Lessons Learned for Tandem Launches

Mary Bowden[1], Kruti Bhingradiya[2], Daniil Gribok[3], Matthew Griffin[2],
Michael Kalin[2], Jeremy J. Kuznetsov[2], Madelaine Lebetkin[2],
Sam Maddren[2], Saimah Siddiqui[2], and Cameron Storey[2]

University of Maryland, College Park, MD, 20742, USA

The Maryland Space Grant Consortium Balloon Payload Program (BPP) run by the University of Maryland College Park (UMD) has devoted considerable effort in the last few years to developing techniques for tandem balloon launches with the objective of achieving a float configuration using latex balloons. The procedure is to launch a payload string with 2 weather balloons tied above the parachute in a Y-shaped configuration. Approximately 200m below the desired float altitude, the ascent balloon is cut free and the payloads then float on the remaining float balloon, which ideally has been filled to have exactly the lift necessary to counteract the weight of the payload string. This procedure, though very simple in concept, has proven to be surprisingly difficult to execute effectively. The UMD BPP has attempted over 17 tandem balloon flights, of which only 1 achieved a successful float (defined as having an ascent rate of less than +/- 1 m/s) but another 9 attempts came close (defined as having an ascent rate of less than +/- 2 m/s). This paper will discuss the challenges encountered, as well as the best practices developed for a successful tandem float, including necessary weather conditions, filling operation, release procedure, and cut-down devices. Lastly, this paper will provide ideas for future tandem float attempts, including a system that might prevent balloon collisions on ascent.

I. Introduction

Sounding balloon flights are launched every day for numerous reasons that include atmospheric sensing, photography, communications, and testing of engineering payloads, to name just a few. These flights generally require one helium-filled balloon, carrying one or more payloads, which upon release can ascend up to roughly 100,000 ft (30km) at a fairly constant ascent rate (~5m/s) before bursting and allowing the payloads to return to earth on a parachute. Occasionally, there are situations where it would be beneficial for the payload string to spend more time at altitude, either by floating (ascent rate ~ 0m/s) or continuing its ascent more slowly (say around 1m/s). For example, an atmospheric sensing payload that needs sufficient time at a given altitude to take data or accumulate readings would need to float fairly accurately. Additionally, a balloon flight launched during a solar eclipse would benefit from a slowing ascent rate above 60,000 ft (18 km) in order to record good video of the shadow passing across the earth's surface, and to obtain data over a sufficient time span from before to after totality.

One way to achieve a float in the balloon trajectory is to fly a tandem balloon configuration, a configuration that will be described in more detail in Section II of this paper. The concept is to lift the payloads to altitude using two identical balloons, each filled with just enough helium to float the full flight train. Sections III and IV of this paper discuss

---

[1] Senior Lecturer, Aerospace Engineering, University of Maryland College Park
[2] Undergraduate Researcher, Aerospace Engineering, University of Maryland College Park
[3] Graduate Research Assistant, Space Systems Lab, Aerospace Engineering, University of Maryland College Park

methods developed to fill the balloons accurately and release the system safely. At launch, the system has twice as much lift as it needs so it can ascend to altitude quickly; then, when the desired altitude is reached, the cut-down device under one of the balloons (the ascent balloon) is commanded to cut. Once this balloon is released, the flight train should float somewhat indefinitely on the other balloon (the float balloon), until a command is sent to cut off the second balloon. Trajectory details and flight experiences are described in Sections V and VI, followed by a discussion of lessons learned and recommendations in Section VII, and a look at some future ideas in Section VIII.

The Maryland Space Grant Balloon Payload Program (UMD BPP) has been launching balloons in and around Maryland since 2004, and more recently campaigns have been conducted in Oklahoma and Kansas. The team has launched well over a hundred flights over the years, launching 1600g latex balloons most often that are released in western Maryland and that must thread their way between numerous areas of restricted airspace to land before hitting the coast. Most of these flights have carried student payloads constructed by UMD undergraduate students, but we have also flown payloads for other colleges, some high schools, and occasional STEM groups, as well as a few graduate-level research payloads investigating such things as stratospheric turbulence and high altitude particulate matter. The team is composed of 30 or more undergraduate researchers who develop expertise in all the many aspects of the program, including payload design, launch operations, tracking, and recovery, as well as teamwork, technical communications, and lab skills. The BPP is currently gearing up to become a leading team in the Nationwide Eclipse Ballooning Project.

II. Tandem Configuration Flight Train

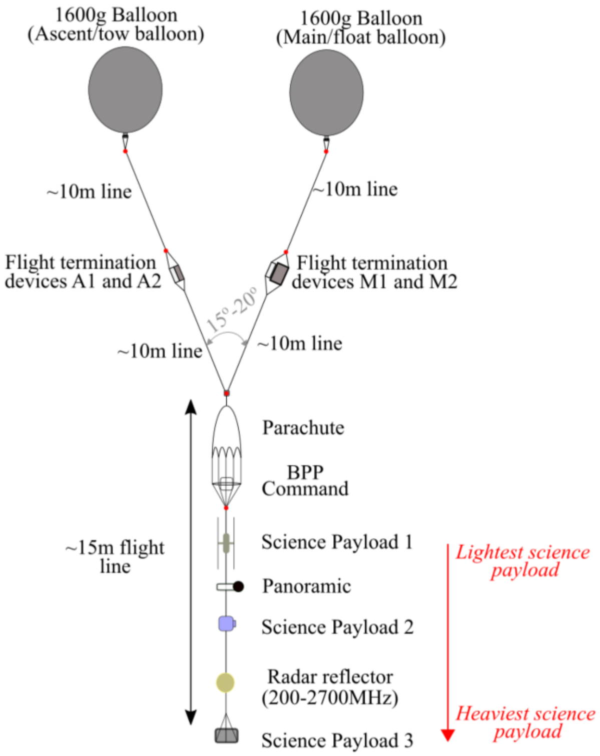


Figure 1: Flight Train configuration for a typical tandem launch; red dots indicate swivel locations

Figure 1 shows a typical flight train configuration for a tandem launch carrying a few payloads as well as a tracking module (BPP command), a panoramic camera with views both up and down (very useful for post-flight failure analysis), and a radar reflector (always a good idea). All parts of the flight train need to be accurately weighed prior to or on launch day in order to have a measured flight train weight to within a few grams ideally. Any launch pad changes, even as small as additional duct tape or flight line, should be weighed and taken into account in order to achieve as accurate a float as possible.

III. Balloon Inflation

Figure 2: Simultaneous inflation of two 1600g latex balloons - the neck of each balloon is already tied to an anchoring sandbag with an inline lift measuring scale

Helium Calculations

Once the final weight of the flight train is accurately known, along with the parameters of the float that is being attempted, helium calculations are done to determine the required neck lift in each balloon. The calculations are done in a spreadsheet which, after requiring several input parameters, iteratively solves for two neck lifts which will meet the desired float parameters while minimizing the difference in lift between the balloons. The reason the lift in the two balloons must be as similar as possible is so that both balloons can have as close to the same shape, size, and momentum as possible so they will ascend at the same rate, and one balloon will not end up dragging the other.

Helium Calculation Inputs:

1. **Launch Site Temperature** -- used for gas/lift calculations
2. **Launch Site Pressure** -- used for gas/lift calculations
3. **Desired Float Altitude** -- used for gas/lift calculations

4. **Desired Float Termination Altitude** -- used for solution validation
5. **Desired Sea-Level Ascent Rate** -- used for gas/lift calculations
6. **Balloon Brand and Size** -- affects outputs that rely on balloon manufacturer data
7. **Flight Train Mass** -- equal to target free lift at float altitude
8. **Balloon Drag Model --** toggles drag coefficient between low (.25) or high (.30)

Helium Calculation Outputs (for each balloon):

1. **Balloon Size at Launch** -- volume, radius
2. **Lift Gas Mass** -- mass of helium in balloon
3. **Free Lift** -- should be near zero on float balloon
4. **Neck Lift** -- measured neck lift of each balloon on launch pad
5. **Predicted Burst Altitude** -- based on balloon manufacturer data, ideally much higher than float altitude

As is discussed later in this paper, we consistently obtained a positive ascent rate after the ascent balloon was cut away, instead of achieving a true float (ascent rate = 0 m/s). The team intends to revisit the assumptions made in our helium calculation process to try and account for and possibly fix this effect.

Launch Pad Setup

Upon arrival at the launch site, the launchpad should be first set up prior to any other technical task for flight preparation. Choose a large, empty area outdoors to lay out two tarps. The area chosen should be an open space that is as far away from trees as possible with roughly ~128 ft^2 on level, solid ground. Two additional sheets should be laid out on top of the previous two tarps and then swept with a broom to remove any debris. From this point forward in the process, no one should step on these sheets while wearing shoes. Take the balloons while they are still in their packaging and weigh them for helium calculations. Then, while wearing latex or cloth gloves, remove the balloons from their packaging and weigh the remaining packaging to find the balloons' actual weight. Place the balloons on the now cleaned sheets and gently unroll them until they are both flat and ready for inflation, with the necks of the balloons are facing upwind.

Next, after noting the weight, for each balloon take the custom 3D printed neck insert and insert the base about 2.5 inches into the neck of the balloon. Next, wrap the paracord that connects three harness lines around the neck and above the neck insert's base for later. This is known as the tether harness. Using a flight-rated zip-tie, tie two u-loop knots on one piece of microcord and place both ends on the zip-tie. Secure the zip-tie around the neck of the balloon as tightly as possible and centered on the neck insert, and then snip off the ends with wire cutters and layer duct tape on top of the zip-tie and around the neck. Insert the ball valve into the fill hose and secure it in place using a zip-tie. Now, take a luggage scale and secure it to the microcord hanging from the neck. Luggage scales are used for monitoring the actual neck lift of the balloon throughout inflation. Next, tie a piece of paracord to the handle of the luggage scale and attach a carabiner to the opposite end. Finally, clip the carabiner to a heavy mass to anchor the balloon in place; 40 or 50 pound sandbags are a very reliable option for doing so.

Inflating the Balloon

Measure tank pressure and take tank temperature reading using an infrared thermometer on the underside of the tank. Record these two values for helium calculations and bookkeeping. Attach the inflation hose to the regulator outlet valve and connect the other end of the inflation hose to the ball valve that is attached to the neck insert. Offset the weight of the inflation hose by zip-tying it to the luggage scale. This way the neck insert tubing is not fatigued or damaged by the added weight of the inflation hose. If more than one tank of helium is needed, measure the final pressure and temperature of the empty tank and record these values for helium calculations and bookkeeping. Remove the regulator and swap out the tank for a fresh one. Re-attach the regulator using the same steps as with the first tank, and record pressure and temperature once again for the new tank. Continue to regulate the flow of helium into the balloon throughout the entire inflation process until the balloon has reached the desired lift.

Throughout the inflation process, multiple lift measurements will be taken to ensure that the balloon is approaching and has not exceeded the desired lift. This value is determined by the helium calculations as mentioned above. Before taking a lift measurement, make sure the main valve and ball valve are completely closed. This will ensure that the helium does not leak while you take the measurements. Next, detach the inflation hose from the ball valve. Taking lift measurements is typically a three-person job. Person A should lift the tether harness ring so that it is not touching the balloon, while Person B pulls the balloon down using the micro-cord harness. Then, Person C should zero the luggage scale. Once tared, Person C should indicate to Person B to slowly release the balloon back into the air. Wait for the scale to hold on a number and record this number. Repeat this process two more times for a total of three lift measurements. Take the average of the three values and cross-check this number with the helium calculator. If the current lift is lower than the desired value, continue inflating the balloon and periodically measure neck lift. If the current value is higher than the desired lift, then open the ball-valve and vent helium from the balloon and periodically measure the neck lift. Once the desired lift is achieved, record the final neck lift. Inflation is now complete.

Tying off balloon & attaching payload string

In order to send the balloon off into near space, the balloon must properly be sealed. First, remove the ball-valve from the neck insert tubing. Next, pinch the tubing near the top, twist, and then flip the bottom part of the tubing upwards. Use two zip-ties to secure the tubing in this position and place duct tape around the tubing once secured in place. The balloon is now sealed and ready for the payloads to be attached.

Figure 3: Final Adjustment of Lift

Figure 4: Balloons ready to be tied onto flight train

IV. Flight Train Assembly and Release Procedures

For the purposes of assembly, the flight train is split into two distinct sections - the assembly above the parachute and the assembly below the parachute. The detailed description and rationale of the assembly below the parachute is beyond the scope of this paper, but suffice to say, it is a continuous line of 550 paracord, terminated with figure-eight follow-through knots, and segmented with alpine butterfly knots to provide payload locking points. This is the nominal setup for both tandem and single balloon BPP flights. In contrast, the assembly above the parachute varies greatly between the tandem and single balloon flights.

For a tandem flight, the balloons are attached to the flight train and parachute through a series of long lead lines and cutdown units. The neck of the balloon has a U-shaped loop of cord attached to it, called the U-loop. This loop is attached to a 33 ft length of microcord. It terminates at the live end of the cutdown system. The fixed end of the cutdown module is followed by another 33ft length of microcord. This end is then attached to the top of the parachute with a swivel. This setup is replicated for the other balloon. A single swivel is placed immediately above the parachute to allow both balloons to rotate about each other, and not tangle the line. The rest of the connections are made with quick links.

Flight train assembly is straightforward, and follows typical assembly methodology: determine the necessary lengths of line, determine the type of connection points needed, and finally cut and tie the line. Typically everything is assembled as soon as possible on the pad, save for the final attachment of the flight train to the balloons. This is done to prevent personnel from accidentally tangling or stepping on the flight line.

One of the release methods employed for a tandem launch utilizes tether lines to raise the balloons until the entire flight train is off the ground. The tethers are then cut, and the flight train begins a free climb upwards. This method results in a much smoother walk-up sequence, and less shock load on the cutdown hardware and neck inserts. However, this method requires additional hardware and preparation.

Starting from the balloons and working downwards, first a metal ring is placed onto the U-loop integrated with the neck insert. This ring will act as a pulley for the tethers, and will be lost with the balloon if a cut-down system severs the main flight-line. Since the tether needs to slide smoothly through this ring, welded or rolled rings should be used. Alternately, a quick link could be used with the added benefit of being able to add it to an already taped and inflated balloon neck assembly, providing a backup option in the event the ring insertion step was missed during initial neck insert assembly. Regardless of which ring is used in the U-loop, the remainder of the flight train is assembled as usual for a tandem flight.

The second part of a tethered release assembly is the tethers. Each is a 200 foot length of 330 paracord, wrapped around a spool. One tether (and consequently one spool) is used per balloon that needs to be raised. Each tether is handled by two people. One person holds the end of the tether with the spool (referred to as the dynamic end) and the other holds the non-spooled end (referred to as the static end). The static end of the tether should be fed through the metal loop hanging from the U-loop of the neck insert. Typically this is done after inflation is finished to reduce the amount of loose cordage near the neck of the balloon during inflation. The static end should then be held firmly by the second person or possibly even be tied to them. The operator at the dynamic end should attach the tether spool to themselves so that it can freely spin when it comes time to raise the balloon by paying out the line.

Walk-up consists of 4 major stages: Load transfer to the tether; detachment of anchor line; walk-up; and release. Load transfer occurs first, where both the tether operators approach the anchor line, and with the assistance of a third person, tension the tether line such that the main anchor line to the sandbag goes slack. The third individual should then unclip the anchor line from the U-loop. This process should ideally happen at the same time for both balloons, with two tether handlers on each balloon. While transitioning to walk-up, the operators should separate an approximate distance of 10 to 20 feet, and the operator at the dynamic end should begin paying out the tether line. A spotter with a good view of the relative heights of the two balloons should instruct the tether handlers to speed up or slow down, such that the balloons rise at the same rate. Payout of the tethers should continue until the entirety of the flight train is off the ground. Once everything is in the air, a final check of tracking and comm systems should occur, as well as a check of airspace. Once the launch director has given the go-ahead for launch, a countdown is called out so that the static end of the tether can be cut and released simultaneously for both balloons. If for any reason, the tether line gets tangled or snags, the operator at the dynamic end should cut their end off to allow the tether to go up with the balloon, which is a far better outcome than holding one of the balloons back.

While a tethered walkup provides many benefits, the program has traditionally used a manual walk up method that involves handing the flight line directly. This method requires virtually no setup, but requires a lot of physical exertion (particularly upper body and grip strength) from the personnel involved. The process starts with at least one person per balloon putting on high quality belay gloves. The flight train is then clipped to the balloon U-loop, and the personnel involved with walk-up grab the fight train, and pull it down gently so that the anchor line for the balloon is slack. The anchor line is then unhooked from the sandbag, and cleared from the area. From this point forward, the only thing keeping the balloons from ascending is the grip strength of the personnel holding the fight-line. Note that they will have to hold the full lift of each balloon at least, and then the combined lift of both balloons once below the parachute, and the load can be even larger if there is any wind. This large load, combined with the small diameter of the paracord and low friction, makes it very difficult to hold.

To start the ascent, one person on each balloon will slowly let the line slip. This should be done simultaneously for each balloon, and a spotter should direct each person to go faster or slower, such that the balloons rise at the same rate. Upon reaching the cutdown unit, ascent should stop, and the line slowly tensioned below the unit so that it slowly takes the load. Ascent continues until the personnel meet at the parachute. Care should be taken to avoid the balloons colliding if possible. At the parachute and below it becomes infeasible to slide the line though your hands, so a leapfrog approach is taken. One person grabs the flight-line with their hands and then raises them. Once they have raised their hands to about head-height, another person grabs the free end of the fight train below, and slowly takes the load off the previous person. Once the load has been fully transferred, the person holding their hands above their hands lets go, and steps away. The other person can now slowly lift their hands, and the process is repeated until the end of the flight line is reached. At that point, standard pre-release checks for communications and tracking can be conducted, and the flight released.

Note that all the operations described above can generally proceed in a deliberate and careful manner if the winds are light or negligible. If the wind picks up and conditions get gusty, however, this process becomes increasingly problematic and risky with the possibility of bursting a balloon or damaging a payload before the flight train is released. Also, when doing a manual walk-up of a flight train this long, the balloons will be downwind by the time the release team is holding the bottom payload if there is any significant breeze. Releasing that bottom payload will then result in a pendulum swing that drags the payload along the ground until the balloons gain altitude. So, even more than for single balloon launches, it is essential to have good weather for tandem flights. In relatively calm conditions, the balloons tend to stay apart once they have established a steady ascent rate.

V. Trajectory

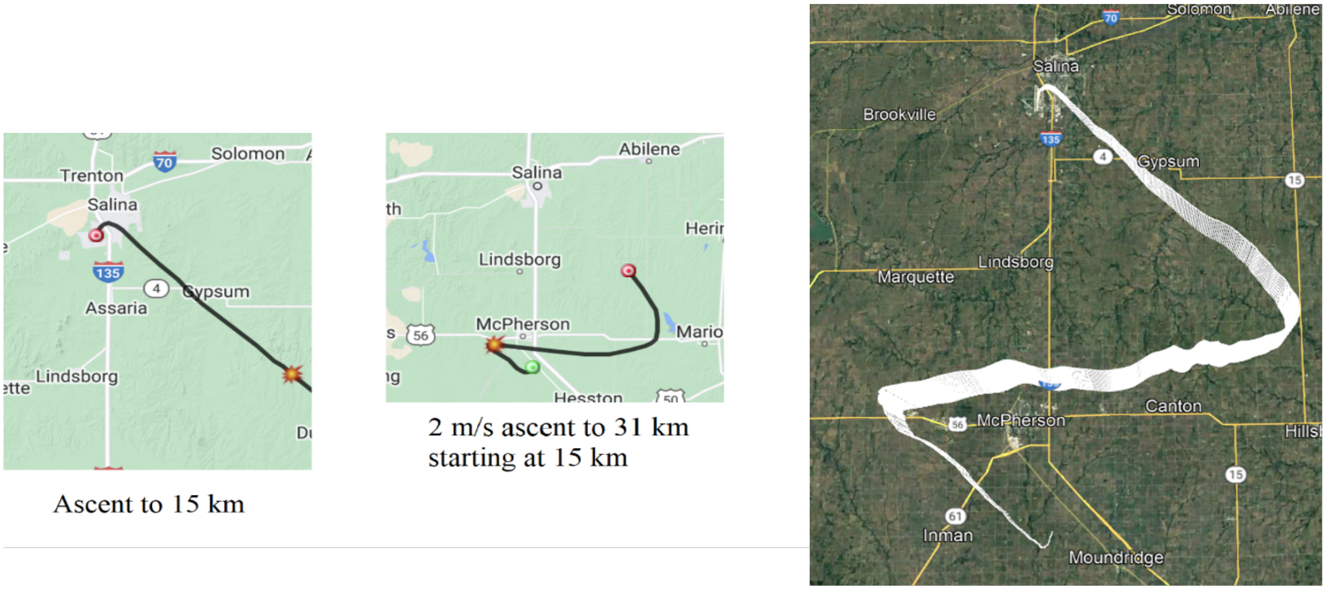
Trajectory Prediction

The team has reliably used http://predict.habhub.org/ for float trajectory predictions. Although there is not a “float” trajectory prediction built into the website, it is easy to perform a prediction using two separate single balloon trajectory predictions:

1. Run a prediction for a single balloon flight from the launch site with the burst altitude set to the desired float altitude. The ascent rate should be set to the predicted ascent rate during the tandem ascent phase. The descent rate does not matter

2. Pull the coordinates of the burst from the first prediction and use those coordinates as the launch site for the second prediction. Be sure to set the launch altitude to the desired float altitude. Perform a second single balloon prediction from the new ‘launch’ site using the predicted float ascent rate. Set the burst altitude to the altitude that corresponds to the predicted float ascent rate times the desired float duration (ie. a 1 m/s float for 1 hour will result in a burst altitude that is 3600m higher than the float altitude). Use a standard descent rate.

Float trajectories predicted using this process the morning of the launch have generally been fairly accurate assuming the tandem balloon flight train actually reaches the float altitude and successfully releases the ascent balloon. An example of this technique and the resulting actual flight path is shown in Figure 5, demonstrating remarkably good agreement.



Ascent to 15 km

2 m/s ascent to 31 km starting at 15 km

Figure 5: (left) Predicted flight trajectory with 2 step process; (right) actual tandem flight trajectory with float phase (BIRDIES-09)

Tracking

Balloon tracking is accomplished using standard methods. Two APRS transmitters (either Lite-APRS [https://github.com/lightaprs/LightAPRS-1.0] or StratoTrack [https://www.highaltitudescience.com/products/stratotrack-aprs-transmitter]) are flown with offset transmit timing. A Rockblock 9603[https://www.adafruit.com/product/4521] with a custom flight computer board is used for two-way satellite communication with the balloon using the Iridium network. Finally, a SPOT Trace [https://www.findmespot.com/en-us/products-services/spot-trace] is used as a reliable backup locator system, especially post-landing. During ground testing, the team's in-flight tracking systems have been shown to function for over 12 hours before running out of power. This is enough to make us confident that our systems will remain functional for any reasonable duration float we attempt. We also transmit battery voltages as a part of our in-flight telemetry to allow for monitoring of power status during float attempts. Another useful telemetry value to have during tandem flights is an on-board ascent rate calculation. With ground derived ascent rate calculations being prone to error due to skipped packets and erroneous data, an ascent rate value within the telemetry stream is a welcome secondary source of trajectory information. See Figures 6, 7, and 8 for an example of a good flight profile with a significant float phase, and graphs showing downlinked ascent rate data.

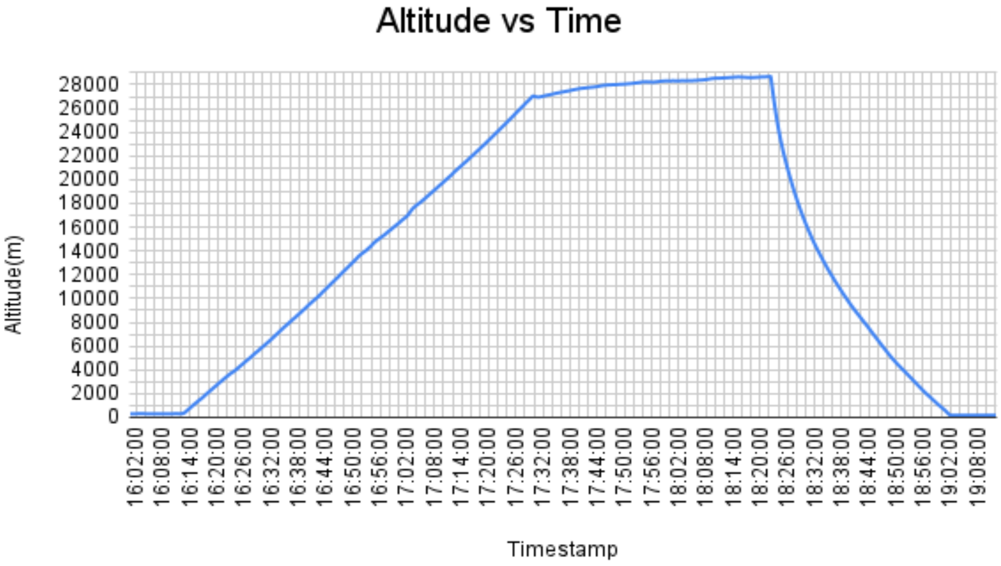


Figure 6: Sample Float Flight Profile, NS-108

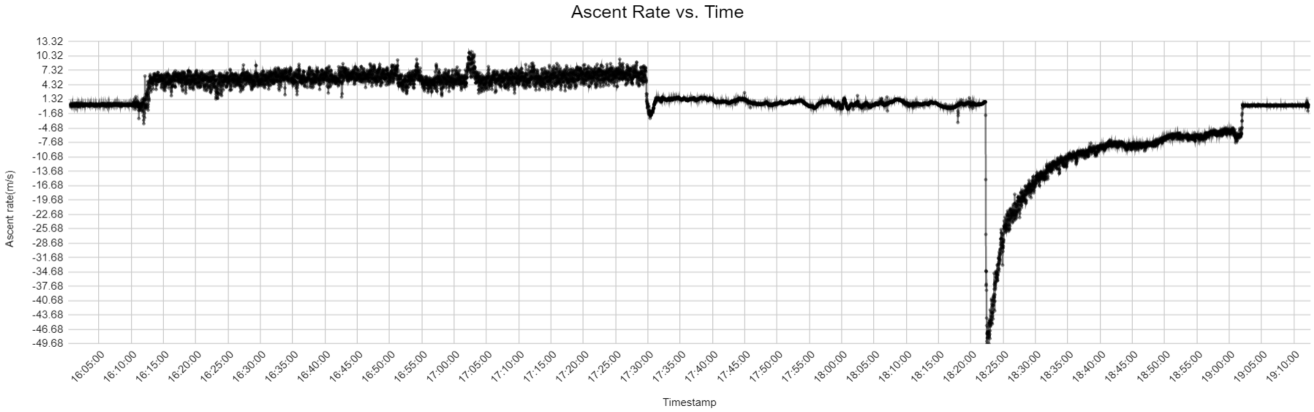


Figure 7: Ascent rate plot, NS-108

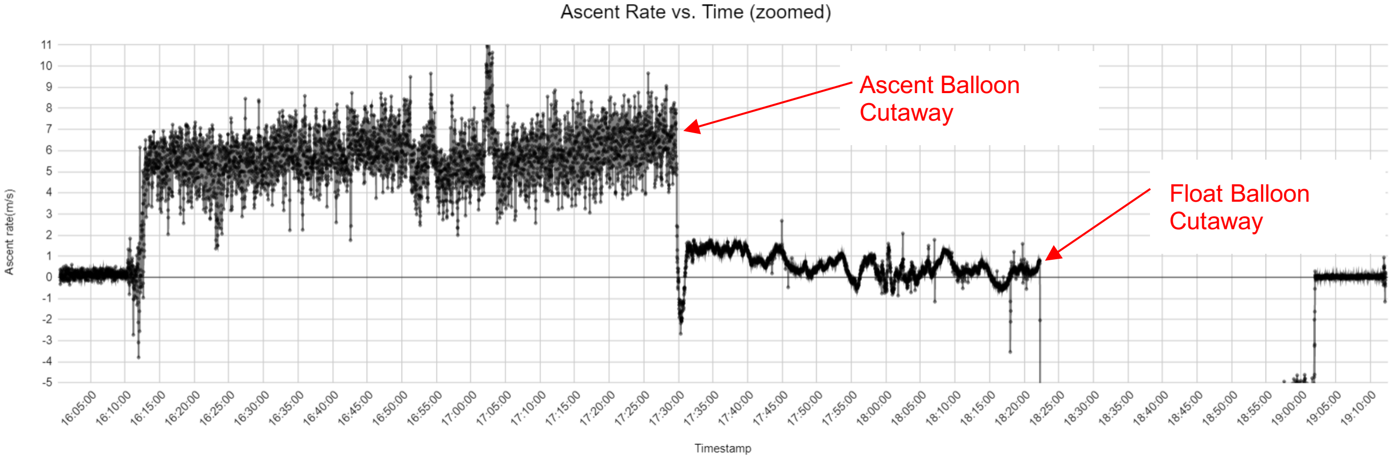


Figure 8: Ascent rate plot, NS-108, zoomed in

Cutdown System

The team has used Loonatec High-Altitude Balloon Bounder systems [https://loonatec.com/product/bounder/] as its main cutdown units throughout its experience with tandem balloon flights. These cutdown units can be programmed with multiple triggers that will terminate the flight in the case that any one of them is activated. The triggers that we use are:

- **GPS altitude** -- triggers a cutdown when specified altitude is reached as measured by GPS
- **Timer** -- triggers a cutdown after specified time has elapsed (countdown begins at device power-on)
- **Geofence** -- triggers a cutdown when balloon exits specified flight zone (flight zone is rectangle specified with two lat/long corners)
- **GPS ascent/descent rate** -- triggers a cutdown when specified ascent rate is measured (based on rolling average of change in GPS altitude)
- **External trigger** -- triggers a cutdown if the measured voltage of a specified pin drops from high to low

In the future, it would be beneficial to modify the implementation of the timer trigger. Since the cutdown units have to be powered on prior to being tied-in, and since unexpected holds can occur on the launch pad, the cutdown timer needs to be padded with margin to account for launch delays. If the timer could instead be set to begin counting down once a certain altitude is reached, the team could set cutdown times much more predictably. We fly two cutdowns on each balloon in a redundant configuration such that the triggering of either cutdown will cut the balloon away. If manual flight termination capability is required on either balloon, we fly a cutdown in a modified housing that contains the hardware required to receive a command from the ground and send an external trigger to the device. This system is discussed further in the "Float Termination" section.

Float Initiation

Setting the cutdowns for float initiation is very simple. The altitude trigger on the cutdowns for the ascent balloon is set to trigger at ~200m below the desired float altitude. The other triggers are set to trigger in contingency cases. For example, the timer trigger is set so that the ascent balloon will cut away shortly after the time the flight train is expected to reach the float altitude (based on predicted ascent rate) regardless of whether the float altitude has actually been reached. The GPS descent rate trigger is set to trigger a cutaway in the case of a negative ascent rate because a negative ascent rate being measured on the ascent balloon cutdown means a failure has occurred. A manual cutdown unit could also be used on the ascent balloon to deal with contingencies, but this has not yet been implemented.

Float Termination

Flight termination capability is critical in the case of a successful float. Without the ability to command (either pre-launch or in real time) the end of the float there is no way of guaranteeing a successful recovery of precious payloads. There are two main flight termination methods that have been used successfully by the team during tandem balloon flights. One method is set-and-forget, and relies on pre-launch predictions about the balloon's trajectory. The other method is directly commanding the termination from the ground, but this requires a more complex set of hardware.

- **Set-and-Forget**: This method involves specifying all of the cutdown trigger parameters before flight based on the predicted trajectory of the balloons. Assuming that the ascent balloon will successfully cut away at the specified float altitude, the float balloon triggers are set in the following way:
  1. **GPS altitude** -- The GPS altitude trigger is set by calculating the altitude the balloon will reach after floating for the desired amount of time at the desired float rate

     Eg. Float at 27 km at .5 m/s for 1 hour, 27000 [m] + .5 [m/s] * 3600 [s] = 28800 [m]
  2. **Geofence** -- The geofence is set based on the predicted ground track during the float

Eg. Based on ground track predictions, after floating for 1 hour at 27 km, the payloads will cross -77.0781° longitude, so set -77.0781° as the eastern border of the float balloon geofence

3. **Timer** -- The timer is set based on the predicted duration of the ascent and float, plus some margin

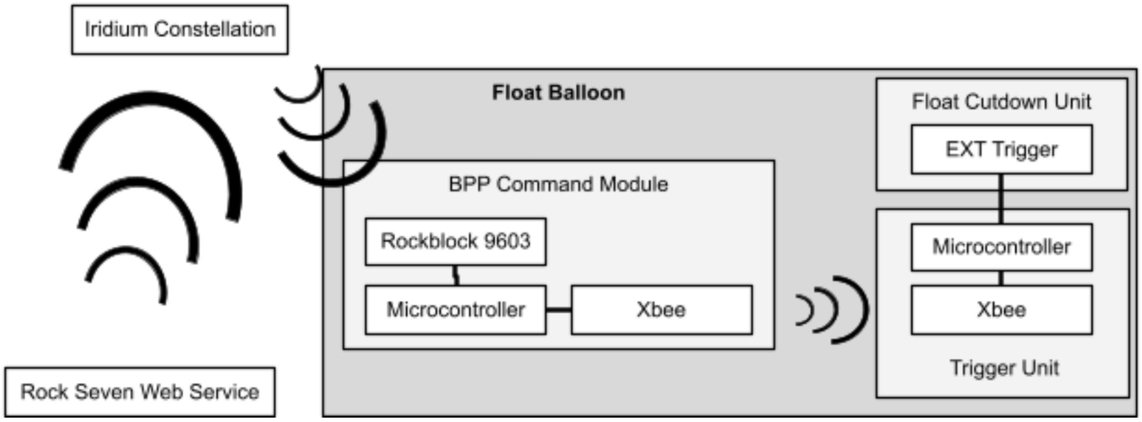
   Eg. Ascend to 27 km at minimum of 5 m/s, float for 1 hour, and add 30 mins of margin,

   `27000 [m] / 5 [m/s] + 3600 [s] + 1800 [s] = 5940 [s] ≈ 100 [min]`

4. **GPS ascent/descent rate** -- The ascent rate trigger is set to trigger in the case of a high descent rate after ascent balloon cutaway, because float ground track predictions can no longer be relied on and the float balloon may not burst if it is descending.

The set-and-forget method works surprisingly well. Trajectory predictions are very accurate within 12-24 hours of launch and it is quite easy to design a safe and precise float trajectory by tuning each of the cutdown triggers accordingly. This method was used exclusively during the BIRDIES flights outlined in Table 1.

- **Manual Cutdown**: For flights utilizing manual float termination, the cutdown units are set in mostly the same way that they would be if using the set-and-forget method. Since there is the option to cut down manually at any time, less conservative estimates can be used when generating the set-and-forget trigger parameters. In order to implement a manual cutdown system, one must be able to send signals to the balloon from the ground during flight and a way to relay that signal to the float balloon cutdown unit. For manual float termination BPP uses the following system architecture:



This system has been quite reliable in ground testing. It has not been exercised very many times in flight, but when it was used it was successful. This system also is designed to fail safely, as the external trigger pin of the cutdown unit is set to trigger on a low voltage. In the event that the trigger unit suffers a loss of power, the cutdown unit will cut away. For more information about Xbee radio modules, see https://www.sparkfun.com/pages/xbee_guide.

VI. Tandem Launch Experience

					Target	Actual	Float	
Flight	Date	Balloon	Ascent Rate	Float Rate	Float Altitude	Float Altitude	Time	Comments
		(1600g)	(m/s)	(m/s)	(m)	(m)	(min)	
NS-93	8/22/20	Hwoyee	6	–	22,900	–	–	Ascent balloon burst early ~ 20,100m
NS-95	11/7/20	Hwoyee	4	–	20,000	–	–	Ascent balloon damaged due to bird strike immediately after launch, slow ascent rate caused timer to trigger cutdown at ~19,000m
NS-96	3/21/21	Hwoyee	5	–	24,500	–	–	One balloon damaged by string of the other ~ 3,660m
NS-98	6/12/21	Hwoyee	3	–	23,800	–	–	Ascent balloon damaged ~ 12,800m
NS-99	7/10/21	Hwoyee	5	-2.5	23,500	23,200 - 16,200 (descending)	45 min	Ascent balloon burst just below target altitude
NS-101	7/24/21	Hwoyee	3	–	23,100	–	–	Slow ascent rate due to leaking float balloon, geofence triggered cutdown early ~12,200m
NS-103	10/2/21	Kaymont	4	1.5	23,500	23,500 - 27,400	80 min	Float balloon had slightly too much lift
NS-107-OK	12-Jan-22	Kaymont	6.1	1.3	23,000	22,400 - 26,000	30 min	Ascending float until burst
NS-108-OK	13-Jan-22	Kaymont	5.7	0.5	27,000	27,000 - 28,700	53 min	Excellent float for almost an hour
NS-109-OK	16-Jan-22	Kaymont	6.2	1.9	24,000	24,000 - 28,200	82 min	Ascending float until burst
BIRDIES-04	5/31/22	Kaymont	6.1	2.0	23,000	8,200 - 14,700	–	Swivel failure at 8,206m, ascending float until geofence
BIRDIES-05A	2-Jun-22	Kaymont	6.4	1.4	23,000	7,850 - 17,700	118 min	Swivel failure at 7,853m, ascending float until geofence
BIRDIES-07A	7-Jun-22	Kaymont	–	–	23,000	–	–	Ascent balloon failure at < 1,000m
BIRDIES-07B	7-Jun-22	Kaymont	6.2	1.5	23,000	23,100 - 26,400	38 min	Ascending float at altitude
BIRDIES-08	9-Jun-22	Kaymont	5.8	–1.8	22,000	22,100 - 22,000	–	Descent rate trigger activated due to larger than expected descent rate immediately following ascent balloon cutway
BIRDIES-09	11-Jun-22	Kaymont	6.4	1.3	20,000	20,100 - 27,300	93 min	Ascending float at altitude until burst
BIRDIES-10	12-Jun-22	Kaymont	6.3	1.6	15,000	15,100 - 25,000	104 min	Ascending float at altitude until burst

Table 1: Summary of BPP Tandem Balloon Launch Experience

Several of these flights were unable to achieve a float due to balloon systems failing. Premature cut-downs and swivel failures denied us the ability to evaluate our float balloon's performance at the target altitude. Premature balloon bursts which occur before the targeted float altitude is reached, also make it impossible to know whether we would have floated as predicted or not. Early burst failures have been caused, almost exclusively, by damage to the ascent balloon during ascent, especially after collisions with the float balloon and the flight-line, which have been observed shortly after release and in video footage during flight. Ascending float configurations, on the other hand, generally occurred if the float altitude was reached and the ascent balloon was successfully cut-away. In most cases, the ascent rate was between 1m/s and 2m/s – whether this can be considered successful or not would depend entirely on the nature of the payload being lofted. For a payload that simply needed to loiter at altitude (for example for providing streaming video during a solar eclipse), that level of float precision would probably be sufficient. However, for a payload that needed to ingest large quantities of air at a precise altitude, the float rate would have to be considerably lower.

VII. Lessons Learned and Recommendations

Suitable weather conditions

One of the most evident and, in retrospect, obvious lessons learned from our experience attempting tandem launches is that calm weather is essential for a successful launch and flight operation. High winds can disrupt the inflation process, will inevitably lead to inaccurate lift measurements, stress the balloons excessively during the tie-on and walk-up process, and result in numerous collisions between the balloons and possibly other flight train hardware at the time of release or thereafter. Our recommendation would be to postpone a tandem launch if wind predictions at the launch site are any higher than 6 mph steady and/or 12 mph gusts, and less wind is significantly better. As with any launch system, there may be significant pressure to perform a tandem launch in sub-optimal weather conditions, but this is ill-advised and unlikely to be successful. It is in part for these reasons that we would not recommend using the tandem approach to achieve a float or near-float trajectory during a solar eclipse - the launch window is too tight, the weather is too unpredictable, and the stakes are too high.

Reliable Hardware

Another very simple conclusion that can be drawn from Table 1 is that the make/brand of the balloon appears to matter significantly. For the first 6 launches, Hwoyee balloons (from Scientific Sales, Inc.) were used and only one flight made it to altitude; for the other 5 flights, one of the two balloons appeared to burst early, well below the float altitude. Kaymont balloons were then used for the rest of the launches and showed significantly more reliability, with only 1 flight compromised due to an early balloon failure. Kaymont balloons tend to be more spherical at launch, and they have a smaller diameter neck which is easier to interface with both for inflation and for attaching the flight line.

There is a lot of room for variation in the number of swivels used, the placement of the cut-down units, and the lengths of line used between the parachute and each balloon. For example in our earliest tandem attempts, we placed the cutdown unit for each balloon almost directly under it (within about 0.5m), but then when it seemed like one balloon might be contacting the cut-down below the other balloon (although there really weren't any sharp edges anywhere), the cut-downs were moved to half way between the balloons and the parachute (so about 10 m below the neck of the balloon). This is the configuration we continued using throughout even though it was never clear that modifying the position made any difference.

Of much greater importance, but recognized only later in these flight efforts, was the placement, number, and strength of the swivels. Initially, swivels were placed just below the balloon, above and below each cut-down unit and immediately above the parachute. These swivels were rated for a tension load of 71 lbs but unfortunately, after swivel failures on two subsequent flights, it became clear that they could fail at a much lower load (around 15 lbs). This happened if they became misaligned with the tension force in such a way that there was a bending load also acting on the swivel which opened it up and pulled it apart at the joint. Once the swivels were identified as a weak link, they were replaced with stronger ones and the swivels below each cut-down unit were removed as unnecessary. See Figure 1 for a diagram of the later swivel placement.

Reliable Inflation Process

Successful tandem balloon flights rely heavily on helium fill calculations and the inflation process prior to flight. Currently, our inflation calculations output a target neck lift in pounds for both the ascent balloon and the float balloon. The inflation team tries to inflate both balloons such that the measured neck lift is as close as possible to the calculated target neck lift. These measurements, however, are quite difficult to do consistently as there are a multitude of perturbing factors that come into play during a real-world balloon launch scenario. In our experience, small wind gusts cause large changes in measured lift, thermal effects can cause measured lift to increase during long holds on the launch pad, and in a dynamic launch environment it is often difficult to account for the effect that necessary tethers and inflation equipment have on measured lift when attached to the balloon.

The use of a mass flow meter to directly and accurately measure the mass of helium within the balloon during inflation has been proposed as a supplement to (and hopefully, in the future, a replacement of) the current neck lift measurement system. The neck lift target that we calculate for inflation can also be expressed as a mass of helium at a specific pressure and temperature. It is unlikely that simply filling the balloon with this calculated mass of helium will immediately result in achieving perfect floats. However, the mass flow meter will allow us to build a dataset of inflation data that we know is consistent and reliable across different launches. It is our hope that with this dataset we will be able to refine our inflation model and gain more intuition about inflating the balloons.

Reliable Release Methods

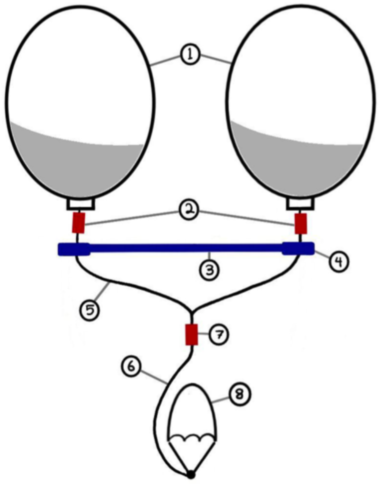
All of the tandem launch attempts listed in Table 1 were released using a manual hand-over-hand walkup procedure. While this method can be made to work, it is stressful on the balloons, cut-downs, and any other high load, low strength element in the flight train because of the stop and go nature of the process. If the tethered release process, described in Section IV, were used instead, the expectation is that raising and releasing the flight train could be a much smoother procedure and may also be able to hold the balloons upwind until they can be released without swinging the payloads. It is recommended that this type of release be further developed and tested particularly for long and heavily loaded flight trains.

It should be noted that many of the problems we have encountered with these tandem launches may be due to the fact that we have been attempting to launch and float fairly heavy payloads (on the order of a few kilograms) and the flight trains have generally been very long in order to lower the payload well below and out of the wake of the balloon at float. Some of our tandem flights have been launched with a flight train (balloons to bottom payload) over 50m long which, in some cases, would extend in flight to over 200m long thanks to multiple unwinders hooked up in series. It is unclear why the high-weight and long-length flight train would compromise the system, but it may just be that the higher loads and more stressful configuration pushes the capability of these balloons. Lighter weight payloads flown on smaller balloons by other teams have demonstrated on numerous occasions that the concept is sound.

VIII. Ideas for Future Launches

Tandem balloon collisions during release or on ascent may harm the integrity of both balloons, potentially leading to a premature burst. A system that may prevent balloon collisions is pictured in Fig.9 . This system separates the tandem balloons using a lightweight structural member (3) at a distance greater than the diameter of either balloon at float altitude. This is an important consideration, since the balloons expand considerably throughout their ascent. The primary connective flight-line (5) is joined to the ends of the structural member (4) and forks in two, to aid in level flight. If this assembly were to tilt significantly before the ascent balloon is released, some balloon collisions may still occur. A balloon is released by triggering its respective primary cut-down module (2). The recovery line (6) attaches the structural member below the parachute so that, after float termination, the member will not fall on, puncture, tangle, or collapse the parachute during descent.

If either primary cut-down module (2) fails, the backup cut-down module (7) may be triggered to begin descent of the entire payload line. It is important to note that this would cause the loss of both primary cut-down modules and the structural member. However, the ends of the structural member are bulbous and padded to slow the member's descent in freefall and to cushion its landing. The emergency cut-down redundancy is optional, and more complicated configurations could compensate for primary cut-down module failure without losing the structural member. Also pictured on the right in Fig 9, is a representation of this system after the ascent balloon is cut away.



1	Latex balloon(s)
2	Primary cut-down modules
3	Lightweight structural member
4	Structural member padded end(s)
5	Primary connective flightline
6	Recovery line to retain structural member
7	Emergency cut-down module
8	Parachute

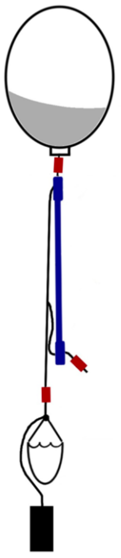


Fig. 9 - (Left) Proposed Balloon-Separator System for Collision Mitigation on Tandem Flights; (Right) System after release of ascent balloon

The largest constraint to this design is its weight, as the structural member would need to be 10m or longer to properly separate two 1,600g balloons at their float altitude. As an example of the current state of balloon separators, the company JP Aerospace has successfully launched their "microtandem" platform which weighed 6kg with the inclusion of payloads, and which used a hollow-tube structural member as its separator. By implementing a lightweight wound composite truss technology, such as the one developed by the University of Maryland Rotorcraft Center as part of its effort to build a human-powered helicopter, the weight of the structural member could be reduced significantly. An example of a wound composite truss is pictured in Fig. 10. Based on extrapolated test data[3][4], a structural member of this style at 10m in length, able to withstand over a 100N axial load in buckling, would need to have a linear mass density of approximately 50g/m. This means that the balloon separator truss could weigh as little as 500g for typical tandem applications, and a bit more with added padding. The 100N load estimate is simply based on the typical lift of an ascent balloon, with the assumption that it is unlikely the two balloons will produce forces towards each other in excess of their lift. Further design and development will be necessary to build such a structure, integrate it into a workable flight system, and assure that it is safe to fly.

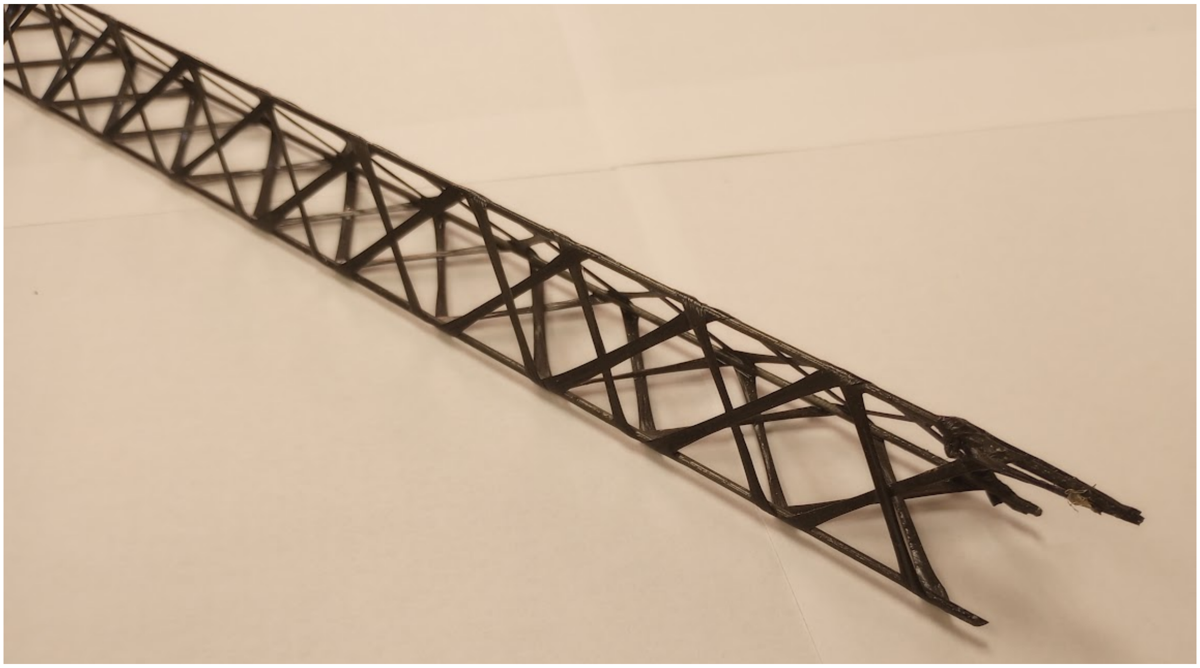


Fig 10 - Gamera composite wound truss using string dipped in resin
(this triangular truss has longerons that are spaced roughly 1 inch apart)

Acknowledgments

The authors would like to acknowledge the Maryland Space Grant Consortium for its support of the UMD Balloon Payload Program over the last 18 years. We would also like to recognize Lawrence Livermore National Laboratory for funding the payloads and the tandem launch campaigns in Oklahoma and Kansas. The Team owes thanks to colleagues in the Space Systems Lab, run by Dr. David Akin, in the Aerospace Engineering Department of the Clark School of Engineering at the University of Maryland. And most of all, we would like to give full credit to Dr. Shaun Skinner, previously a post-doc in the High Speed Aerodynamics and Propulsion Lab at UMD, who raised the bar and personally developed numerous techniques for high accuracy balloon launches.

References

[1] Andreas Kräuchi, Rolf Philipona, Gonzague Romanens, Dale F. Hurst, Emrys G. Hall, and Allen F. Jordan, "Controlled weather balloon ascents and descents for atmospheric research and climate monitoring," *Atmospheric Measurement Techniques*, Atmos. Meas. Tech., 9, 929–938, 2016 www.atmos-meas-tech.net/9/929/2016/ doi:10.5194/amt-9-929-2016

[2] Matthew Griffin, et al., "BIRDIES Launch Operations Technical Report" for Kansas Launch Campaign, June 2022

[3] Benjamin Woods, Ioan Hill, and Michael Friswell, "Ultra-Efficient Wound Composite Truss Structures," in *Composites Part A - Applied Science and Manufacturing*, June 2016.

[4] Nagaraj, Vengalattore T., et al. "*Gamera: A Human Powered Helicopter*," American Institute of Aeronautics and Astronautics, Inc., 2021.