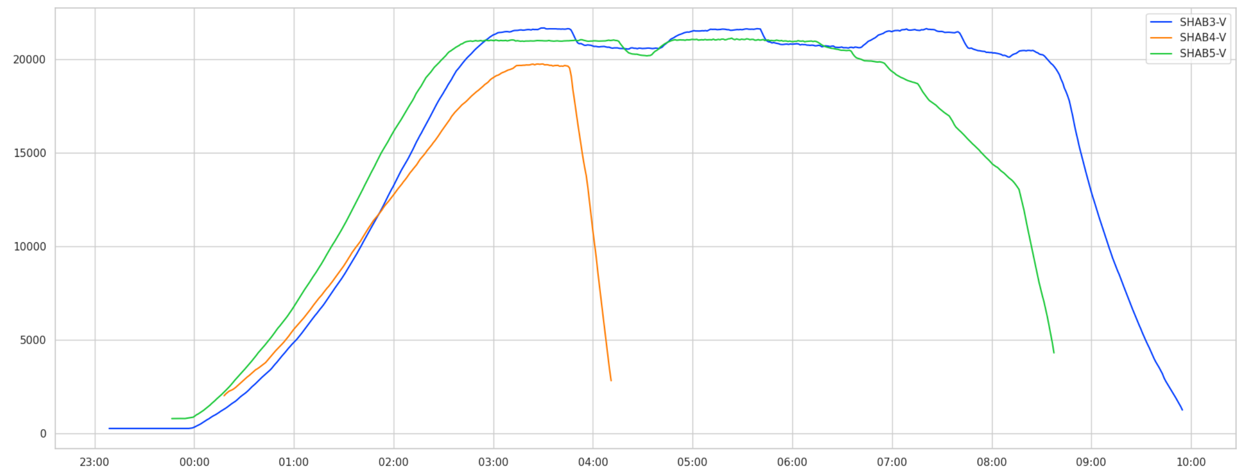


Fig. 16 Vented 6m Charcoal Coated Clear Plastic SHAB Envelope Altitude Profiles

SHAB5-V was the last significant vented SHAB flight. This balloon opened the vent in a succession of angles and showed that reaching a variety of altitudes using the vent is possible. The vent was able to open in increments, which resulted in large altitude changes. The commanded angle increments were first increased and then decreased to show the balloon was able to descend to an altitude and then reascend back to the same float altitude. Next, the angle increments were increased again to allow the balloon to descend in steps, which eventually led to the balloon descending to the ground in a semi-controlled manner (as the balloon got closer to the ground, the dynamic pressure from descent increased enough to collapse the balloon envelope). This flight showed the feasibility of using the vent to achieve a variety of altitudes, with a controllability range between 13km and float. This experiment demonstrated the feasibility of future research into further altitude control using the vents. This balloon was unable to be recovered as well, and thus no analysis was possible on the envelope or vent.

The final significant vented balloon flight was SHAB6-V. This balloon did not yield any significant data on the vent performance and was omitted from Figure 16 because it behaved like a standard free SHAB flight. This balloon flew directly over a thunderstorm, and the updrafts and downdrafts from this storm created massive altitude changes that completely overpowered any altitude changes from the vent. However, this balloon did fly over the storm safely, and continued to fly into the evening as normal, and was also recoverable. While this flight did not provide any data on the vent performance, it did show that the SHABs are able to traverse over extreme weather, with no harm to the balloon or payload, and only moderate disruption to the altitude profile. This balloon also hit a vented SHAB altitude record of 24243 m, pushed up by updrafts from the thunderstorm.

Fig. 17 Recovered Vent from SHAB6-V

The recovery of SHAB6-V also allowed for examination of a vent after flight. Figure 17 shows the vent after removal from the balloon envelope (the balloon envelope is generally tattered and shredded after landing, from dragging along the ground after impact). The vent is largely in the same shape as when constructed, but the Styrofoam is somewhat distorted and weakened. This is hypothesized to occur because, at high altitude, the low air pressure causes gas to escape from the closed cell foam. Once the balloon descends, the increasing air pressure crushes down the foam, now depleted of internal gas, causing it to weaken and buckle during descent. This results in the vent being non-reusable, but it still performs satisfactorily in flight (the increased altitude of SHAB6-V is not hypothesized to significantly increase this effect beyond the normal float altitude of the balloons).

(a) SHAB3-V

(b) SHAB4-V

Fig. 18 Aerial Photos of Flapping Vent SHAB Flights

The ascent speed of the vented balloons was slower than the unvented balloons, about 1-2 m/s, which is understandable considering both payloads were heavier and the envelope also had extra weight at the top due to the mounted vent. Aerial footage captured from a drone in Figure 18 also reveals that (at least near the surface) the SHAB envelope shapes were significantly warped during ascent due to the vent at the top of the balloons. Not only did the warping of the envelope reduce the volume of the balloon, but the absorption of solar irradiation would also be affected due to the change in effective area.

VII. Conclusion

This paper presents the results and analysis of several new solar balloon designs and materials as well as the results from flight experiments. The MiniSHAB flight experiments show that the solar balloon design can be scaled to handle various sized payloads. SHABs with black polyethylene are currently unreliable for flight experiments due to the melting plastic, so more materials need to be tested. The vented solar balloon flights show that altitude control of a SHAB is possible. With altitude control of a SHAB, we will build on this work to improve vent durability, controllability, and autonomous capabilities.

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