Flight Analysis of an Autonomously Navigated Experimental Lander for High Altitude Recovery

Jeffrey Chin[1], Justin Niehaus[2], Debra Goodenow[3]
NASA Glenn Research Center, Cleveland, OH 44070

Storm Dunker[4], David Montague[5]
Airborne Systems, Santa Ana, CA, 92704

First steps have been taken to qualify a family of parafoil systems capable of increasing the survivability and reusability of high-altitude balloon payloads. The research is motivated by the common risk facing balloon payloads where expensive flight hardware can often land in inaccessible areas that make them difficult or impossible to recover. The Autonomously Navigated Experimental Lander (ANGEL) flight test introduced a commercial Guided Parachute Aerial Delivery System (GPADS) to a previously untested environment at 108,000ft MSL to determine its high-altitude survivability and capabilities. Following release, ANGEL descended under a drogue until approximately 25,000ft, at which point the drogue was jettisoned and the main parachute was deployed, commencing navigation. Multiple data acquisition platforms were used to characterize the return-to-point technology performance and help determine its suitability for returning future scientific payloads ranging from 180 to 10,000lbs to safer and more convenient landing locations. This report describes the test vehicle design, and summarizes the captured sensor data. Various post-flight analyses are used to quantify the system's performance, gondola load data, and serve as a reference point for subsequent missions.

I. Introduction

Planetary science missions often send payloads to near space using balloon gondolas for a fraction of the cost of rockets. These balloon gondolas, however, are usually not reusable after their mission. Expensive flight hardware frequently impacts the ground with high velocities and can sometimes land in inaccessible areas that make them difficult or impossible to recover. A substantial cost and effort savings can be realized by guiding the balloon gondola or its' experiments to a convenient specified location, away from hazards, after the mission is complete.

Figure 1. GPADS traditionally deployed from aircraft.

The flight test is collaboration between engineers at NASA Glenn Research Center (GRC), the Columbia Scientific Balloon Facility (CSBF), and Airborne Systems (AS) as a first step towards qualifying a GPAD system for subsequent scientific missions. The parafoil canopies and Airborne Guidance Unit (AGU) have an expansive flight history for commercial and military missions, typically deployed from around 25,000ft via static-line cargo plane drops. GPADS of this scale have never been tested, and scientifically documented, from altitudes of 108,000ft, where the atmosphere is significantly colder and less dense. This flight seeks to characterize the performance of a GPAD system under these harsher environmental conditions and rapid descent speeds. The on-board avionics will monitor the condition of both the navigation system and the payload it carries.

[1] Aerospace Engineer, Propulsion Systems Analysis Branch, Mail Stop 5-11, AIAA Member
[2] Aerospace Engineer, Combustion Physics and Reacting Processes Branch, Mail Stop 77-5, AIAA Member
[3] Electrical Systems Engineer, Diagnostics and Electromagnetics Branch, Mail Stop 86-5
[4] Parachute Systems Engineer, Airborne Systems, CA, US, AIAA Member
[5] Senior Software Engineer, Airborne Systems, NJ, US

The ANGEL system consists of the drogue, parafoil, AGU, and the Balloon Flight System payload (BFS) subsystems, where the first three form the GPAD system. The individual components and systems overview, as packed, are illustrated in Figure 2.

This document describes the post-flight data analysis of the information gathered by the ANGEL avionics platform. This data is used to validate engineering analyses, document lessons learned, and act as reference data for future flights where GPAD systems could provide appreciable benefits. The stored data is used to verify thermal and structural models, as well as validate electrical power system and telemetry performance. The information also serves to measure the gondola's descent stability and characterize the parafoil performance. The on-board data acquisition platform recorded environmental conditions, measuring the avionics performance and verifying expected impact forces.

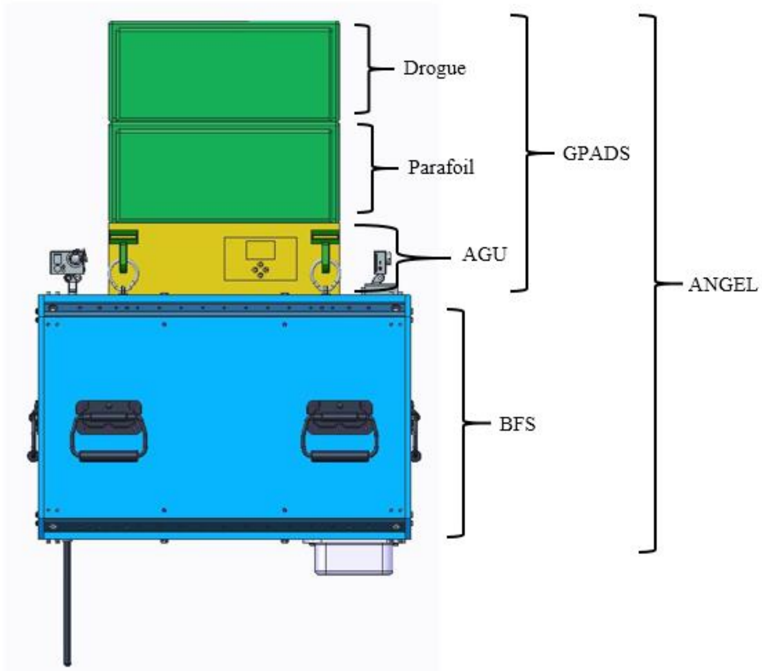


Figure 2. ANGEL system overview.

II. Vehicle and Mission Description

Figure 3. Balloon launch.

The ANGEL system was launched as a piggyback payload on a CSBF Mission of Opportunity on September 4th, 2015 from Fort Sumner, New Mexico. The 6,000lb max gross-weight host vehicle, nicknamed "Thunderbird", was lifted by a 29 million cubic foot Helium balloon envelope pictured in Figure 3. Figure 4 shows Thunderbird in white with the ANGEL system mounted front and center. The Airborne System drogue, parafoil, and AGU are the yellow components, sitting on top of the Balloon Flight System (BFS) painted orange.

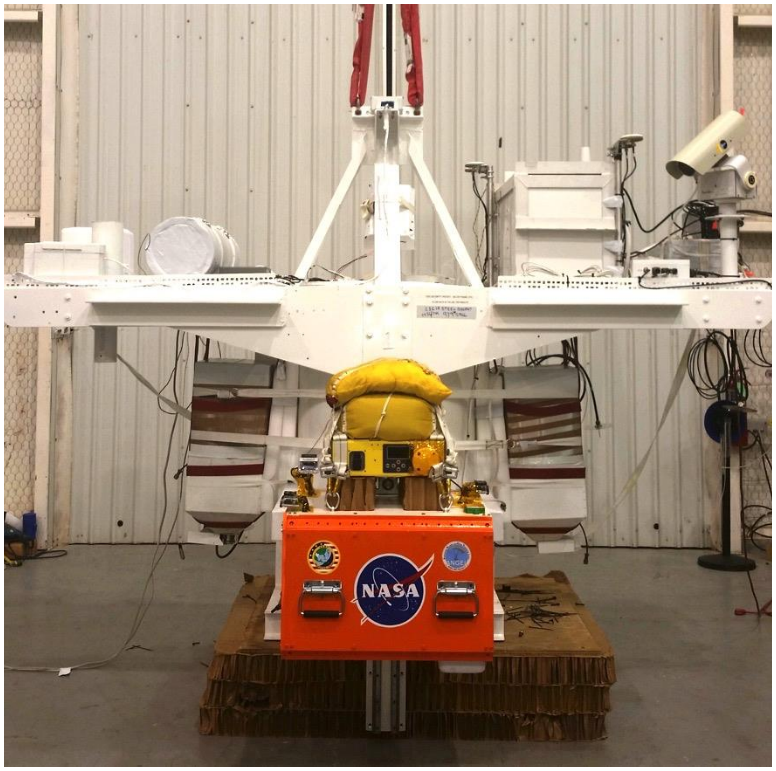


Figure 4. Thunderbird Gondola.

The BFS gondola, designed and built at NASA Glenn Research Center, is composed of a beveled rectangular aluminum skeleton reaching a total system weight of 230lbs including the AGU and canopies. During integration, the drogue, parafoil, and AGU are stacked vertically on top of a honeycomb spacer and connected via four tie-down D-rings. The BFS is attached to the Thunderbird gondola by a single eyebolt on the top surface and restricted from motion after release using a guide rail on the side of the gondola seen in Figure 5. An interference pin mounted to the gondola engages the BFS eyebolt. In order to release ANGEL, a linear actuator pulls the interference pin, disengaging the eyebolt, see Figure 6, allowing the ANGEL system to fall from the host vehicle after reaching its floating altitude. After release of the BFS, a four-roller guide on the side of the BFS, shown in red in Figure 5, travels along the rail on the gondola, minimizing pitch, roll, or yaw motion, and improving the likelihood of a straight trajectory for ANGEL during release. The drogue static line is fastened through a hole in the top of the separation device housing. During release, the drogue static line is pulled taught and the drogue bridle, drogue, and attenuation stitching are extracted. An attenuation strip applies a near constant force to the apex of the drogue for the first approximately 70 ft of descent. This prevents the drogue from recoiling into the BFS after release and allows the system to build airspeed. Approximately four seconds of freefall was predicted as necessary to build sufficient dynamic pressure to inflate the drogue.

ANGEL then intended to descend under drogue for approximately 400 seconds, keeping the payload stable and below Mach 1 until it reaches a GPS trigger altitude of 6,250m (20,505ft) above the programmed IP elevation. For the area being tested, the trigger altitude is about 7,620m (25,000ft) MSL. At this point the AGU commands the release of the drogue using a dedicated motor, and the drogue is jettisoned, while simultaneously deploying the main parafoil. The drogue and deployment bag separate from the main canopy by design. The AGU then commences GPS navigation using standard GPADS flight software. The parafoil is controlled using motors contained within the AGU. In the event of a GPS lock loss, a timer backup was present to trigger the drogue release and main parachute deployment.

All active control sensors were located within the Airborne Guidance Unit, with all redundant data acquisition systems contained within the gondola. Redundant GPS and multiple cameras were placed on the corners of the top plate, with streaming 2-way telemetry antennae located on the bottom face. Live two-way telemetry and video feed were used to monitor and log the system status and trajectory. Data was gathered starting in the pre-launch segment, through ascent and descent and logged to multiple on-board storage devices and ground stations.

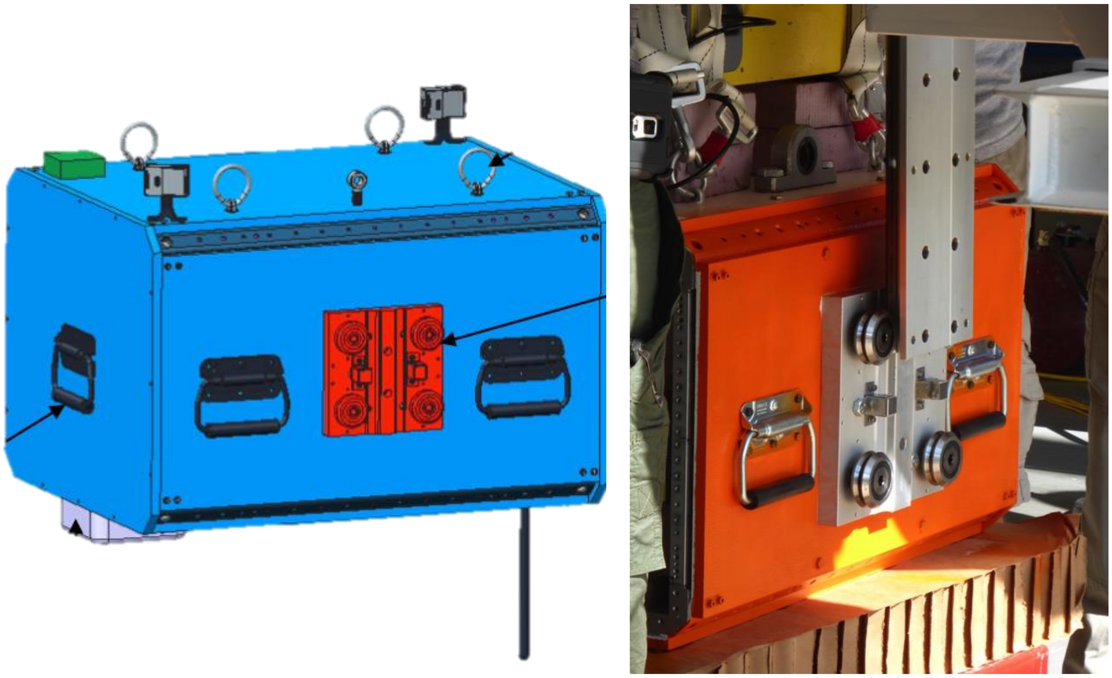


Figure 5. (Left) Front side of the BFS with separation carriage in red.
(Right) Actual system being mounted to the host vehicle guide rail.

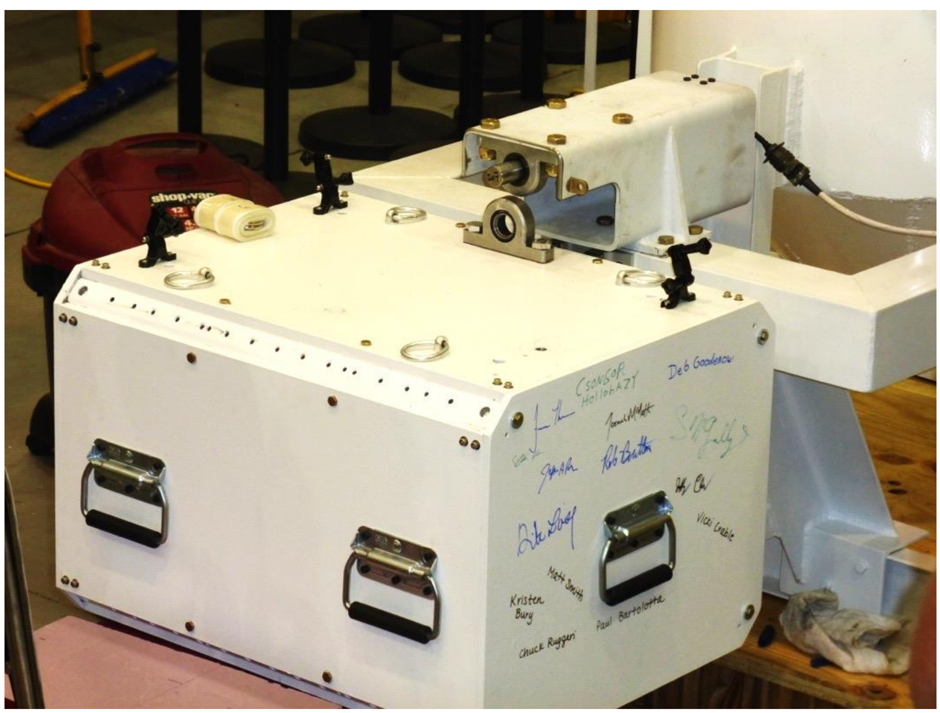


Figure 6. The payload is secured vertically from a single 1" diameter steel pin.

III. GPADS Objectives

Concerning the advancement of GPADS technology to space recovery applications, the ANGEL test has provided the opportunity to test this GPAD system at conditions not previously possible. Specifically, the challenges to surmount include:

- Operating electro-mechanical systems at combined low densities and low temperatures
- Textile tolerance to radiation exposure
- Safely and reliably releasing the payload and the subsequent inflation of the drogue
- Remaining under Mach 1 and transonic regimes during droguefall
- Using GPS sensors at or beyond their altitude limits
- Mission Planning for large offset balloon flights

A. Thermal Management

Due to the combination of low temperature and low density, design attention was given to the battery packs in the AGU. Too low of an operating temperature will quickly drain and potentially damage the Li-ion batteries. A common minimum safe operating temperature is -20C. The GPS receiver had a minimum operating temperature of -40C. Accordingly, the airborne guidance unit included a thermostatically controlled battery heating system. This configuration was designed and environmentally tested to function over the ascent and descent to/from 100,000-ft MSL. The warming function would turn on when the internal temperature dropped below a pre-selected temperature. The GPS receiver chip was not directly thermally controlled, but confidence was provided in the form of successful environmental tests.

It was thus a critical objective that the batteries health to be maintained throughout the flight envelope. From previous flights at lower altitudes, where the thermal management system was first tested, overheating due to reduced thermal capacity of air was not expected to be an issue. The AGU draws relatively little power during ascent, and during descent, wind chill plays a dominant role.

B. Textile Exposure

Textiles react strongly to UV light exposure. Normal exposure rates at earths surface can require days to observe degredation to material properties. However, at higher altitudes, with less filtering performed by the atmosphere, increased exposure to light and radiation sources were expected to accelerate the degredation process. As a result, lighter colors were selected for textile components since they absorb less light, material strengths were intentionally overbuilt, and a minimum of structural elements were left uncovered by deployiment bags. It was thus anticipated that significant tolerance to material degredation was present in the design of the system. However, longer duration missions will likely require light and radiation barrier protection until the time when the system would be used.

A GPADS objective was therefore to demonstrate that the materials selected and methods of textile protection were adequate for short duration balloon missions.

Figure 7. ANGEL Packed and Rigged

C. Safe Release

Of critical importance to the ANGEL flight was to have a safe and controlled release from the host vehicle. Fouling a release could result in a loss of all mission objectives. On release of the ANGEL mass, in addition to some balloon dynamics, the gondola rotates so that the new CG (less the ANGEL system) is directly beneath the balloon tether. Initially conceived separation mechanisms posed a potential risk for the lowest portion of the gondola to possibly re-contact the BFS or parachutes by rotating into them as they fell by. With this 'kick', the ANGEL system could theoretically rotate as a mass in motion for 4 or more seconds until a suitable stabilizing force was available from the drogue, by which time, the drogue bridle could be wrapped up and tangled on the payload. Furthermore, due to the lack of real estate on the top face of the BFS and the requirement to keep the parachutes clear of obstruction, all vertical forces were concentrated through single cantilevered eyebolt and pin. A dual pin system (one in each back corner) was considered, but ultimately deemed more likely to fail or induce rotation upon release. The final release design implemented the single pin and rail system, previously discussed, minimizing any rotation induced by the abrupt release.

Parachute deployments in low density atmosphere are known to have unique inflation characteristics. Particularly important is the need to manage rebound after elongation of the flexible elastic textile structure (risers, lines, and gores) due to conservation of momentum between payload and the drogue itself. There are documented cases where the parachute has rebounded to be below the payload (i.e. closer to earth than the payload), which is especially dangerous as it could tangle on the payload itself and compromise the entire flight. The design of deployment was therefore important. As a preventative measure, a load attenuation strip was added between the drogue and the drogue deployment bag. This attenuation strip would peel for about 85 ft of payload descent. A longer distance was desired, but not permitted at the time. It would be desirable to maintain attenuation until sufficient dynamic pressure could be achieved to inflate the drogue.

A GPADS objective for the ANGEL drop was to prove the pin and rail release systems by having a clean release from the host gondola, with no rotation motion or re-contact with the gondola after release. Further, it was also an objective that the drogue remain above the payload at all times.

D. Descent Speed Control

Fundamentally, a decision was made early to avoid Mach 1 and transonic speeds to prevent sonic boom shock wave, forebody vibrations, changes to drogue performance, and other challenges. At the time of architecture selection, the planned release was to be from 130,000ft. A 9.85 ft D_O ribbon parachute was selected as the preferred drogue which would ensure velocity < Mach 0.75 if dropped from 130,000ft. The release altitude was later reduced to 105,000ft, which only provides more margin. This drogue is a mature qualified design which has a known performance at lower altitudes. A secondary objective of the ANGEL drop was to characterize the drogue's opening, stability, and descent rate performance at these yet-tested higher altitudes.

To understand the droguefall performance with an ANGEL representative payload configuration, a C_D characterisation test was performed. This information was important to ensure both Mach limits were maintained as well as calculating the correct droguefall time for the backup timer functionality.

Figure 8. Drogue C_D Characterization Test

E. GPS in Adverse Conditions

Because the planned altitude of the test, there was uncertaintly how the U-blox GPS module would perform. As a result of the concern wether the AGU would lose GPS lock at higher altitudes and regain it, or not, during high-speed descent, a backup timer was added as an *either / or* condition with the 25,000ft MSL GPS altitude trigger. An objective of the test was then to prove out the GPS functionality and the programming logic for deployment of the main parachute. GPS reception was also a concern given the presence of multiple other communication systems and the large metal body of the vehicle itself. During integration it was discovered that an external antenna and filter was necessary to maintain GPS lock when exposed to CSBF communication signals.

F. Mission Planning

Mission planning is routine for existing commercial applications of GPADS. However, special efforts were required to assist the ANGEL mission. Due to the nature of balloon flight, where the system blows with the wind, it is never precisely certain what the ascent trajectory will look like, or where the release location will be. Consequently, numerous hazard restrictions were levied onto ANGEL. Hazard avoidance included the following restrictions, shown in Figure 14:

- 8 nm diameter No-fly zones near population centers – entire failure footprint (red circles)
- 4 nm keep out zones from roads, highways, interstates, and high tension power lines – entire failure footprint
- 1 nm diameter keep out zones from dwellings (inhabited or uninhabited) – ballistic failure footprint (purple circles)

As a result of the uncertain ascent path, there was the expectation that release would be decided on-the-fly when the ballistic footprint was acceptable. Therefore, the decision to release places a higher priority on safety than accuracy of landing.

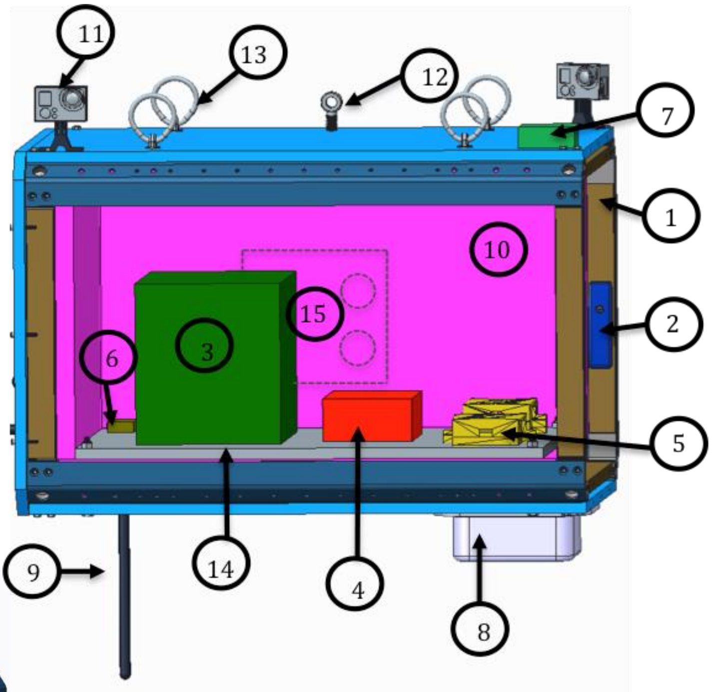
Prior to the first launch window, suitable impact points (IP's) were sought and surveyed, based on anticipated ascent trajectory. This involved a day or two of scouting safe, accessible land with landowner consent. However for the actual launch day there was not sufficient time based on changed wind conditions and personnel availablility to scout for IPs.

The GPADS objective for mission planning was for the ANGEL to land within 150 meters of a pre-selected landing point based on the predicted ascent trajectory and release point, while successfully avoiding the hazards identified.

IV. Passive BFS Data Acquisition System

Balloon Flight System Components:

1. *NASA Gondola*
2. *NASA Impact Sensors*
3. *NASA Battery*
4. *NASA PMAD*
5. *NASA Avionics*
6. *NASA Radio*
7. *NASA GPS*
8. *Airborne Systems Antenna*
9. *NASA Antennae*
10. *Thermal Foam*
11. *Go-Pro Camera Systems*
12. *Eye Bolt*
13. *Tie-Down Rings*
14. *Subsystem Shelf*
15. *Separation Carriage*



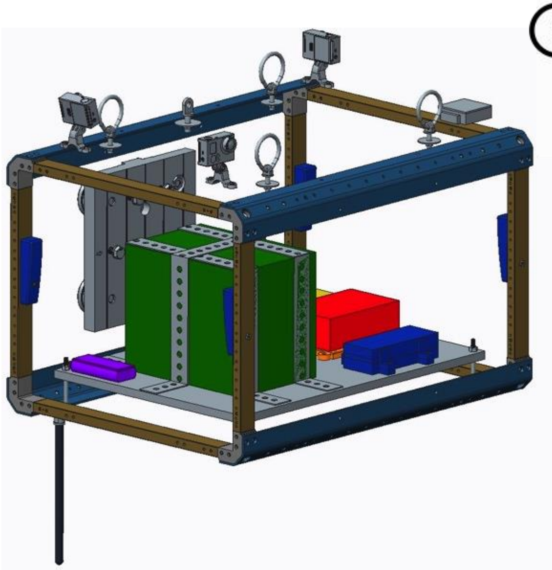


Figure 9. (Above) CAD model showing the internal arrangement of BFS sensors.

Figure 10. (Left) Isometric view, with insulation hidden.

Arrays of sensors were contained within the aluminum BFS frame to record the flight from the perspective of the test payload. This passive data acquisition system was used to measure the GPAD performance and quantify the flight loads. The platform consisted of a power source, radio, sensors, flight computer, insulation, and ballast. A three-cell battery pack each comprised of 5 series connected SAFT B0562 Lithium Sulfur Dioxide batteries were enclosed within a passive thermally controlled foam shell. Power was distributed from the battery using a custom power management and distribution (PMAD) board connected to the data acquisition units, and radio transmitter. The data acquisition units were comprised of the following sensors types*:*

1) **GPS**- Measure position, altitude, velocity, heading and time
2) **Accelerometers**- 3D accelerations, vibration loads and orientation
3) **Gyros**- Orientation and angular velocity
4) **Magnetometers**- Aid in calculating heading and IMU sensor fusion
5) **Thermocouples**- Monitor temperature of electronics
6) **Cameras**- Visual feedback
7) **Current/Voltage Monitoring**- Battery performance

Each of these sensors was redundantly measured from multiple locations and multiple power sources. All BFS sensors were independent from the sensors inside the AGU that were used to actively navigate the payload on descent. This system also periodically broadcasted and received telemetry data from a ground station located along the projected mission path. The two secondary data acquisition (DAQ) systems passively monitored gondola conditions from inside the blue structure in Figure . These sensors provided redundancy, along with a secondary perspective on the flight loads while the AGU was suspended above the gondola during its final glide segment. One of the internal DAQ systems also continuously streamed data to ground stations to help monitor the payload status. This secondary radio system helped ensure maximum data recovery, even if the payload were to be destroyed on impact.

V. Results

A. Day of Flight Conditions

A regional weather forecast was used to plan for acceptability of landing locations. The temperature, wind speed, and wind heading conditions predicted for the flight are shown in Figure 11 below. The inherent canopy forward airspeed of the parafoil, based on the suspended weight, is also displayed to demonstrate that the forecast wind is about half of the speed of the system for the portion of altitudes using the parafoil.

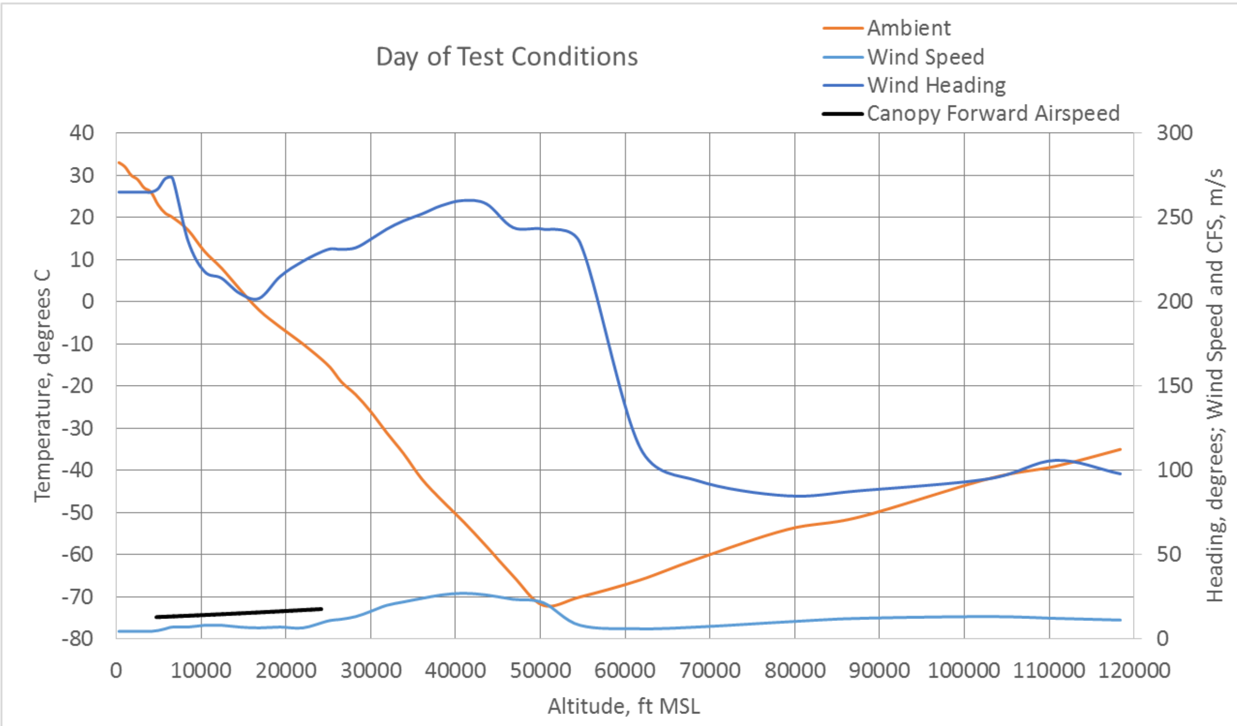


Figure 11. CSBF Forecast for the Area.

B. Launch

After a two-hour prelaunch inflation period, the host vehicle was launched at 6:50am. Given the size of the balloon and payload, pendulum effect during release was eliminated by driving the payload until it was directly beneath the balloon at release. This ground vehicle, nicknamed “Big Bill”, can be seen in Figure 12 as the balloon began to ascend.

Figure 12. View from just after Launch from Thunderbird.

During this release, the payload experienced a 3 g vertical acceleration and 3 Hz dampening vibration as shown in Figure . At this point the internal temperature was approximately 90°F with a max rotational speeds of 0.26 rad/s occurring.

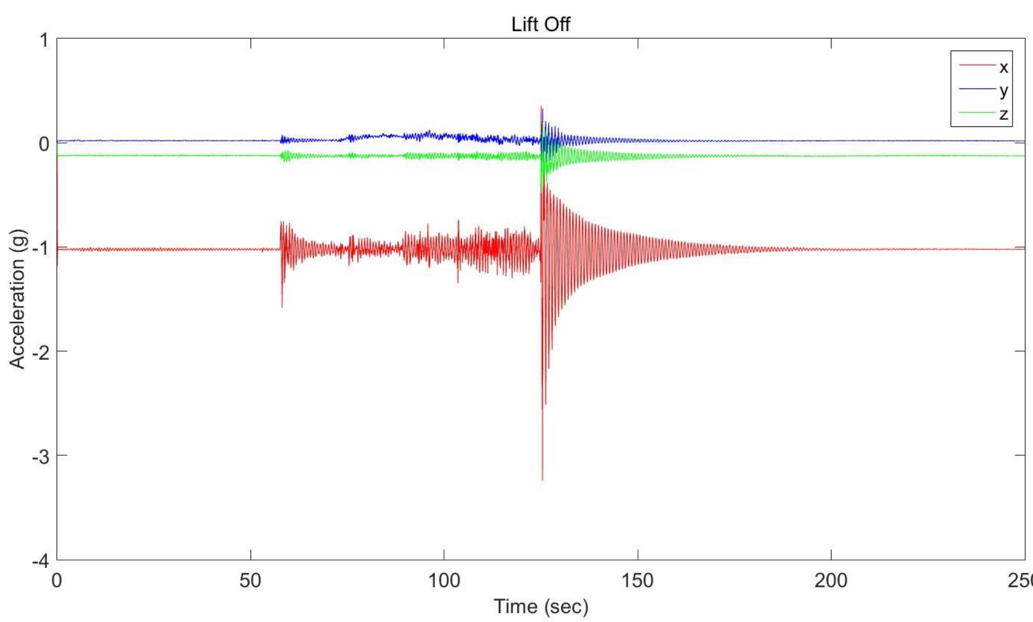


Figure 13. Launch Vibrations.

C. Ascent

The Thunderbird ascended at an average 3.5 m/s (11.5 ft/s). Since the release was to occur based on safe failure footprint compliant with hazard avoidance, it was uncertain exactly what release altitude would be achieved. During final stages of ascent, the balloon track nearly achieved abeam from the IP around 100,000ft. Additional altitude was anticipated to further minimize the offset, however with diminishing returns. As the ascent track was approaching a series of dwellings, a decision to release would need to be made before then.

Figure 14 shows the ascent track of the balloon, dark blue, as well as the forecast track in light purple. The offset between the actual vs. predicted ascent ground track is approximately 9 km. The straight blue vectors represented the estimated error bars.

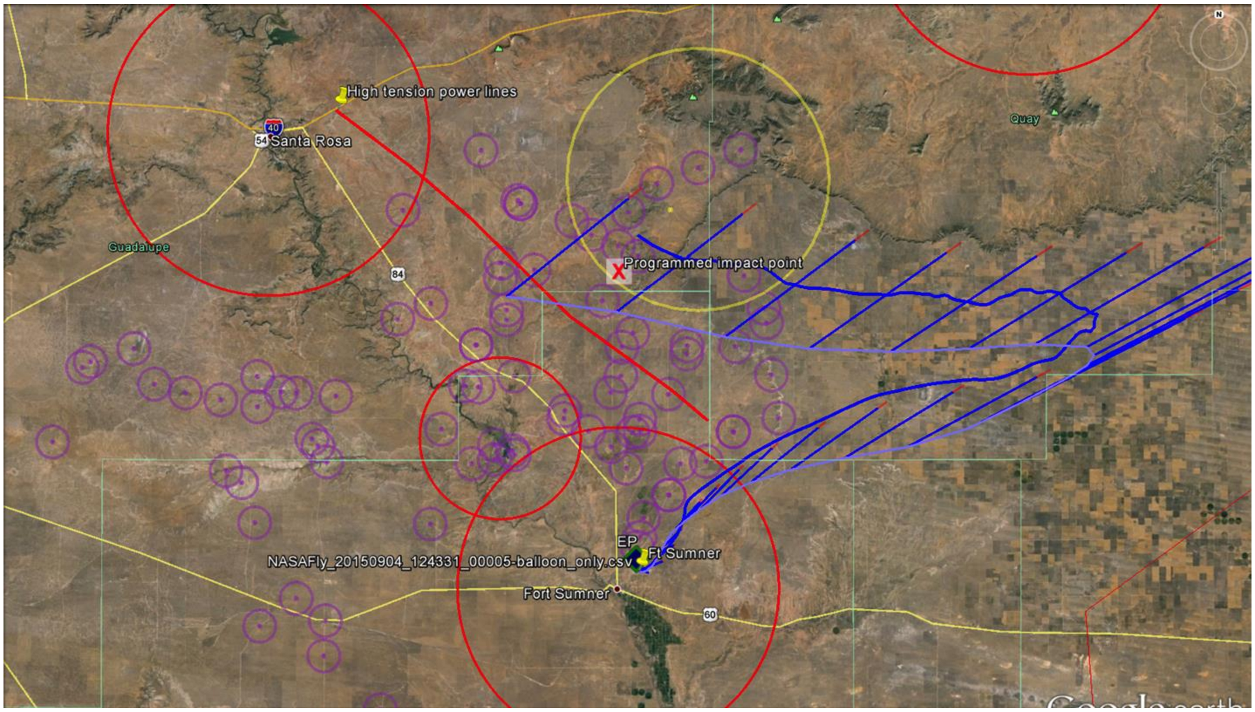


Figure 14. Google Earth with Ascent Track.

D. Release

After receiving an all-clear status from the safety range officer and Airborne Systems operators, per logic discussed above, the ANGEL payload was released at 9:37am. Release occurred with an ascent of about 10 ft/s at an altitude of 32,900m (108,002ft). At this point, the internal payload temperature was roughly 70°F.

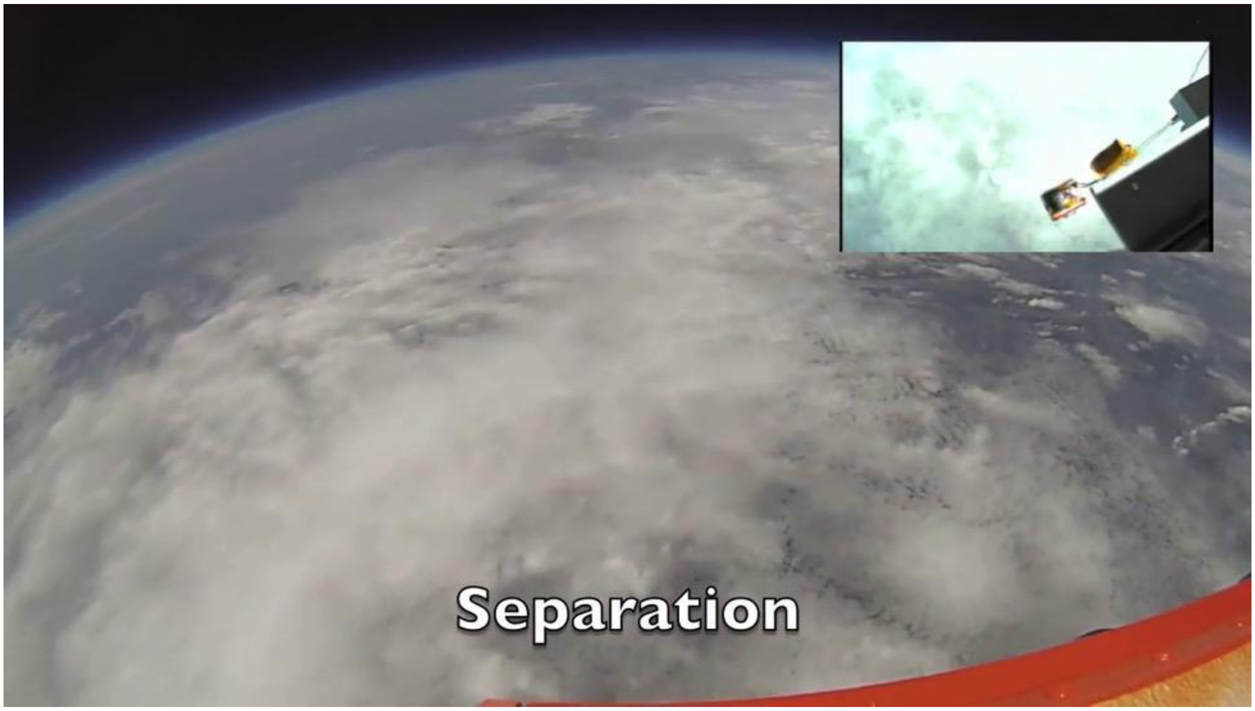


Figure 15. BFS View at Release.

As designed, the steel pin was retracted from the cantilevered separation eyebolt resulting in a small vibration caused by steel rubbing against bronze raceway and molybdenum disulfide lubricant. The payload experienced 0.4 g, 40 Hz vibrations, followed by a 0.5 g max shocks as the linear guide carriage rolled down a guide rail eliminating any rotations induced in the off-C.G. release. The payload experienced a 4.8 second free-fall (within 0.1g) before beginning to decelerate under drogue and air resistance. During drogue, the payload pitched as far as ±30 degrees and rolled up to ±40 degrees.

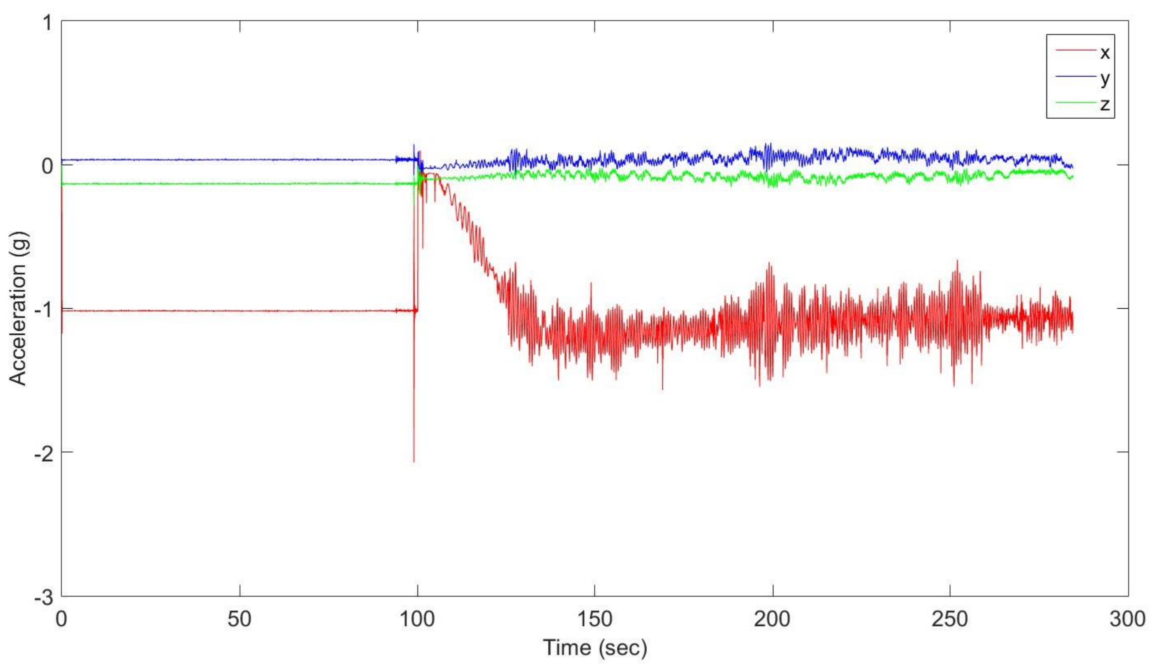


Figure 16. Accelerations of BFS during Release and Fall to Terminal Velocity.

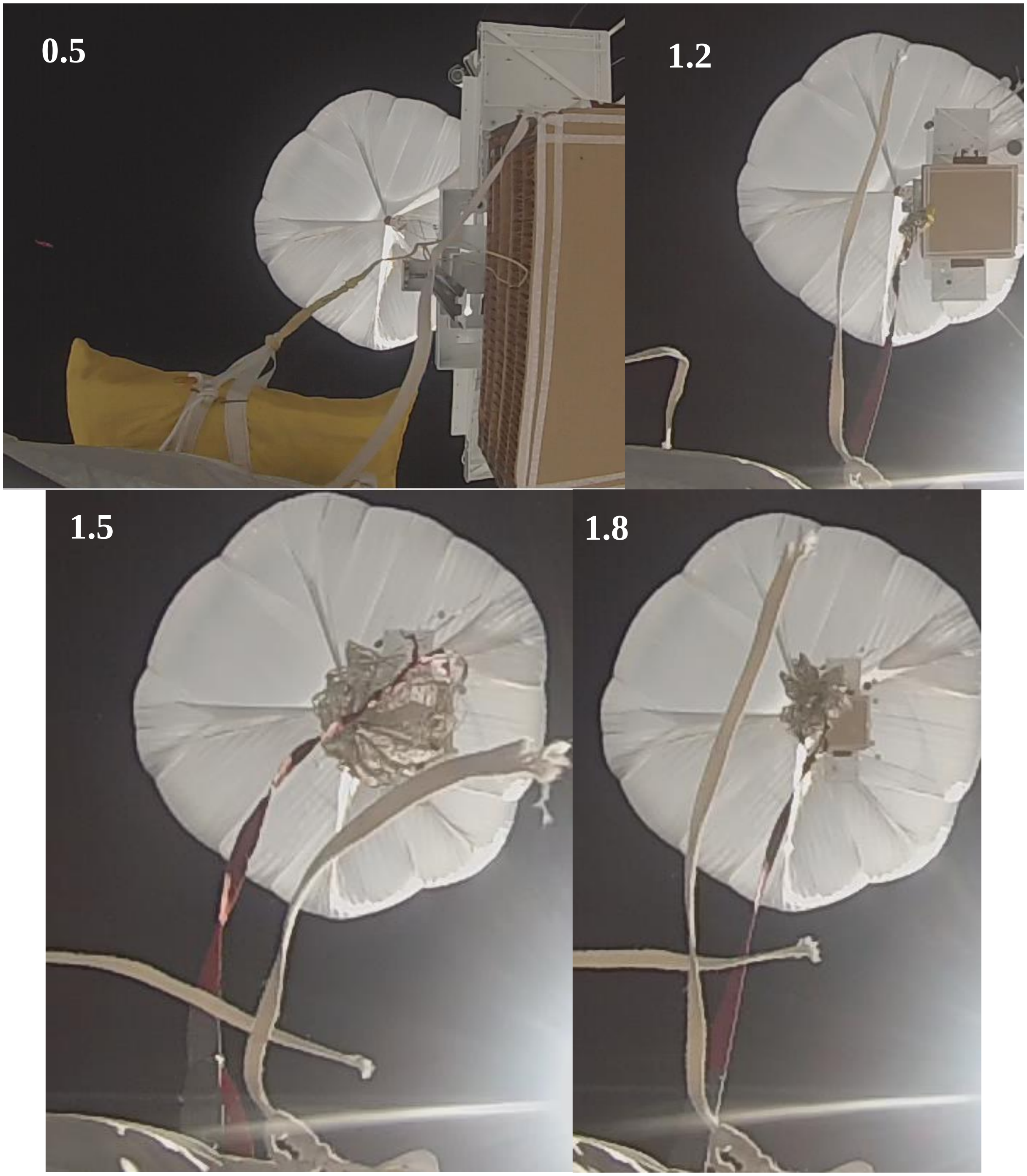
After release, as the BFS, AGU, Main, and Drogue fell away, the drogue static line, attached to a hard anchor point on the gondola, was extended. Once taut, it lifted the drogue deployment bag off of ANGEL and extended the drogue riser before extracting the drogue parachute from the deployment bag. The drogue riser became tight at this instant (1st riser-tight event). Following drogue egress from the deployment bag, the drogue attempted to rebound toward the BFS, as evident by slack in the drogue riser. However, the attenuation strip between the drogue apex and the deployment bag was then loaded and prevented the drogue from further rebound. At this moment, the riser became tight again, marking the 2nd riser-tight event. As ANGEL fell further, the attenuation stitching began ripping at a resistance force designed for this purpose. A 3rd riser-tight event occurred during attenuation rip-out as a product of the intended design of the attenuation.

The initial deployment performed as planned, with the AGU experiencing almost no rotation and no re-contact. The attenuation successfully prevented the initial drogue recoil. Following the release of the attenuation after about 85 ft of payload descent, a late recoil was experienced, which was not unexpected. The ANGEL team had desired a longer attenuation strip which would maintain tension until the drogue could inflate, but it was not possible to vet this concept within the integration timeframe. The drogue rebounded toward the BFS but did not come close enough to contact, which was the main goal. The attenuation strip, due to its length, did reach the BFS and became entangled for about 7 seconds.

The sequence of events and their timings are detailed in Table 1 and in the following screenshot images.

Time, sec	Observation
0.0	Release from Thunderbird gondola
0.5	Drogue static line tight
1.2	Drogue extracted out of d-bag, snatch, riser tight event #1
1.8	Recoiled after snatch and then attenuation pulling drogue tight; riser tight 2nd event at this moment
2.2	Retightening of drogue riser, 3rd event; Attenuation over
3.0	Recoil of parachute towards payload; this is the point of closest proximity to payload, canpy is sideways; attenuation strip now tangled on payload
4.0	Canopy spreads (sideways) and presents more surface area; at this point it begins being blown back away from payload again
4.6	Riser tight due to drogue drag, 4th event
5.6	Drogue partially open; approx. 30% CdS
6.4	Drogue open
6.7	Skirt of drogue partially closes (reaction to overinflation, probably ribbon inertial forces rather than drag)
10.3	Attenuation strip entanglment freed

Table 1. Deployment and Inflation of Drogue.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1.2
1.5
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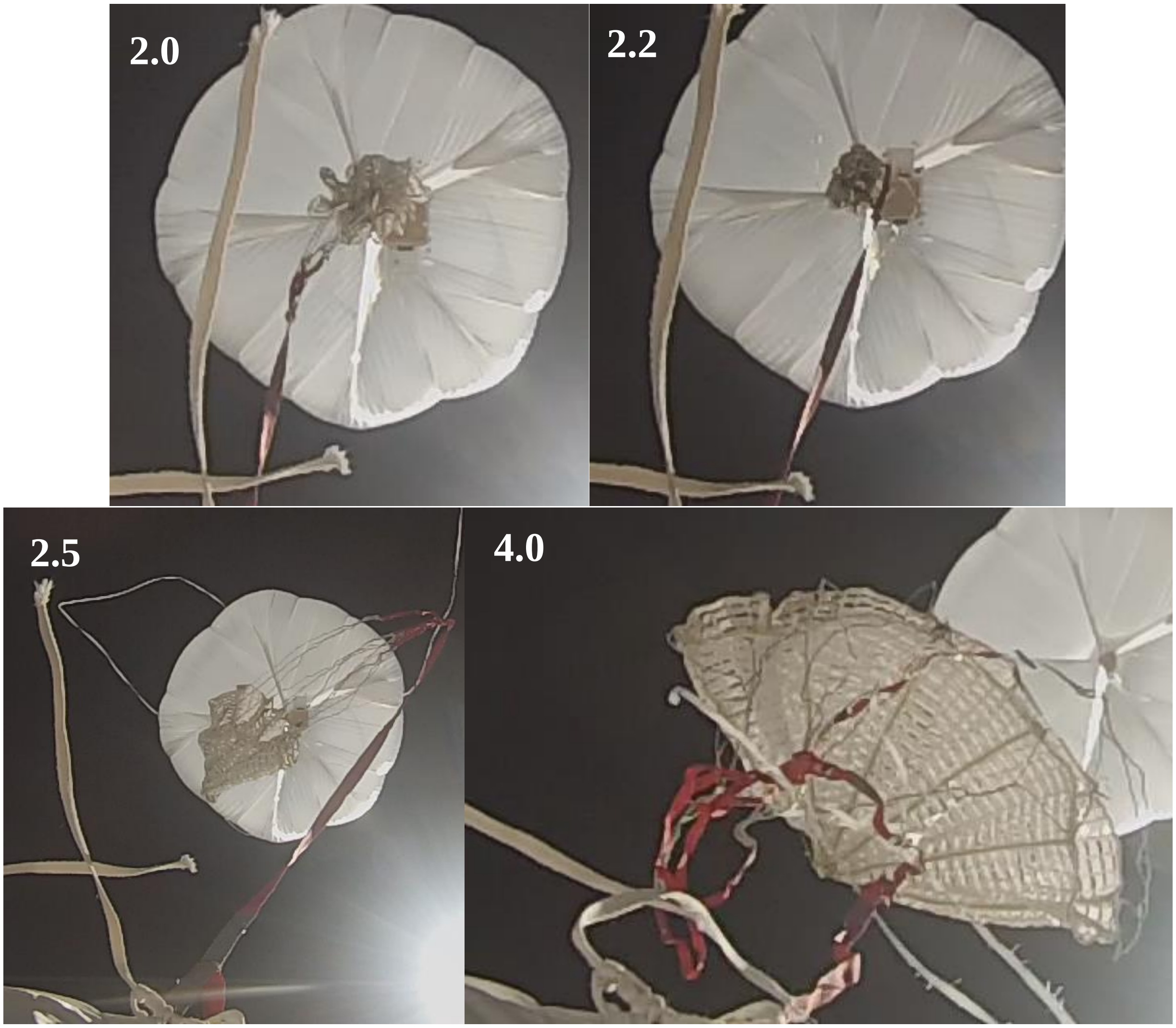
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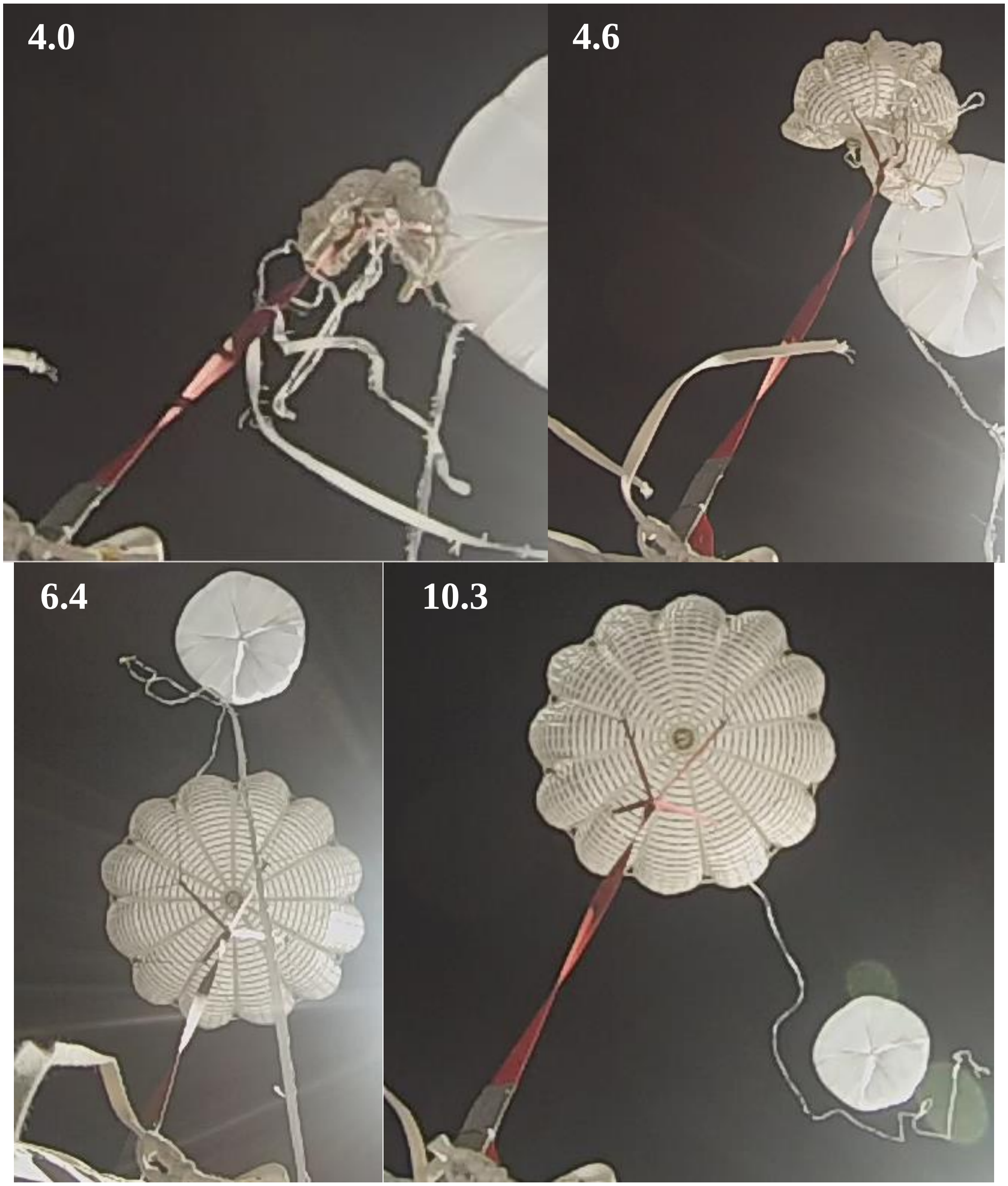


Figure 17. Drogue Deployment and Inflation Screenshots.

E. Drogue Descent

The ANGLE system descended under drogue until about 7,668m (25,163ft), at which point the AGU commanded the drogue release. At about 7,635m (25,050ft) MSL, the drogue released and deployed the main parachute. The payload experienced pitch and roll rotations up to ±2 rad/s under the drogue descent lasting 403 seconds. The AGU maintained a 7-10 satellite GPS lock for the entire flight.

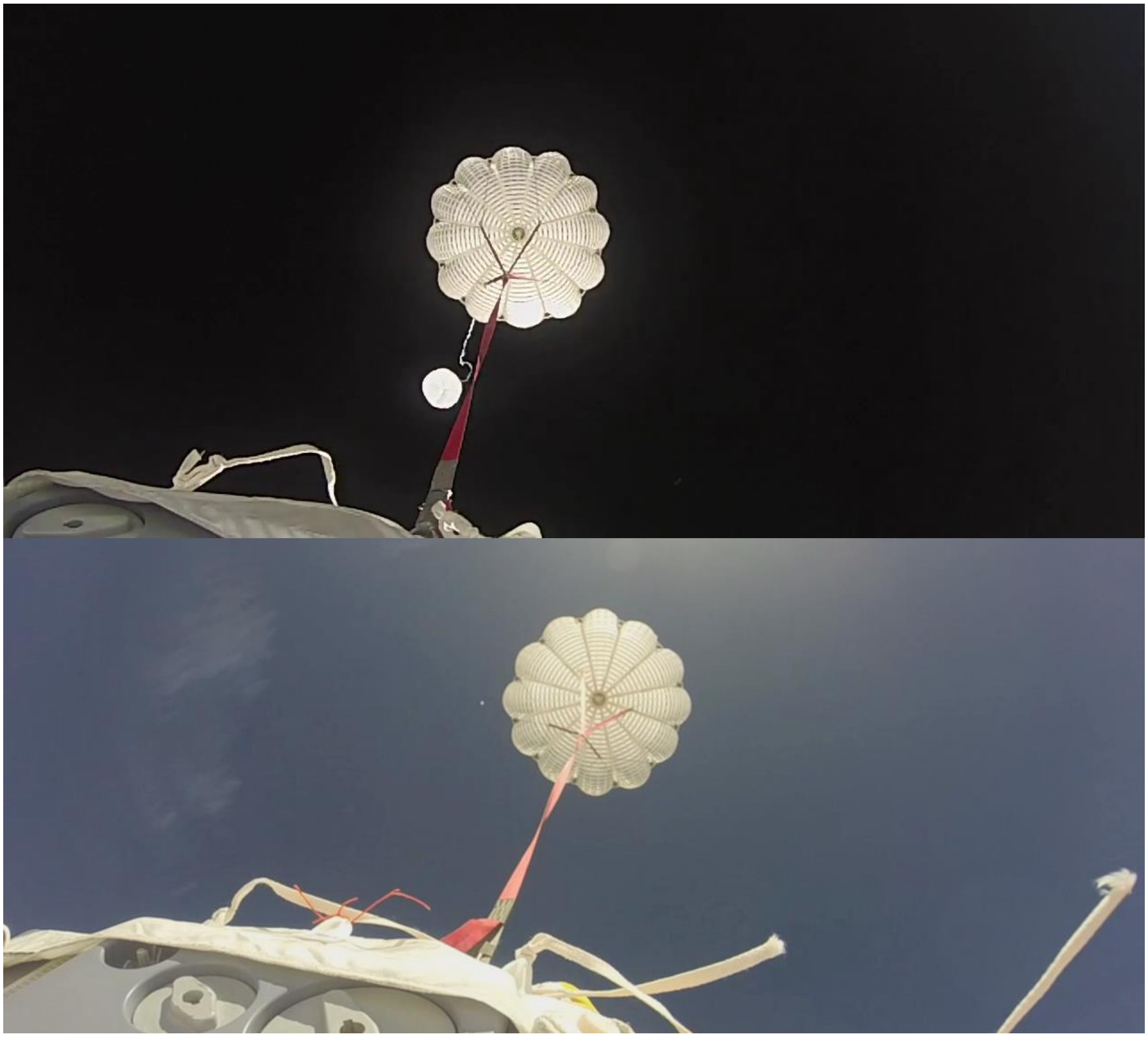


Figure 18. Drogue Descent at about 107,000ft and 25,500ft MSL.

A swivel in the drogue riser load path allowed the drogue to spin, if needed. Drogue spinning was observed for some portions of flight, but not more than about 0.3 Hz, which is considered generally benign. The two images in Figure 18 show that the swivel worked as designed as not more than one full twist was collected in the drogue riser throughout the course of the descent.

Observations taken from video over major observations during drogue descent are shown in Table 2.

Time, sec	Observation
0.0	Release from Thunderbird gondola
13.3	Begins 5 second coning behavior, probably < 5 degrees; clockwise
28.3	Drogue starts spinning at less than 0.3 Hz also clockwise
70.3	Spinning slows by about 50%
91.3	Trailing attenuation strip appears to have some kind of coning or spinning at about 1.2 Hz COUNTERCLOCKWISE
99.3	Spinning of drogue relative to payload stops, canopy and payload are now synchroniously spinning (sun now rotates around drogue)
152.3	Coning cycle extending to about 8 seconds
162.3	Coning to about 10 seconds
177.3	Coning to about 13 seconds; still no spinning between drogue and payload
192.3	Single coning cycle of 5 seconds; some drouge spinning relative to payload counterclockwise
212.3	Back to 12 second cycles
237.3	About 12-15 seconds no coning or spinning; then resumption of coning at 8 sec cycles
282.3	15-18 seconds no coning or spinning
312.3	20 second coning cycles syncronized with canopy spinning, still counterclockwise
397.3	Relative no coning or spining up till this point
398.3	Drogue release

Table 2. Observations during Drogue Descent.

F. Parafoil Deployment

At 9:43am, the Airborne Guidance Unit released the drogue, which deploys the main parachute and at the same time orients the AGU vertically and extends the slings. At this time, the AGU is suspended between the BFS and canopy as shown in Figure 20. The payload attitude during deployment reached approximately -60 degrees pitch and +60 degrees roll before returning to level flight. The internal temperature of the BFS was approximately 66F.

Figure 19. Main Parachute Deployment and Inflation.

In the 4th image, the two pieces of honeycomb can be seen coming off the payload. One of the two pieces contacted the parachute during deployment. These could be secured to the payload on future flights to prevent and FOD issues with the deployment. The notable events from the parafoil deployment are listed in the below table. The parachute opening was of about 3.4 seconds duration. It is noted that there is a slight time drift in the estimation of video vs. AGU timing. The AGU log file times supersede video indicated times.

Time, sec	Observation
0.0	Release from Thunderbird gondola
398.3	Drogue release
398.9	Main parachute line stretch
400.7	Slider first movement
401.7	Slider down and parafoil inflated

Table 3. Parafoil Deployment Observations.

G. Parafoil Descent

Using GPS and inertial measurement sensors, the AGU autonomously retracted and extended canopy lines causing the parafoil to change its glide direction and fly towards it's pre-programmed destination. The GPAD system used commercial flight software for guidance navigation and control without any major issues. The payload had an average forward ground speed of 5.38 m/s and average descent speed of 4.45 m/s. Ground distance traveled under parafoil 8.7km (5.4 miles). A modest right turn bias resulted in the trim auto correction routine applying compensating input on the left motor, as designed. The parachute experienced small stroke oscillating control inputs which resulted in a small wavy ground track. This minor inefficiency would have reduced the offset capable, but not by the amount which the system landed short.

Figure 20. Inflated Parafoil in Steady State Flight.

Causes of turn bias could have dependency on payload CG, subtleties in rigging differences, canopy asymmetry or other causes, and are relatively common. The turn bias was autonomously corrected on this flight.

The causes of the oscillating stroke inputs can be attributed to stroke amounts used and a coupled sling. A simple adjustment to these strokes and the flight software turn logic as well as a confluence in the sling can reduce or eliminate this phenomenon.

The parafoil performance and waypoint navigation was otherwise nominal and considered typical for commercial GPADS.

H. Impact

Impact occurred at 10:07am, 3,118 meters short from the target location. Due to a slightly higher landing altitude, 60 ft higher than the IP, no flare was commanded. The landing occurred in a safe unpopulated location sparsely populated by small trees.

Figure 21. Final Landing Site, Into Wind.

VI. Data Analysis and Visualization

A. Conditions Review

On first look, the actual winds appear to agree relatively well with prediction from the CSBF Forecast. Small differences, however, accumulated throughout the duration of the 151 minute ascent and resulted in approximately a 9 km offset from the predicted ground course.

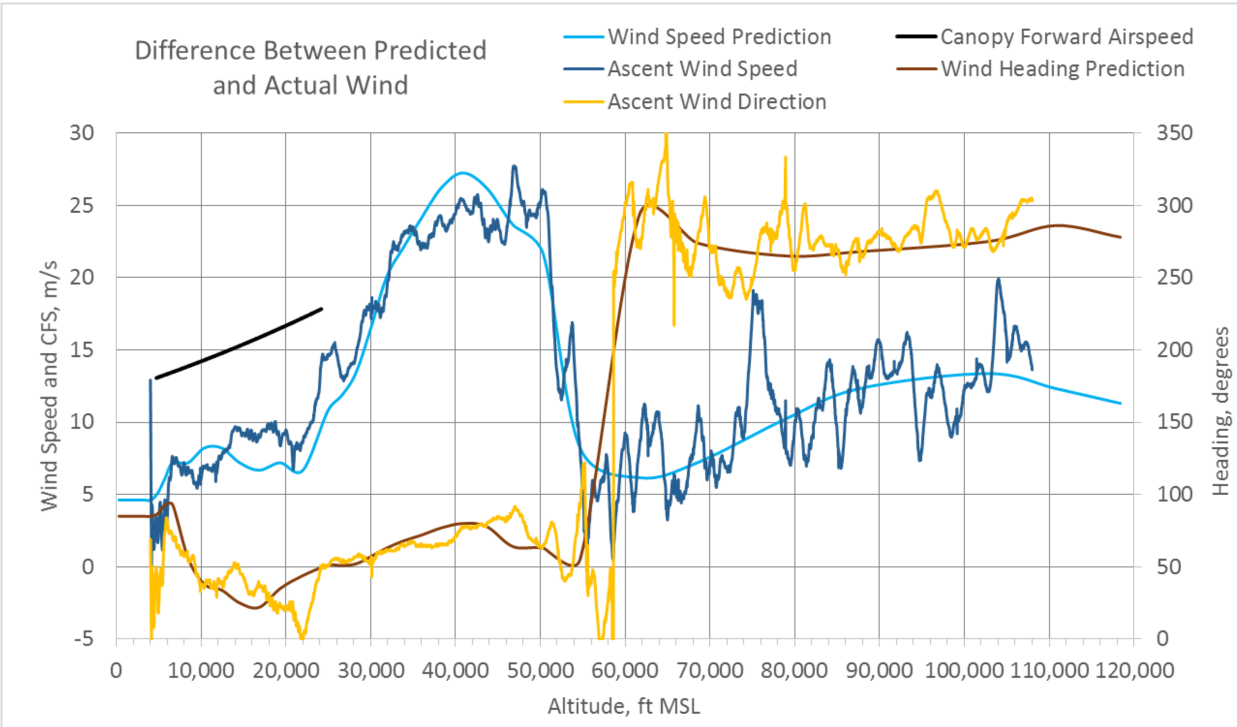


Figure 22. Actual vs. Predicted Winds.

The offset, unfortunately was downwind from the IP resulting in an ANGEL parafoil flight nearly directly into wind for the entirety of the flight. This significantly reduced system offset capability and contributed to the final landing accuracy.

B. Trajectories and Loads

1. Overview

The duration of the ANGEL flight, ascent and descent was about 191.5 minutes, where 150 minutes of this was ascent. The ascent appears to have three distinct ascent rate phases, as seen in changes of ascent slope at about 20,000ft and 50,000ft. Each subsequent phase is a reduced ascent rate. A more turbulent ascent can be seen beginning at about 50,000ft based on the unsteadiness of the ascent rate.

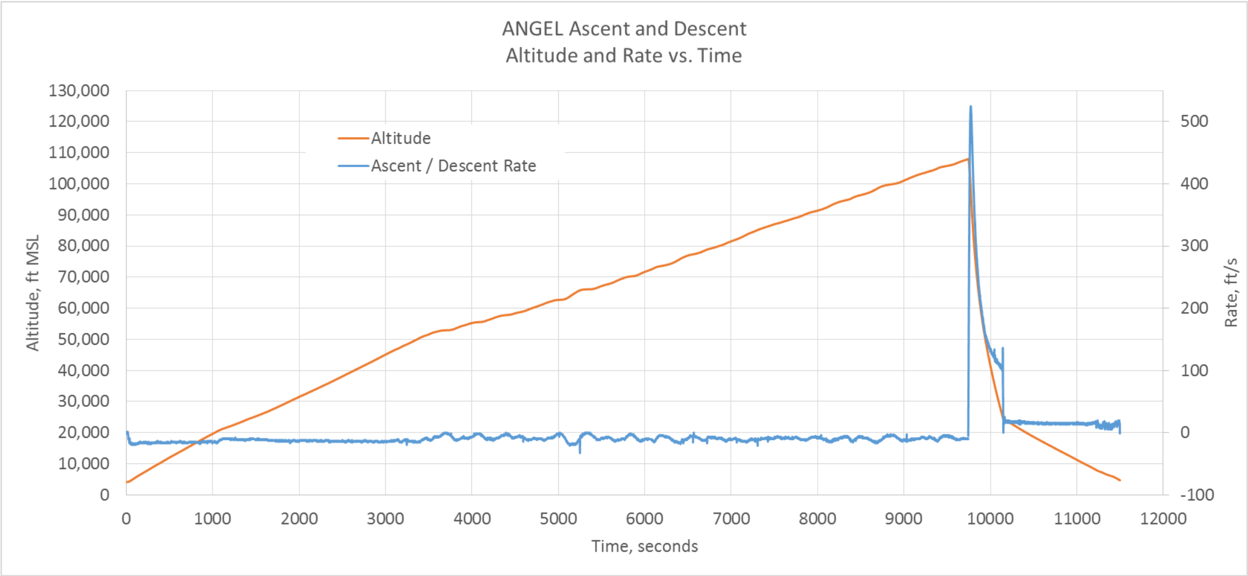
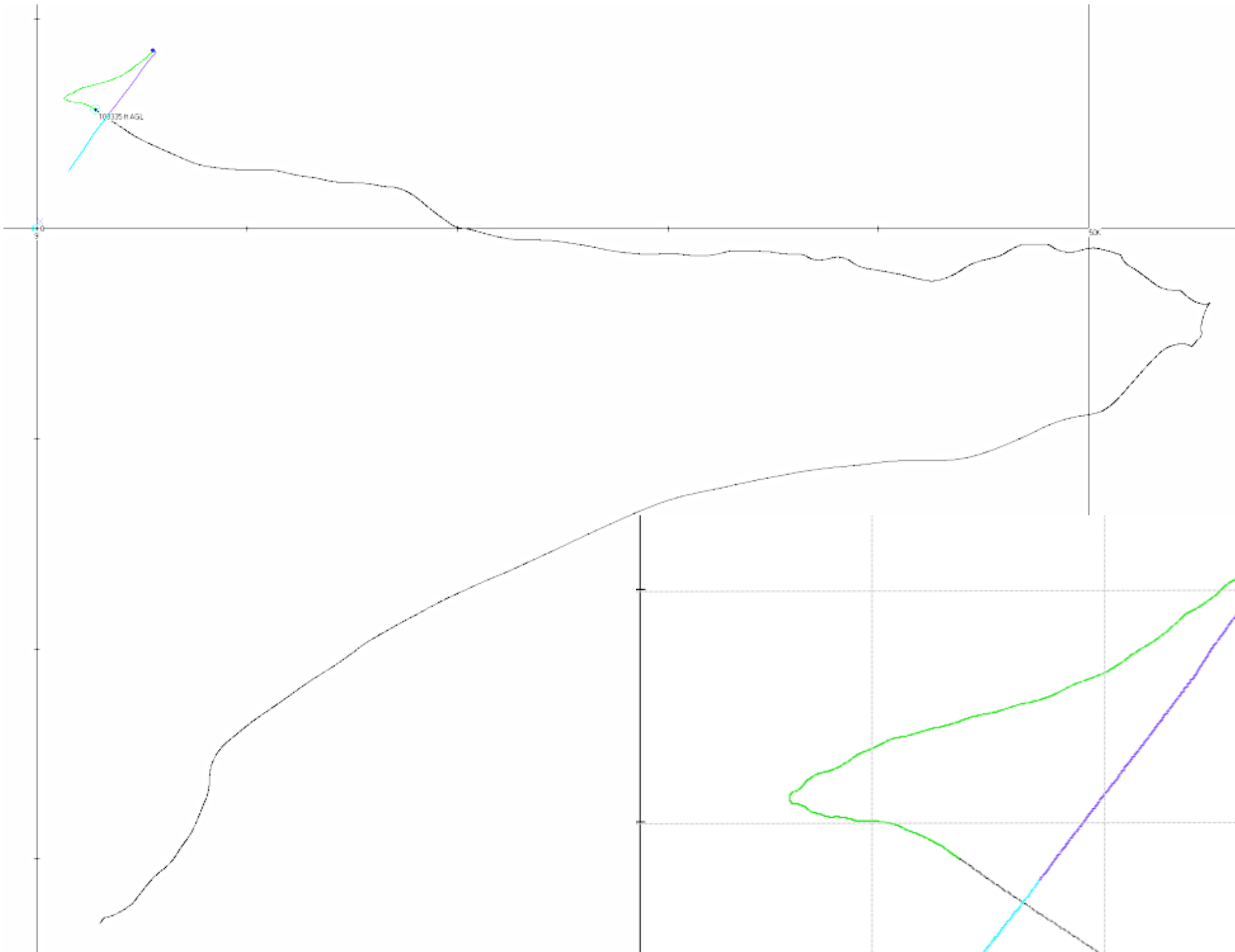


Figure 23. ANGEL Flight Profile.

Figure 24. Google Earth View of 3D Descent and 2D Ground Track.

Illustrations of the flight (3D and 2D ground track) are shown in Figure 24.The flight tract from the AGU log file shows the ground course with color-coded flight portions. In Figure 25 black represents the ascent, green the droguefall, and purple and blue represent the guided parafoil flight. The grid squares are 50 km with 10 km tick marks and 10 km with 2 km tick marks for the top and right images respectively. It can be seen that the ANGEL system drifted significantly away from the IP during droguefall, about 3 km.



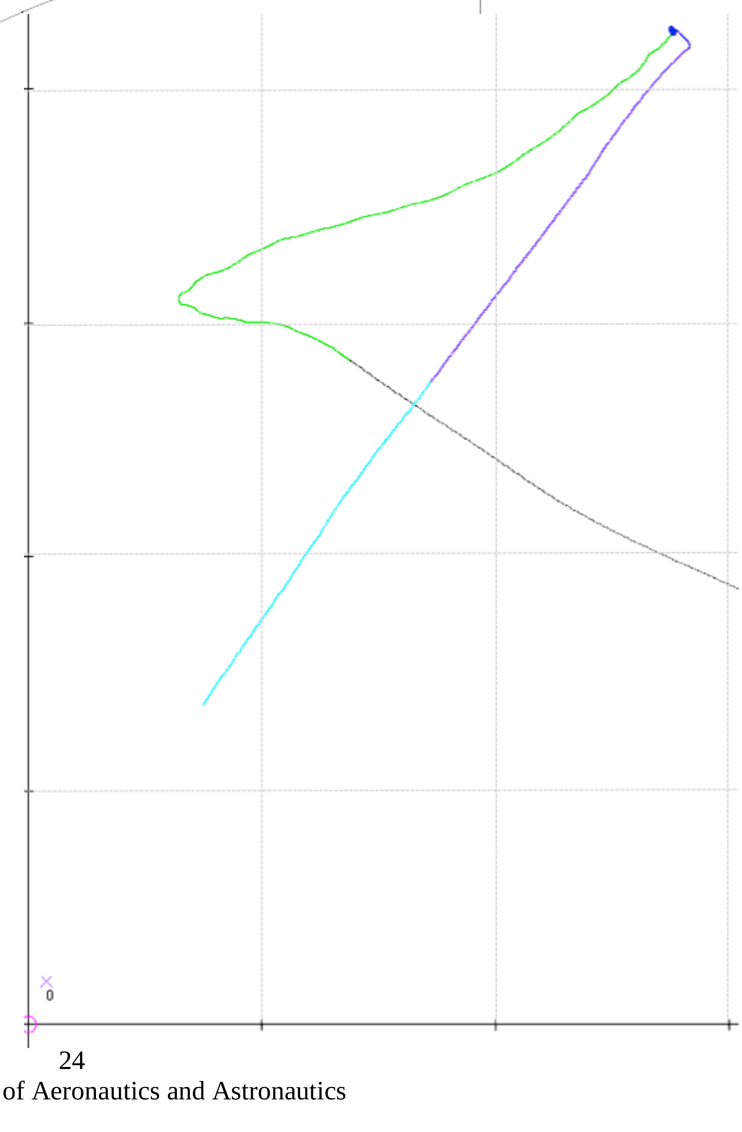


Figure 25. AGU Log File Ground Track (Top) and Enlarged Descent Path (Right).

The impact point is marked with a magenta circle and can be found in the bottom left corner of Figure 25.

2. Descent Rates and Loads

The AGU registered a maximum of 160 m/s (525 ft/s) descent rate at 29,919m (98,160ft) MSL. Using the predicted drogue performance, ANGEL would have reached the main parachute deployment altitude at 390 seconds, 13 seconds sooner than was experienced. Differences in drogue stability at higher altitudes may have affected the net drag performance of the ANGEL system.

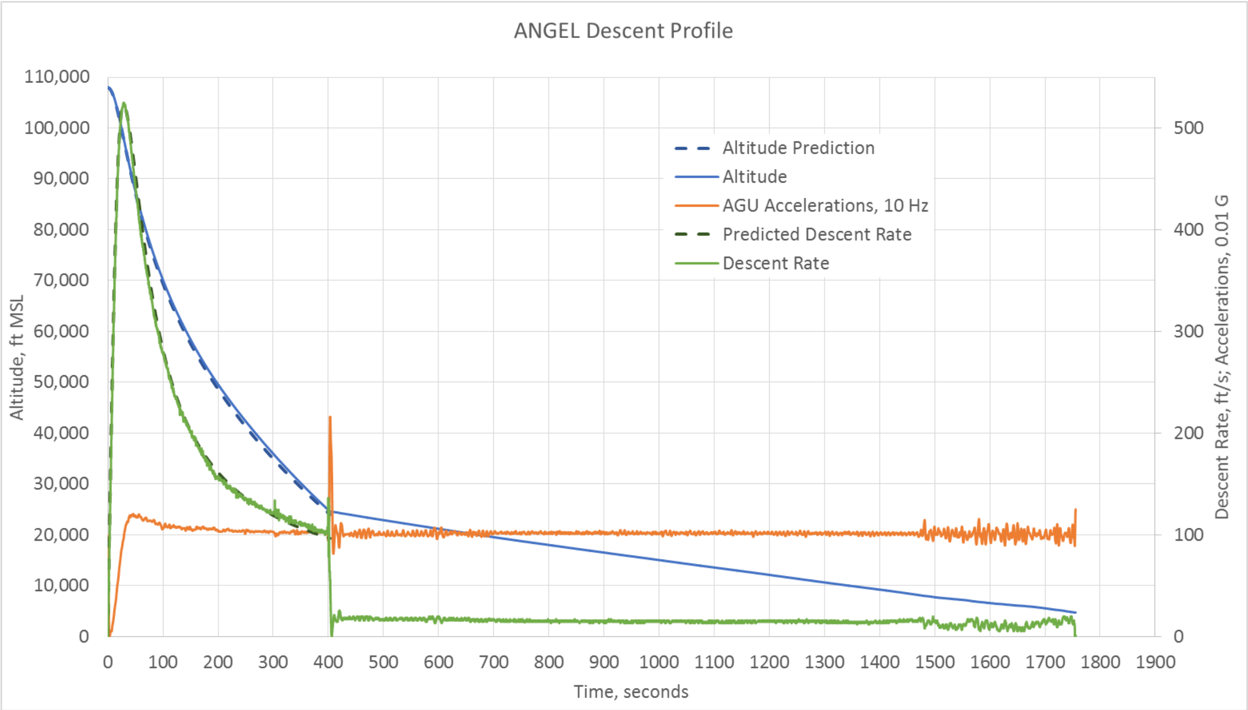


Figure 26. Angle Descent Profile.

The trigger to deploy the main parachute was driven by GPS altitude, as desired. The backup timer requirement had not been met. For reasons explained later, it would be advantageous if the altitude and timer functions could be made more flexible to permit higher or lower openings as may be desired by conditions of the day. These could either be ground station commands or preferably autonomous decisions made by the GPADS.

The BFS recorded a max speed of 161 m/s (528 ft/s) at 29,800m (97,800 ft) maintaining a 13-16 satellite GPS lock for the entire flight. This agrees closely with the onboard AGU GPS measurements.

Unfiltered BFS droguefall accelerations in Figure 27 below show a sinusoidal behavior of a frequency of about 1.4 Hz during descent. These are the drogue swing-out oscillations where the drogue experiences oscillations in angle of attack of approximately +\- 5 degrees. There are periods with more and with less amplitude, with these coinciding to more and less drogue motion, respectively. The accelerations cleanly drop off after release from the gondola from 1 to 0. The acceleration to terminal is followed by a sustained air-braking peak of about 1.2g around 40 seconds from the reduction of terminal velocity due to denser atmosphere.

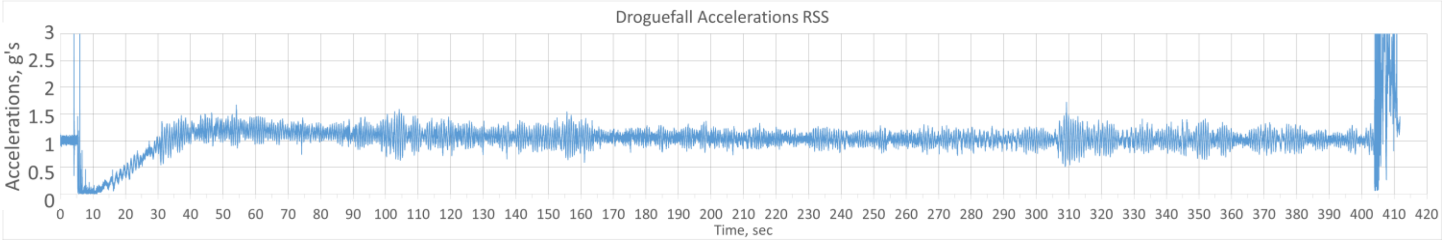


Figure 27. BFS Droguefall Accelerations.

On review of inflation data of the main parachute, several large magnitude peak accelerations were observed, greater than 10 g's. Typically, parachute openings display two main peak events. 1) A short one-time inertial event of the mass of the parachute (and AGU) coming to a stop at line stretch, and 2) the inflation of the parachute which can take seconds.

The below figure shows just over 3 seconds of inflation data, through slider disreef and full inflation. The vertical gridlines are spaced at 30 per second, equal to the frame rate of the camera. The inertial snatch event is marked with 1 and the inflation is marked with 2.

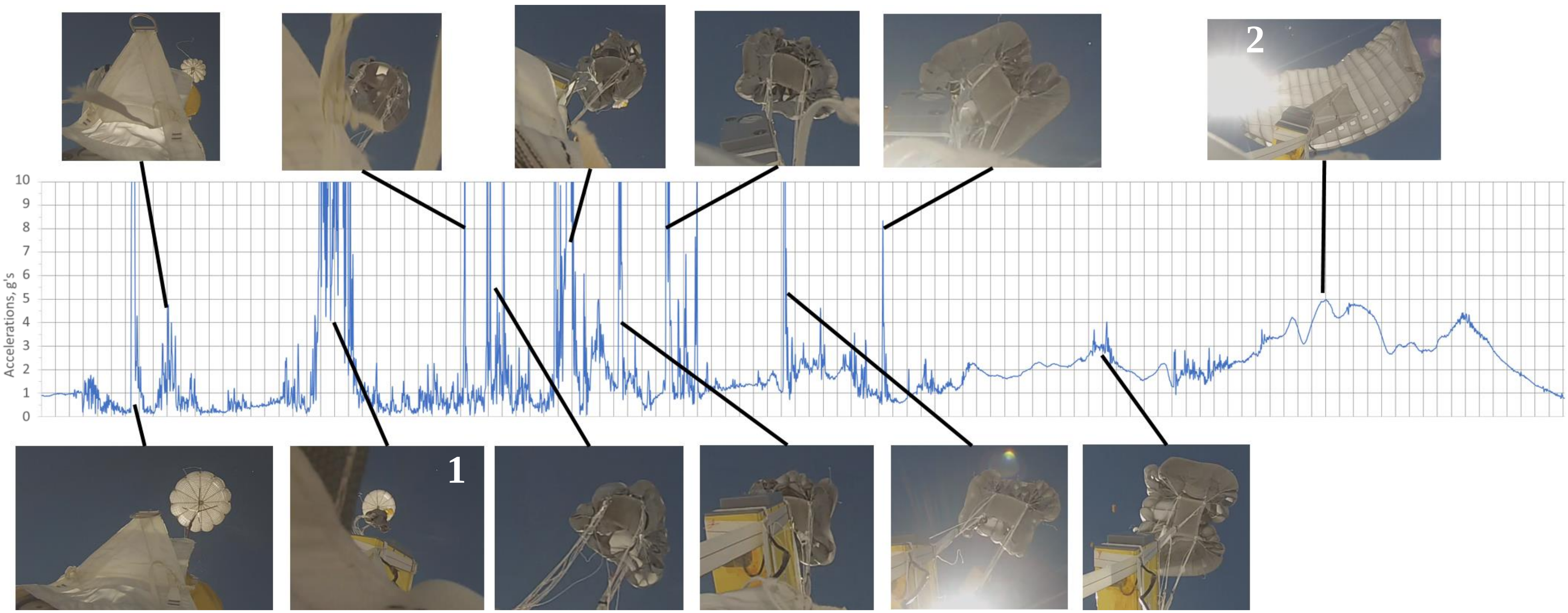


Figure 28. Main Parachute BFS Inflation Loads.

It is normal that spikes occur early during the deployment as a result of individual knocking, or other structural settling, of hardware items as the parachute system is being extended, such as the initial loaded contact between snap hooks and the payload attachment rings. Fewer total component of a payload and the load path can minimize these events. Filtering the acceleration data typical for elastic textiles normally includes some averaging of values and often also a minimum dwell time. On reducing the data with an average of values over 0.025 seconds, and taking a minimum dwell time of 0.05 seconds, the main parachute deployment and inflation loads are shown in Figure 29.

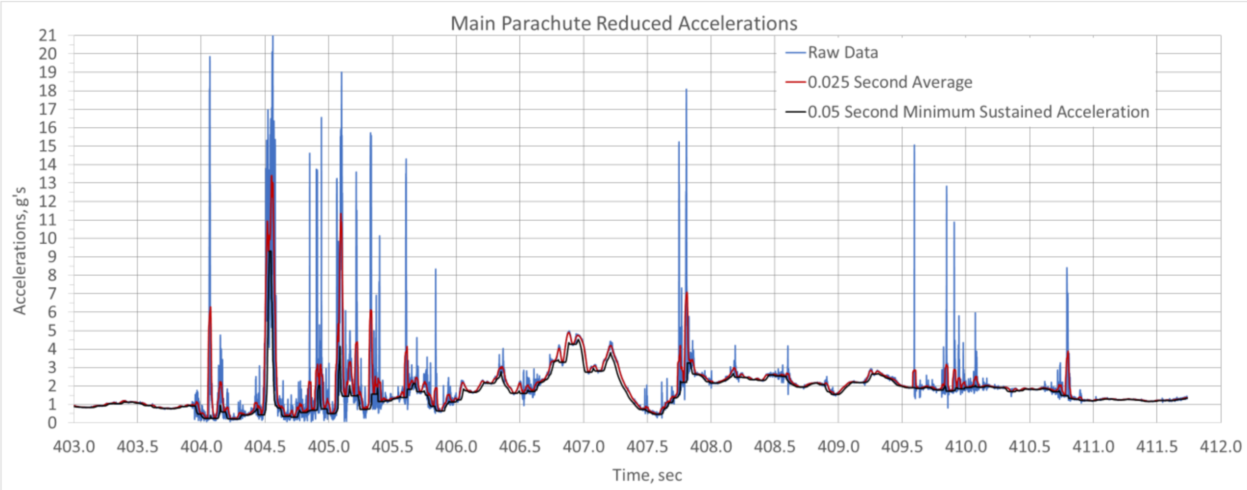


Figure 29. Reduced BFS Inflation Loads.

The adjusted curves show the two expected characteristic peaks as being the largest acceleration events of the deployment and inflation (about 404 – 407.25 seconds on the accelerometer timeline). Accelerations after this, notably the peak at about 407.75 seconds, are to do with twisting between AGU and payload. The left and right parachute riser groups remained separated into left and right sling groups below the AGU. Accordingly, the sling system had left front and rear slings which were separate from right front and rear slings. This resulted in the ability for torsional coupling and loading and unloading of slings in response to rotational inertia. The below figure shows an instance where the front right riser is slack (partially blocked by black wire).

Figure 30. Right Front Sling Slack.

	Accelerations, g's	
	Snatch	Inflation
Raw	20.93	4.99
0.025 sec Average	13.33	4.87
0.05 Dwell	9.26	4.45

Table 4. Summary of Peak AGU Accelerations.

C. Impact Accelerometers

Impact shocks are a key metric for appropriately designing vehicle structural systems. High altitude balloons of this magnitude have relatively small vibrational and maneuvering loads during ascent and cruise, but must sustain extremely short duration accelerations during release, canopy deployment, and impact. These acceleration spikes drive many of the gondola structural requirements, which often impose a 2x factor of safety (FOS) on largest observable loads. The accelerometer data was sampled at 800 Hz, and processed using a 7th order Butterworth lowpass filter with a passband frequency of 20 Hz, and a stop band frequency of 60Hz with a stopband value of -60 DB. Signals above 20 Hz were considered noise due to the mechanical configuration of ANGEL and the specific sensors used. Removing high noise shocks resulted in a total (XYZ components combined) 2 g separation load, 6 g parafoil shock, and 17 g landing shock. These loads were recorded from sensors directly hard-mounted the payload exoskeleton and are independent from accelerations observed from the AGU. Future missions could avoid loads of this magnitude with a variety of attenuation techniques.

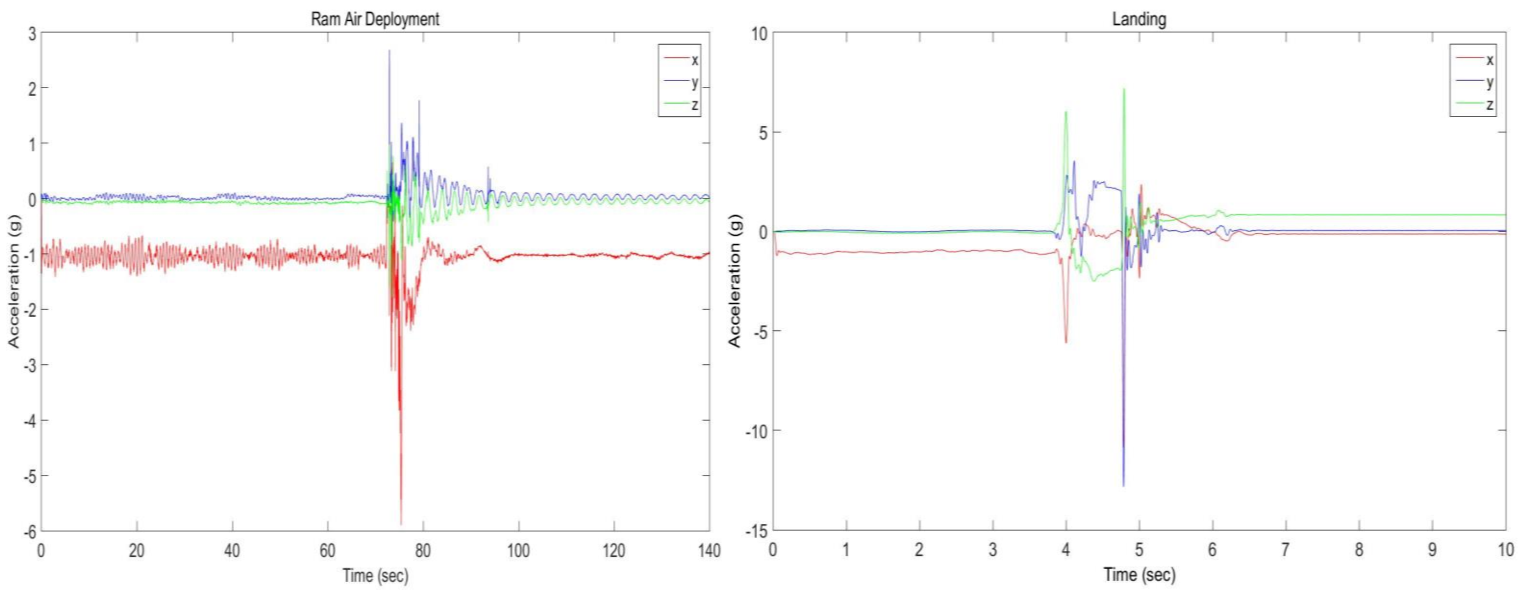


Figure 30. BFS acceleration loads due to canopy deployment (left) and ground impact (right).

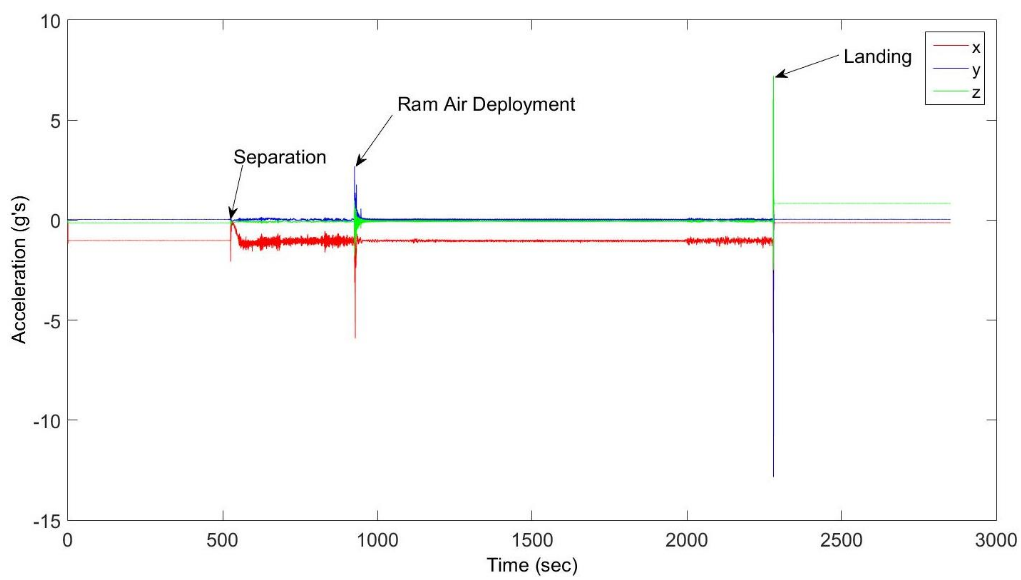


Figure 31. BFS loads displayed over the entire descent segment.

D. Temperature Review

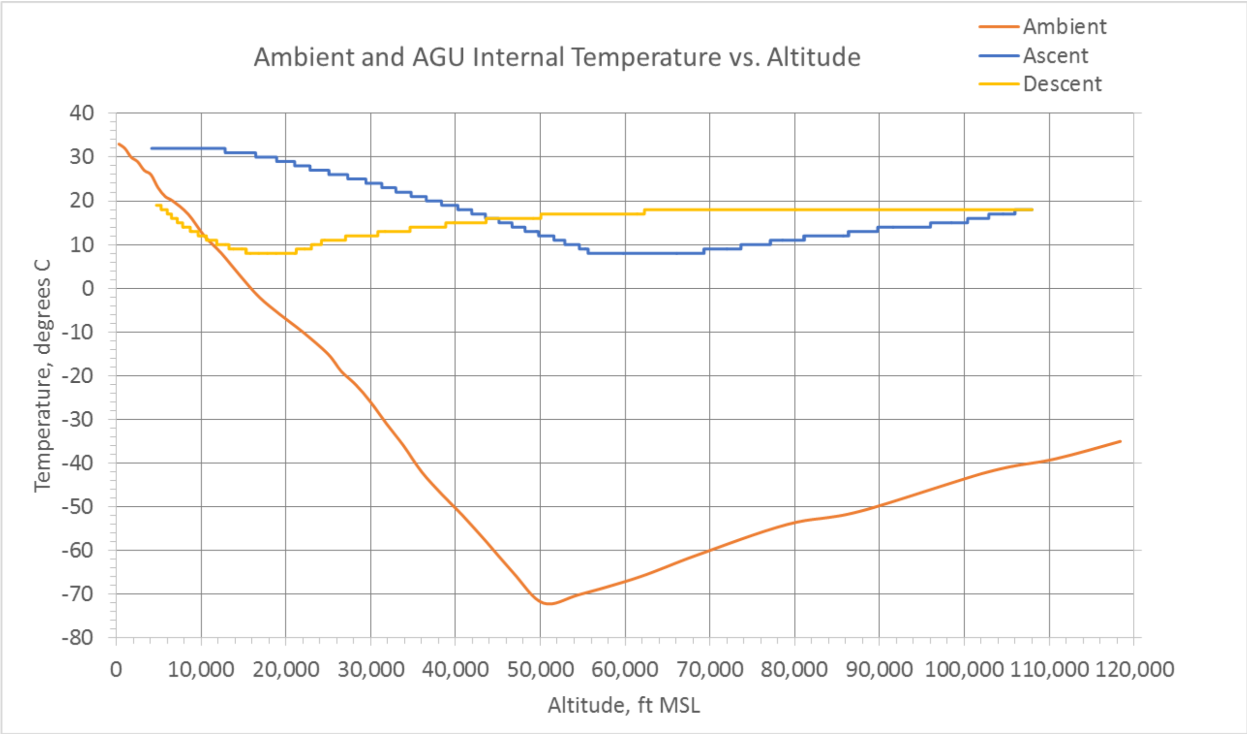


Figure 32. Battery Thermal Maintenance Throughout Flight.

The AGU battery thermal maintenance system successfully maintained a safe battery compartment temperature of greater than 8 C during both ascent and descent, which is well above the requirement of -20 C. The left shifted trough of temperature in the descent curve is due to quick descent (wind chill) and the thermal inertia of the system.

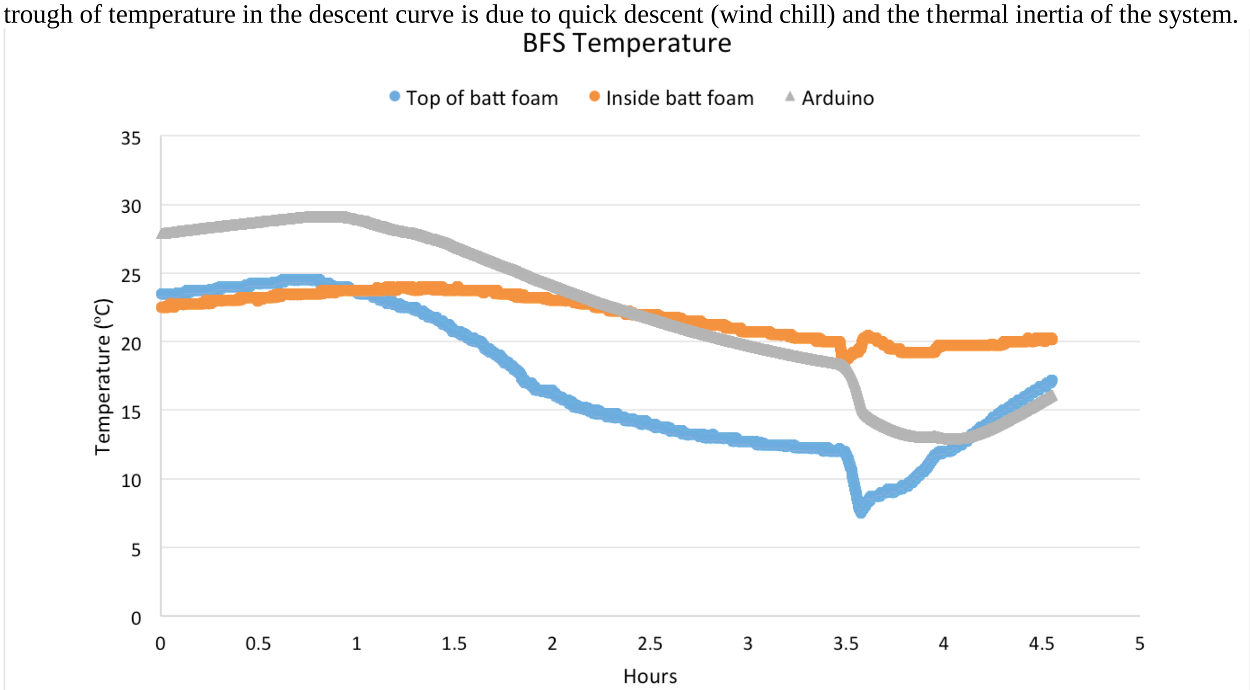


Figure 33. BFS Temperature for the avionics, internal and external battery temperature.

Similarly inside the BFS, thermal management is necessary to keep the flight electronics within their operational temperatures. Figure 33 shows the temperature rise within the first hour as the payload sits. The temperature almost linearly decrease during the ascent of the gondola, with the Arduino staying roughly 5ºC warmer due to electronic waste heat captured in the plastic enclosure. The battery never fell below 18ºC, the ambient gondola temperature stayed above 7ºC and the Arduino stayed above 12ºC. Thermal management was completely passive, with all components contained within two inch thick R-10 insulation foam. The battery was enclosed in a secondary case of foam that was included in the battery pack.

E. AGU Telemetry

The AGU successfully maintained contact with the Ground Station for the majority of the flight. Only minor short dropouts were experienced. Near constant communication with the GPADS is required if a modification to the mission plan is desired, such as a new landing location based on differences in anticipated and actual ground track during ascent. Figure 9 shows the Ground Station ground track in white. Gaps represent brief telemetry losses.

Figure 9. Ground Track as Observed from Ground Station.

VII. Lessons Learned

The ANGEL drop test program has provided valuable experience which has led to a number of lessons learned for high altitude GPAD system applications. The following lessons learned will be useful guidance in subsequent development efforts and drop testing.

- Light and radiation protection needed to protect textiles for long duration missions. Inspection of textiles which were exposed during ascent were not recovered and could not be evaluated, however, their functions were performed nominally.
- Preparations before mission planning should include a suitable number of IP options which can account for a TBD variation of predicted vs. actual winds. This will allow for an IP change mid flight if necessary to ensure a quick recovery..
- This launch provides a valuable data point for the difference between predicted and forecast ground track for high altitude balloon flight (108,000ft MSL, 150 minutes of ascent). In the ANGEL experiment, the actual ground track was approximately 9 km offset from the forecast ground track at release. This information will be useful in determining the number and spacing of IPs to be scouted for future high altitude balloon flights.
- For GPADS that are released from high altitude or have long dwell times at target altitude, the differences between forecast and actual winds accumulate with time. Predicted ground tracks are expected to be less accurate when durations are longer. Consequently, the number of suitable IP's, appropriately spaced, should probably increase as a function of time from launch to release.
- As precision balloon recovery becomes more prevalent, generating a map of adequate landing IPs for a given test range would be very useful. Entering scouted IPs, along with pertinent landowner contact information, into a databank, would allow quick and flexible mission planning, improving the overall likelihood of mission success.
- Use a low elastic material, such as Kevlar, as the attenuation strip. This will reduce rebound of the attenuation strip.
- Lengthen the attenuation tear out distance for as long as is estimated as necessary until the drogue is inflates.
- Consider adding a cutter to the attenuation strip and having it release at the drogue apex after about 4 seconds of fall. This would eliminate the possibility of the attenuation strip interacting with any of the ANGEL components after separation from the gondola. The attenuation strip would have a relatively long strip out length on the order of 300 ft. Alternatively, design an attenuation strip which does not split into half but which detaches at the drogue apex end.
- Consider sewing stiffener material into the drogue bridle to help it remain straight during the initial seconds when there is no stabilizing drag force generated by the drogue.
- There is a desire to make the deployment altitude of main parachute and / or the backup timer adjustable variables *after* launch. If this capability existed on this flight, a higher deployment would have been used to ensure the system could achieve the target IP.
- In retrospect, some of the hazard restrictions were a bit extensive, by relative comparison, given nominal balloon recoveries are unguided ballistic descents and have fewer fine-grain restrictions. For example, the Thunderbird gondola on this flight has the potential to cause much more damage due to the mass involved. Future flights should have a more careful review of the hazard avoidance requirements to remove unnecessary conservatism.
- For GPADS that use a sling set between AGU and payload, it's recommended to incorporate a confluence to prevent coupling between payload yaw and AGU / Canopy, when desired vertical distance between AGU and payload allows for confluence geometry.
- Small turn input strokes were too quick and resulted in some oversteering. A more efficient flight path could be achieved by making changes to the strokes and turn logic.
- Partially collapsing the drogue or using an attenuation strip between AGU and payload *after* drogue release will control the loads into the deployment bag and reduce the snatch load event when line stretch is reached.
- Consumable materials, such as honeycomb, should be attached to the payload, AGU, deployment bag, etc., to prevent becoming FOD during deployment or other operations.
- Incorporation of a GPADS suitable payload mounted range finder could provide altitude information for off landing flaring operations.

VIII. Conclusion

Overall, the experience of the ANGEL drop test program has provided the necessary results, data, and findings on critical operations of high altitude recovery GPADS applications.

The successful operation of the AGU components, batteries, avionics, etc., through these environments and across the duration of flight represent a major validation of the GPAD system AGU for high altitude recovery. Future test flights should seek to expand on system capabilities demonstrated such as increased AGU capabilities, parachute deployment performance, mission planning, and system autonomy.

While the AGU performed as desired, interest exists for expanding the system capabilities to higher altitudes, up to around 130,000ft MSL, longer float times, and faster terminal velocities. Altitudes and float times will tax battery management, and travel at speeds at, near, or over Mach 1 will require system designs robust to vibrations and payload stability.

The parachute deployment displayed good opening characteristics and was relatively clean and organized. Parachute deployment forces were reasonable for the parachute inflation, at 4.45 g's, but could be improved to reduce snatch forces, which were a minimum of 9.26 g's. Further development of the parachute deployment would include testing at higher handover velocities, which could be required by real application requirements.

Mission planning performed nominally within the variances arising high-altitude balloon deployment over conventional airplane drops. Since existing commercial mission planning tools and practices were used for essentially a near space application, the ANGEL system landed short approximately 3 km. The shortfall is primarily due to the difference in predicted vs. actual ground track ascent over such a long ascent time and an insufficient number of alternate landing points, IPs. All indications are that an accurate landings can be successfully planned prior to launch.

More premeditated mission planning, improved processes for real-time flight decisions and high altitude flight software development need to be a major focus of future tests. Mission Planning can be improved in many ways as mentioned in the lessons learned to reduce pre-flight uncertainty. Logistically, scouting an adequate number of acceptable impact points based on a wind forecast might be impossible. In the time required to identify IPs and gain landowner permission, the forecast could change, requiring all new IPs. Mission planning development should focus on gathering of a suitable number of IPs, appropriately spaced, prior to launch, and a commensurate change in the flight software where the selection of suitable IP is determined autonomously by the AGU. Longer float times may require more logistical planning as telemetry range with the ground station, necessary for in flight mission changes, may be challenged. Multiple ground stations may be required along the anticipated path of the balloon.

In addition to the autonomous selection of the IP, the flight software could be modified to make the altitude of main parachute deployment and backup timer adjustable based on actual flight. Higher altitudes could allow more offset and lower altitudes could result in reduced exposure to undesirable winds. Minor changes to the steering and turn management portion of the software will eliminate the oversteering observed in flight, should the same canopy continue to be used.

Other areas of focus for future high altitude balloon flights would be to fly GPADS at different wing loadings and / or larger scale canopies. Currently, four GPAD systems make up the weight range from 250-10,000 lbm payloads. Space application GPAD systems are likely to have a reduced weight range per system, depending on payload requirements, resulting in more systems / sizes to cover the same weight range.

Balloon trajectories often have a degree of uncertainty that is unavoidable before launch; in these scenarios, increased autonomy and access to the proper information can improve real-time mission critical decisions. Multiple complex variables must be considered simultaneously when determining the optimal moment for balloon separation, including estimating the balloon heading, estimated direction of drogue fall, wind speeds at multiple altitudes. Much of this data is available in real-time, however software can be improved to reduce the overhead in distilling all these factors down to a context that better allows mission operators to weigh decisions. This could include clearer estimates of the remaining drop window, and continuous linear quadratic estimation or monte carlo projections to better quantify increasing or decreasing probability of mission success. The addition of an external rangefinder on the bottom surface of the payload, in combination with GPS data, could also dramatically improve the ability to flare the parachute and mitigate landing loads.

The ANGEL program also identified and successfully demonstrated solutions to secondary design considerations influenced by the use of GPADS. The flight validated the AGU's operation in very close proximity to foreign radio transmitters, GPS receivers and large metal obstructions. The novel separation device provides a well tested method for cleanly side mounted payloads, when space is highly limited on the top face of the payload. Temperature and acceleration loads were also well characterized for a basic scientific payload configuration and provided in Appendix B. Overall, the system performed exceptionally with respect to the novel engineering challenges associated with high-altitude recovery and the flight identified multiple straightforward improvements to make future GPAD missions even more successful.

Acknowledgments

The authors would like to thank the contributions from the Rocket University cohort, numerous Glenn Research Center mentors, Columbia Scientific Balloon Facility, and Airborne Systems for the efforts to make this flight test a reality.

References

AIAA-2015-2121; "Guided Parafoil High Altitude Research (GPHAR) Flight at 57,122 ft", S. Dunker, 2015

Appendix

Appendix A.

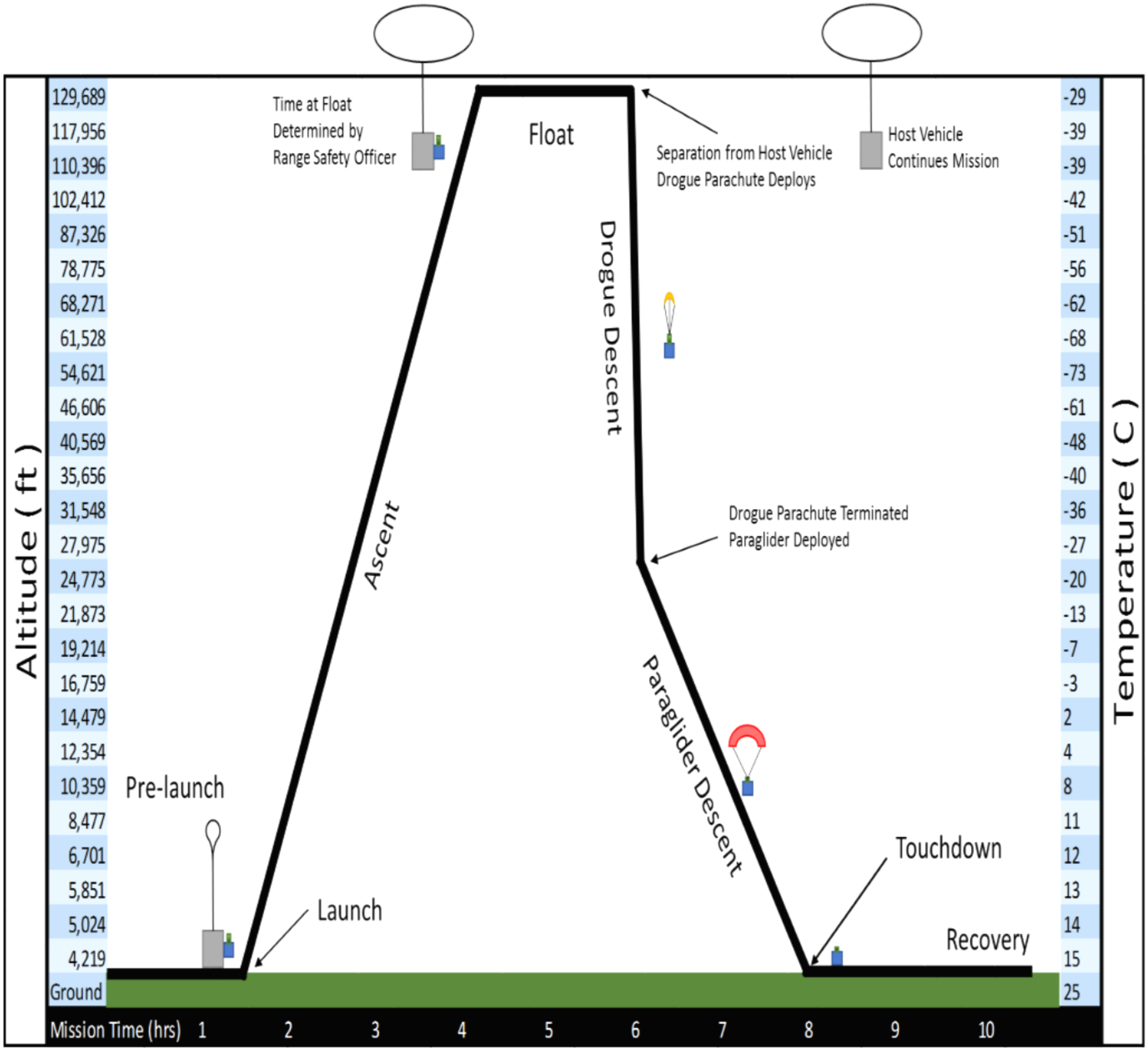


Figure 33 Initial Concept of Operations

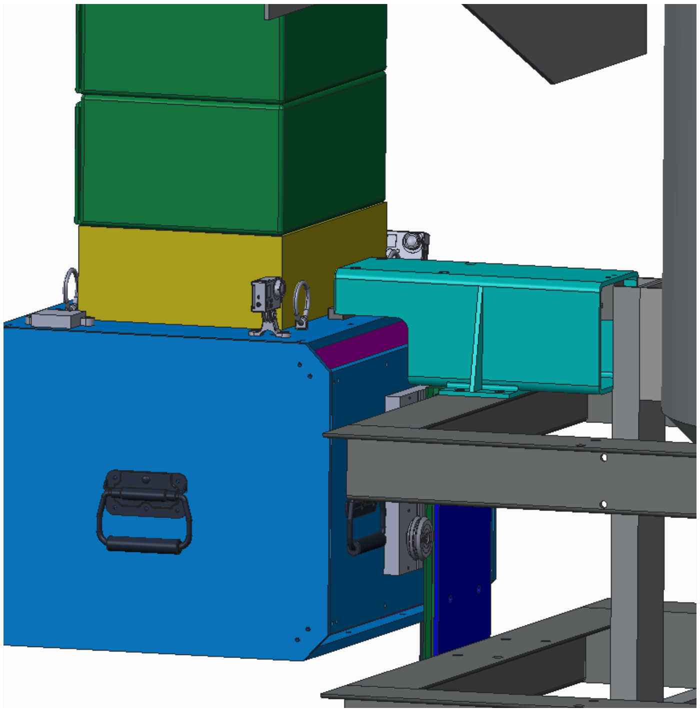
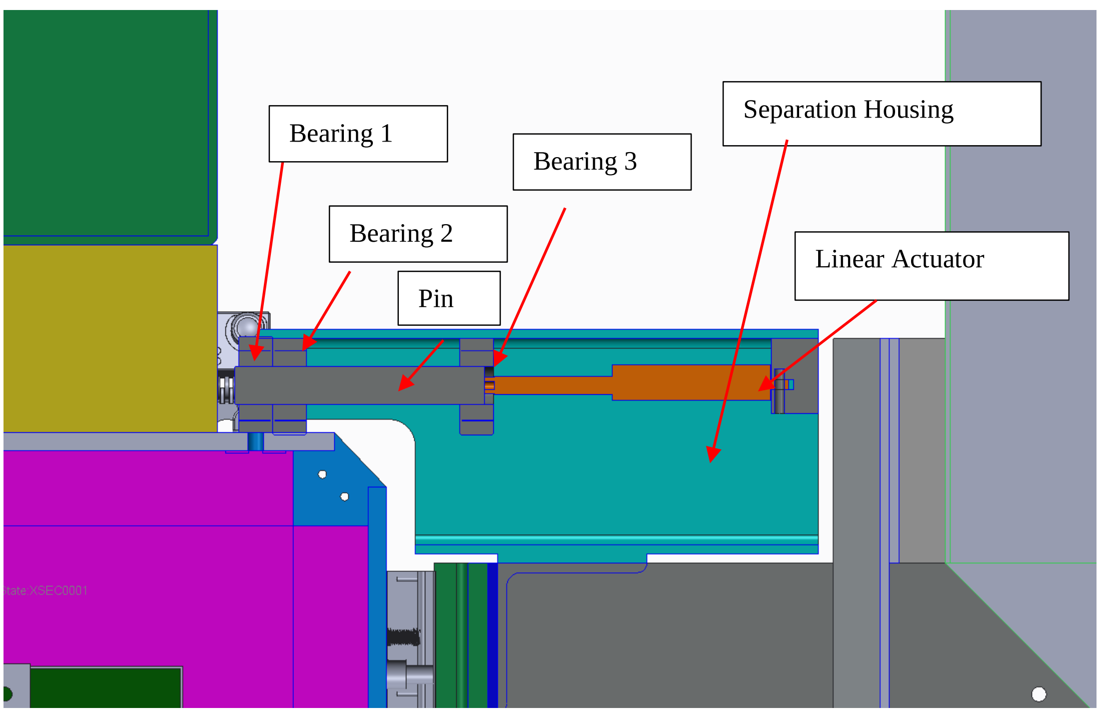


Figure 34 Side and internal view of the single point separation pin and actuator assembly. Bearing 1 is attached to ANGEL, everything else is mounted to the top face of the separation housing.



Appendix B. Source Code

This repository contains avionics source code, engineering calculations, enclosure CAD files, and information regarding avionics construction. https://github.com/jcchin/ANGEL

Raw descent data can be found here:
https://www.google.com/fusiontables/DataSource?docid=1lZTmZSFnDH9bnoQ4QQp47oI-ix9MRaUNMlzMKnpA