NC STATE UNIVERSITY

Tacho Lycos
2021 NASA Student Launch
Flight Readiness Review Addendum

High-Powered Rocketry Club at NC State University
911 Oval Drive
Raleigh, NC 27695

March 29, 2021

Common Abbreviations & Nomenclature

AGL	=	above ground level
APCP	=	ammonium perchlorate composite propellant
ARRD	=	advanced retention and release device
AV	=	avionics
BP	=	black powder
CDR	=	Critical Design Review
CG	=	center of gravity
CP	=	center of pressure
DÁVÍD	=	Device for Assisting in Validation of Integration and Deployment
EIT	=	electronics and information technology
FAA	=	Federal Aviation Administration
FMEA	=	failure modes and effects analysis
FN	=	foreign national
FoS	=	factor of safety
FRR	=	Flight Readiness Review
HEO	=	Human Exploration and Operations
HPR	=	High Power Rocketry
HPRC	=	High-Powered Rocketry Club
L3CC	=	Level 3 Certification Committee (NAR)
LCO	=	Launch Control Officer
LOPSIDED	=	Lander for Observation of Planetary Surface Inclination, Details, and Environment Data
LRR	=	Launch Readiness Review
MAE	=	Mechanical & Aerospace Engineering Department
MSDS	=	Material Safety Data Sheet
MSFC	=	Marshall Space Flight Center
NAR	=	National Association of Rocketry
NCSU	=	North Carolina State University
NFPA	=	National Fire Protection Association
PDF	=	Payload Demonstration Flight
PDR	=	Preliminary Design Review
PLAR	=	Post-Launch Assessment Review
POS	=	Planetary Observation System
PPE	=	personal protective equipment
RFP	=	Request for Proposal
RSO	=	Range Safety Officer
SL	=	Student Launch
SME	=	subject matter expert
SOW	=	statement of work
SSTV	=	Slow-Scant Television
STEM	=	Science, Technology, Engineering, and Mathematics
TAP	=	Technical Advisory Panel (TRA)
TRA	=	Tripoli Rocketry Association
VDF	=	Vehicle Demonstration Flight

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1.1 Team Summary

1.1.1 Team Name and Mailing Address

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1.1.3 Time Spent on FRR Addendum

The team spent a total of 100 hours working towards completion of the FRR addendum.

1.2 Purpose of Flight

The flight conducted on March 27, 2021, was performed to fulfill the requirements of the Payload Demonstration Flight, as well as for a Vehicle Demonstration Re-Flight for the changes to the main parachute bay, forward AV bay coupler, and recovery harness specified in the FRR document.

1.3 Flight Summary Information

The following table provides a summary of the flight conducted on March 27. This flight was originally scheduled for March 20 as of the FRR milestone, but excessively high winds forced the team to delay launch to the backup launch window on March 27.

Table 1-1 Flight Summary

Date	March 27, 2021
Location	Bayboro, NC
Time	17:14 EDT
Temperature	76°F
Pressure	30.06 inHg
Humidity	71%
Wind Speed	10 mph
Motor Flown	Aerotech L1520T
Final Payload Flown	Y
Airbrake	N/A
Ballast Flown	N/A
Target Apogee	4473 feet
Predicted Apogee	3174.5 feet
Achieved Apogee	3087 feet

During the recovery sequence, the drogue parachute failed to fully unfurl. As a result, the main parachute deployed while the fin can was hanging above the rest of the launch vehicle.

This resulted in the fin can falling through the main parachute, which damaged some of the main parachute shroud lines. No additional damage to the launch vehicle occurred as a result. This is discussed in more detail in Section 3.1.

1.4 Changes made since FRR

1.4.1 Payload Integration and Deployment

The major change to payload integration at the FRR milestone was the addition of an Arduino Nano. It was mentioned in the FRR document that the Nano was going to be implemented directly onto the nose cone bulkhead; however, the actual setup changed. The Nano is now connected to its own 12V battery mounted to the nose cone bulkhead. A TB6612 motor driver has been added to translate the output signal from the Nano to 12V of electric signaling to the rotary latch.

1.4.2 LOPSIDED

LOPSIDED leg attachment brackets were intended to be elliptically curved in order to provide additional shock absorption and lessen the landing deceleration. This design was altered slightly to feature straight bracket arms instead of curved. This decision was made mainly due to the manufacturing tools available to the team. The outside bracket was straight while the inside bracket was bent at 45 degrees in two places. This allowed the legs to fit closer to the body so that it could fit inside the payload bay. The legs ended up being too close to the body, not allowing them to lay flush with the lower section making it impossible to fit within the inside coupling of the payload bay. In order to fix this, a section of the lower body was routed out to allow the legs to lay flush.

Another change was made to the leg splay angle system. Two torsional springs force the legs to splay out. The original intention was to set the leg splay angle to a fixed angle using a cable that wrapped behind the leg mounts on the outer ring. The team had designed this system to use a 1/16” steel cable. The cable that the team selected was not strong enough to endure the forces encountered by the legs. Multiple tests were conducted to see how the cable would react. The cable would stretch considerably and then break. This meant that not only could the legs not be set to a desired angle because the stretching would change that angle, but they would not be able to withstand landing forces and the payload could not land evenly. The solution to fix this problem was to increase the cable strength by braiding it and treating it as a shock absorber. The stretch would help absorb some landing energy, but the legs would not be entirely reliant on the cables. Neighboring legs were tied to each other using short lengths of shock cord. This also helped to set the leg splay angle but was much stronger than the braided cables, so that LOPSIDED could land on impact and not be destroyed.

Figure 1-1 Leg Shock Cords

Figure 1-2 Braided Leg Cable

Another change to the lower section includes having a face of the lower section be removable. It was designed originally to be glued together, but after some difficulty fitting in the electronics sled, it was decided that having a face that could be attached using wood screws would allow the sled to fit in better while giving better access to the electronics when connecting wires.

After multiple drop tests, the method of mounting the four locking solenoids was deemed too weak. 3D printed brackets reinforced with metal were fashioned and bolted onto their mounting surfaces. This greatly increased the strength as the team found that the previously used epoxy and 3D printed brackets alone resulted in the solenoids shearing off.

1.4.3 POS and Payload Electronics

It was realized that acceleration data from the on-board 9-DOF orientation sensor would not be sufficient to initiate important payload events such as parachute release. For this reason, a pressure sensor was added within the lower section of LOPSIDED, wired directly to the Raspberry Pi. This sensor allows the Python flight script to utilize multiple different conditions before initiating and timing-specific payload events. This is especially crucial for the release of the payload parachute. Since the parachute is designed to be released as soon as the LOPSIDED-POS lands, improper detection of payload landing could result in premature release of the parachute and ultimately a critical mission failure. The pressure sensor is an Adafruit BMP280, which is able to read and provide altitude data based on detected pressure, accurate up to ±1 m. This pressure sensor can be calibrated the day of launch using local altitude above sea level and barometric pressure readings.

2. Payload Demonstration Flight Results

2.1 Mission Overview

When the launch vehicle reaches apogee, a rotary latch attached to the payload bulkhead opens, which will allow the LOPSIDED-POS to be removed from the payload bay. This ejection occurs at 700 feet, when the main parachute deploys and pulls the LOPSIDED-POS from the payload bay. The LOPSIDED-POS will descend with the launch vehicle main parachute until 500 feet, when an Advanced Retention Release Device (ARRD) attached to the top surface of the LOPSIDED-POS, separates the payload from the main parachute shock cord. This event also releases the LOPSIDED-POS parachute from its parachute bag and allows the payload to descend under its own parachute. Once the LOPSIDED-POS lands, two electronic latches will open to release the parachute, and the initial surface inclination of the landing site will be recorded. Then, the solenoid latches will open to release the gravity-assisted leveling system, and the final angle post-leveling will be recorded. After this, the POS will initiate the image capture sequence, the images will be processed and compressed as necessary, and the images will be transmitted to the team's ground station for further processing.

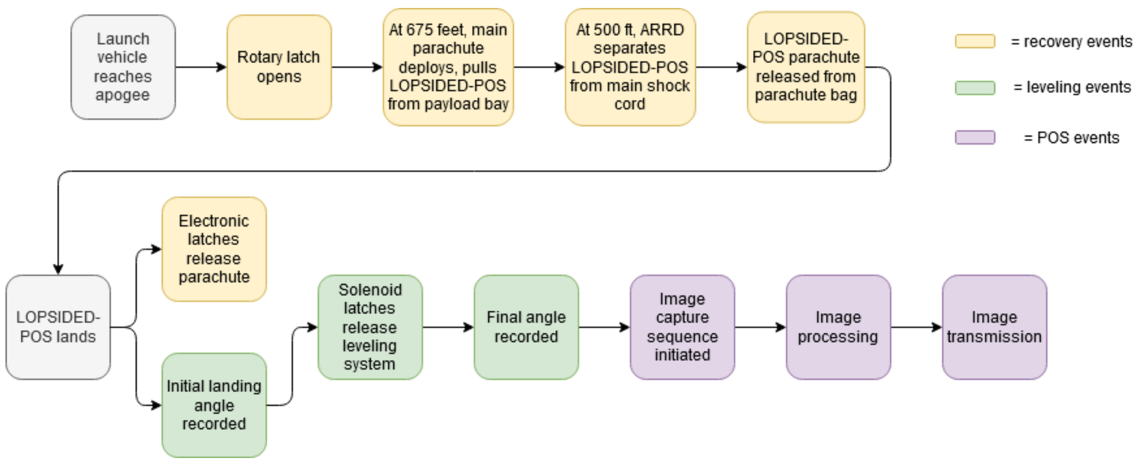

Figure 2-1 LOPSIDED-POS Mission Overview

2.2 Payload Integration and Deployment Mission Performance

The results of payload integration and deployment are considered successful given that two out of three systems worked as intended. The three systems are payload integration, payload deployment and post-landing parachute release.

2.2.1 Successes

Overall Payload integration and deployment went as intended and can be classified as successful. It was successful because the rocket contained the payload through ascent, the retention latch disengaged at apogee, and deployed the payload at the intended altitude. Then, the payload proceeded to hang off the main parachute shock cord and was detached as intended using the ARRD. Moreover, the payload parachute remained connected to the payload parachute release latches, though one was secured by zip ties for load capacity reasons that are discussed later.

Figure 2-2 LOPSIDED-POS Descending Separately from Launch Vehicle

As seen in the Figure 2-2, the ARRD deployed as intended. The pin and toggle were detached from the ARRD and remained attached to the main parachute shock cord. It is also seen in Figure 2-2 that the electromechanical lock on the left deployed while the electromechanical lock on the right remained attached to the parachute. The lock on the right remained attached to the parachute due to the zip ties preventing the lock from unlatching. This is due to strength issues discovered during drop testing that are discussed later. The lock on the left released its locking pin and therefore that side of the parachute connection before touchdown off the payload. The team knows that the lock released before landing because the pin could not be found near the payload landing area. This means that the team made the correct decision to secure the other lock with zip ties to ensure that the payload would not drop away from the parachute prior to landing.

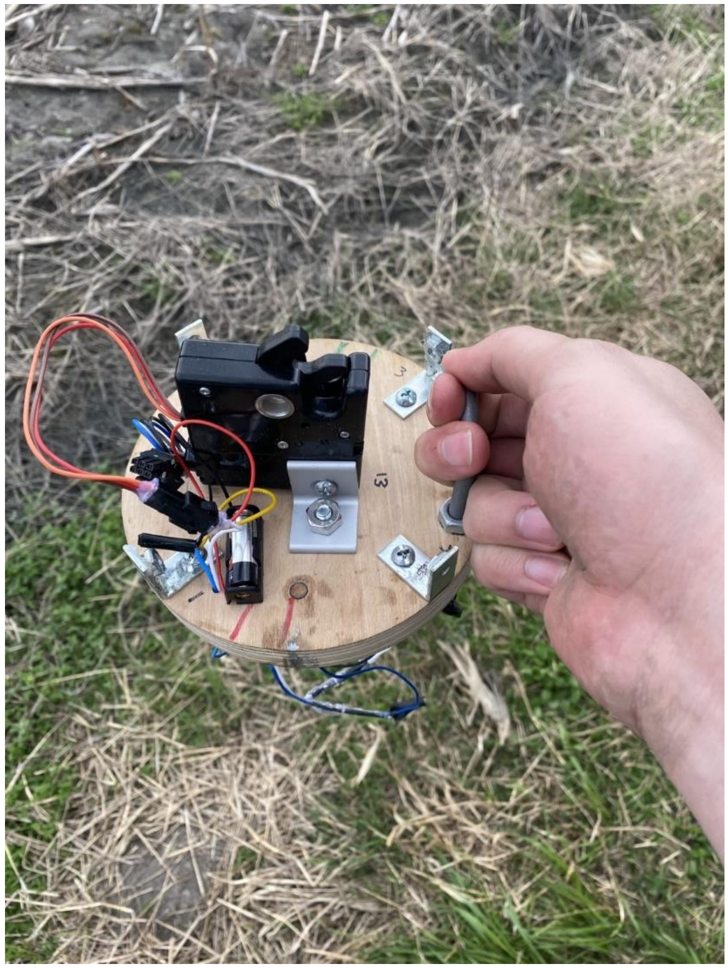

Figure 2-3 Unlocked Rotary Latch on Nose Cone Bulkhead

As seen in Figure 2-3, the nosecone bulkhead remained intact with exception of the 3-D printed battery housing. The battery housing was pushed up on one side given that the nut was not threaded to the screw. This however did not cause any problems given that the battery housing is intact and re-usable. This Figure 2-3 also shows how the Arduino Nano was attached to the nose cone bulkhead. The Nano was attached to the board along with a voltage regulator, a voltage buck converter, a motor driver, and a USB power cable.

2.2.2 Failures and Lessons Learned

The two minor issues that have to be dealt with are the battery of the Nano, which can be replaced by a 9V battery, and the loss of one of the electromechanical lock pins. Ultimately, the parachute can be attached to the payload using the latches and the zip ties. If the Payload team decides to proceed with the detachment of the parachute upon landing, then the implementation of the rotary latch would be a robust system that can solve this problem. Payload integration will proceed to address the pins on the electromechanical locks to see if they work successfully before final launch. Payload integration will address the code to release the parachutes based on acceleration and altitude. Given that there was a problem with collecting pressure data from the pressure sensor the final decision will be made based on the safety of those at launch and the safety of the payload and payload electronics.

The payload was integrated using the R4-EM rotary latch attached to the nosecone bulkhead. The nosecone bulkhead contains the Arduino Nano to control the latch to unlock for 20 minutes after apogee is reached. As seen on Figure 2-4, the Arduino Nano was powered by a 12V battery that ran through a buck converter that dropped the voltage to the Nano to 5V. In addition to the 5V converter, the Nano was connected to a motor driver. The motor driver uses that 5V operating voltage in addition to the 12V from the rotary latch battery. One issue with this set up is that the small 12V battery only lasts around an hour and a half. One hour and a half is not enough given that there may be many setbacks during the implementation of the nosecone end or after; therefore, a new power set up needs to be implemented for the Nano. This can be done by replacing the 12V battery by a 9V battery that can last longer. The rotary latch was attached to the bottom of the payload body to the attachment point that is a U-bolt. During the launch, the rotary latch system worked as intended, as seen in Figure 2-3, where the latch is unlocked, the latch was controlled by the Nano so that it lasted 20 minutes unlocked once apogee was reached. The altimeter sends the signal to the Nano so that the Nano can activate the latch. The Nano setup was attached to a breadboard and the breadboard was attached on top on of the switch housing for the altimeter.

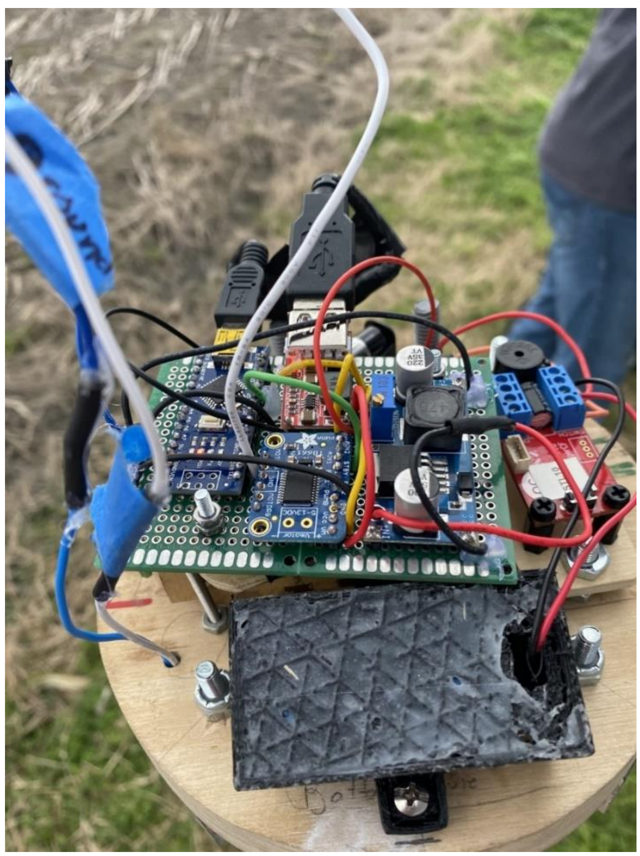

Figure 2-4 Arduino Nano Setup on Nose Cone Bulkhead

The second system is the ARRD. The ARRD was attached to the top of the payload as seen in Figure 2-5. Through a pin and toggle, it connected the payload to the main parachute shock cord. The ARRD works with black powder so that with the signal from the electric charge from an altimeter on the LOPSIDED electronics sled ignites the ARRD black powder. The spring test was implemented when assembling the ARRD. The spring test is to test with one's own fingers that the spring can be pushed in so that the pin can be released. If the spring test passes that means that the black powder can raise enough pressure so that inside the red can, the push cap can be pushed, and the spring can be free. This system worked as intended, which completes the deployment system, and it is recognized as a successful payload deployment.

The last system for payload integration and deployment is the parachute release devices. The parachute release devices are currently the two electromechanical locks. These locks were successfully tested for the drop test; however, they began to free the pin when it was not intended to free. This may be because the pins have a little bit of wearing on them from past uses either from testing or from adjusting the pin to the latch. In addition, one of the pins got lost during the payload demonstration launch. This leads the team to either make another pin or replace one electromechanical lock with a rotary latch. Currently both electromechanical locks do not work as intended as the locking pins can be removed simply by jostling them. A solution to this issue was to use zip ties on the latches and on the U-bolt that attaches to the parachute so that the lock would not release at all; this ensures that the lock is always attached to the parachute. It was required to keep the parachute permanently attached to the payload given that the electro mechanic locks could not be trusted with deploying at the intended time of landing. A solution for next launch could be to adjust the pins so that it cannot wiggle or replace one of the electromechanical locks for an extra rotary latch. The rotary latch is a more robust system that will also release the parachute more reliably as it does not have a pin that needs to be pulled by the payload parachute.

Figure 2-5 Electromechanical Locks, U-Bolt with Pins, and Payload Shock Cord

There were two successful Payload drop tests completed before the payload demonstration flight. The first drop test was done with the two electromechanical locks attached to the parachute on the pins with no zip ties. The second drop test was done with the electro-mechanical locks attached to the parachute with zip ties. The first drop test worked successfully as the pins were correctly attached and held together as intended. The second drop test could not be used with the same pins had already been worn out from the first drop test. The pins can no longer hold on to the payload after being pulled by the payload parachute upon opening. The drop test served to validate the structural integrity of the landing legs and leveling system, as well as to calibrate the accelerometer used to command payload parachute release.

For these tests, LOPSIDED was fully assembled and dropped from a high floor of a university building with the payload parachute, simulating flight immediately following release of the ARRD. The tests were partial successes given that the electronic locks held onto the payload body and to the parachute during descent and landing. However, the locks were only successful on the first test given that they did not need zip ties to hold onto the parachute. Prior to the second test the latches completely failed as they could not hold onto the parachute and could not be unlocked when intended. This resulted to the zip ties being added to the locks to secure the parachutes permanently during flight. The risk of LOPSIDED being dragged or tipped over is much more acceptable than the risk of LOPSIDED detaching prematurely from its parachute and entering a ballistic descent.

2.3 LOPSIDED Mission Performance

2.3.1 Successes

LOPSIDED was successfully removed from the payload bay without any interference caused by the legs. It survived all the forces that were planned for: the launch/vibrations, the deployment/ejection, the opening parachute shocks, and the landing force.

Figure 2-6 LOPSIDED Descending

The landing conditions were ideal, although it was most likely coming down faster than predicted, it still survived the landing and is in condition to fly again. There was very little wind and horizontal velocity which was the team's main worry about the payload being able to land upright.

2.3.2 Failures and Lessons Learned

Even though LOPSIDED had ideal landing conditions, it was moving fast and had very little shock absorption. The payload landed on all four legs and did not dissipate enough energy, it bounced back up and was pulled over its legs and settled on its side. Figure 2-8 shows the configuration after landing. In this picture it is shown that the legs hit the ground considerably hard, the four locations where the legs impacted had visible craters in the ground where each of the feet dug up the dirt. The payload falling over means that the leveling rings could not be tested to validate the vertical alignment tilting.

Figure 2-7 LOPSIDED Tipping on Landing

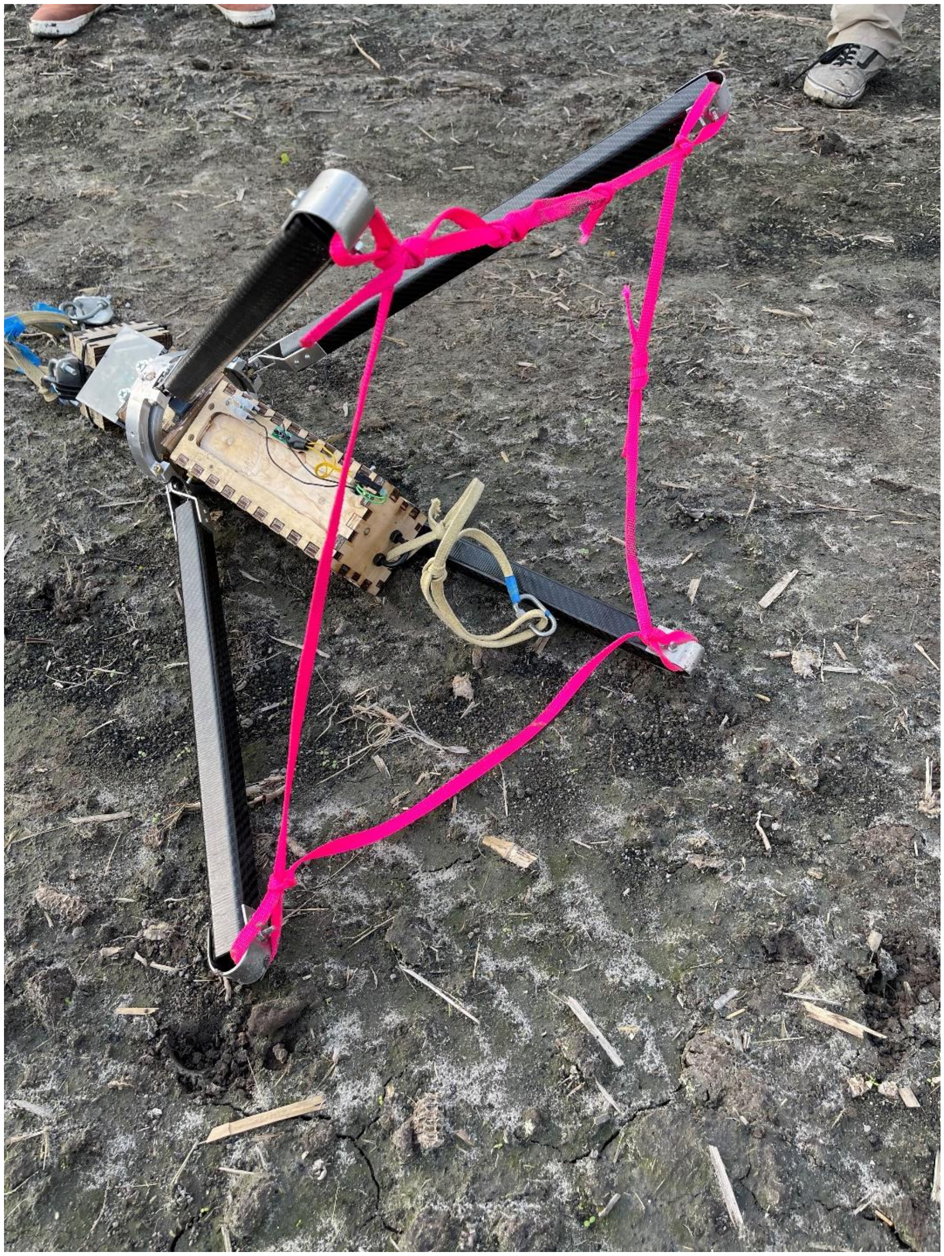

Figure 2-8 LOPSIDED After Landing

The benefit of the design using the shock cords to set the legs is that the splay angle and elasticity/shock absorption can be modified. The shock cord could be tied with longer lengths between the legs to increase the leg splay and there for the landing footprint decreasing the chances of tipping.

While all the solenoids and their mounts survived the fall, some of their nuts that were retaining them were loosened. This was most likely due to the team underestimating the vibrations from the launch and will be tightened better for the final launch.

Figure 2-9 Loose Solenoid Bracket Bolt and Nut

2.4 POS Mission Performance

2.4.1 Successes

Output from the Python launch script, saved to the Raspberry Pi using the nohup terminal command, confirmed the POS stepped through each payload mission event as intended. The on-board orientation sensor successfully detected launch acceleration, which initiated the payload mission sequence. Pre and post leveling angles were successfully recorded and saved to separate CSV files for post-mission analysis. Images from the four POS cameras were successfully captured and saved to the Raspberry Pi and were viewed post-launch. According to the script output, the parachute latches and solenoids were actuated, and the POS transmitter sent transmissions for fifteen minutes.

2.4.2 Failures and Lessons Learned

As mentioned previously, the ability of the POS to fulfill mission performance criteria is heavily dependent on the ability of on-board sensors to successfully detect specific in-flight events. The pressure sensor, which was added to improve the reliability of the flight script, failed to detect proper altitude date. The altitude recorded varies slightly between measurements, which were being recorded every 0.01 second, but never reads below 36 feet or above 39 feet. This clearly does not reflect altitudes reached during launch. Prior to launch, basic tests of the pressure sensor were done by raising and lowering the electronics sled by hand and observing the recorded results. It was noted that altitudes did not seem to vary significantly, and this was thought to be due to the tested altitude changes not being large enough for detection.

Since other events in the payload mission sequence are dependent in part on detected altitude changes, LOPSIDED-POS events did not occur when intended. The code is written in such a way as to initiate LOPSIDED landing detection when the LOPSIDED is below 500 feet, which is when it is released from the main parachute shock cord and descending under its own parachute. Since recorded altitudes never exceeded 39 feet, the conditions for LOPSIDED's landing were reached when the LOPSIDED-POS was still retained within the launch vehicle. If it was not decided to keep the parachute latches mechanically locked during flight, this would have resulted in an early release of the payload parachute prior to its deployment from the payload bay. This would have resulted in a critical mission failure and is a top priority for post-launch analysis and review.

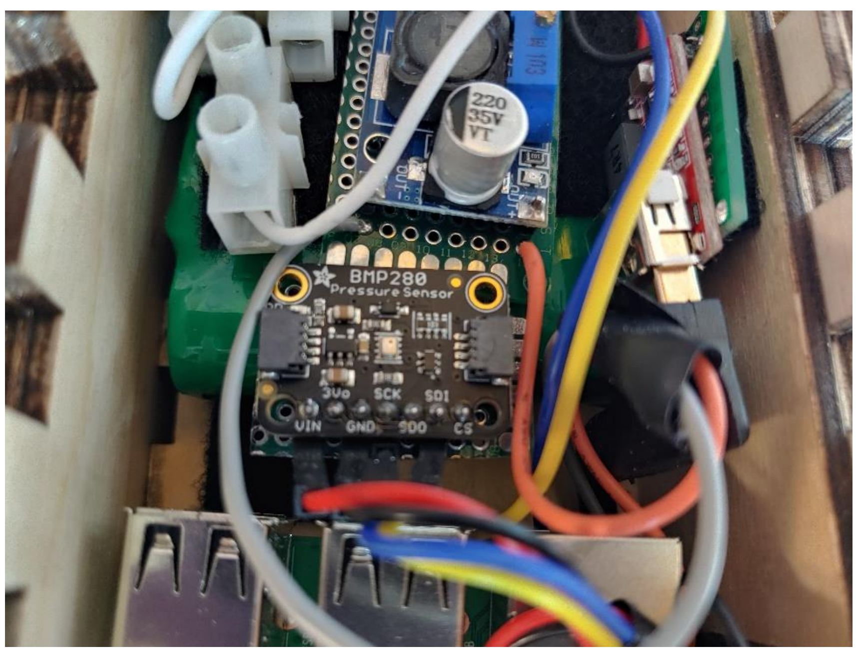

Figure 2-10 Adafruit BMP280 Pressure Sensor

More thorough testing needs to be conducted in order to confirm the validity of the selected pressure sensor. Compared to other electronic components, this sensor was incorporated very late into the LOPSIDED-POS design, which contributed greatly to its likeliness to fail. Subteam leads responsible for payload deployment and electronics will evaluate the performance of the sensor in further drop tests to confirm if it is a viable component for determining the instant that the LOPSIDED-POS lands. Above all else, the conservative nature of the flight script will be prioritized – that is, it will be more likely for the POS to fail to detect landing than to detect landing too early, an occurrence that would result in an early release of the payload parachute. Keeping the parachute release conditions conservative will ensure the safety of not only the payload, but those present during launch.

The self-leveling sequence and POS image capture are dependent on programmed time delays post-parachute release. The solenoid latches are being used as pull solenoids – that is, when they are powered on, their pistons are retracted. For leveling, the solenoids are actuated for 10 seconds before being returned to their original piston-out position. According to the script output, the solenoid latches were actuated, but since this actuation would have occurred while LOPSIDED's leveling rings were contained and secured within the launch vehicle, there is no way of knowing with certainty whether or not the leveling system successfully released.

Since the POS imaging sequence occurred while the LOPSIDED-POS was still within the payload bay, the captured POS images only show the interior of the launch vehicle. The LED light from the cameras, which are turned on while the cameras are capturing images, are reflecting off of the polycarbonate windows.

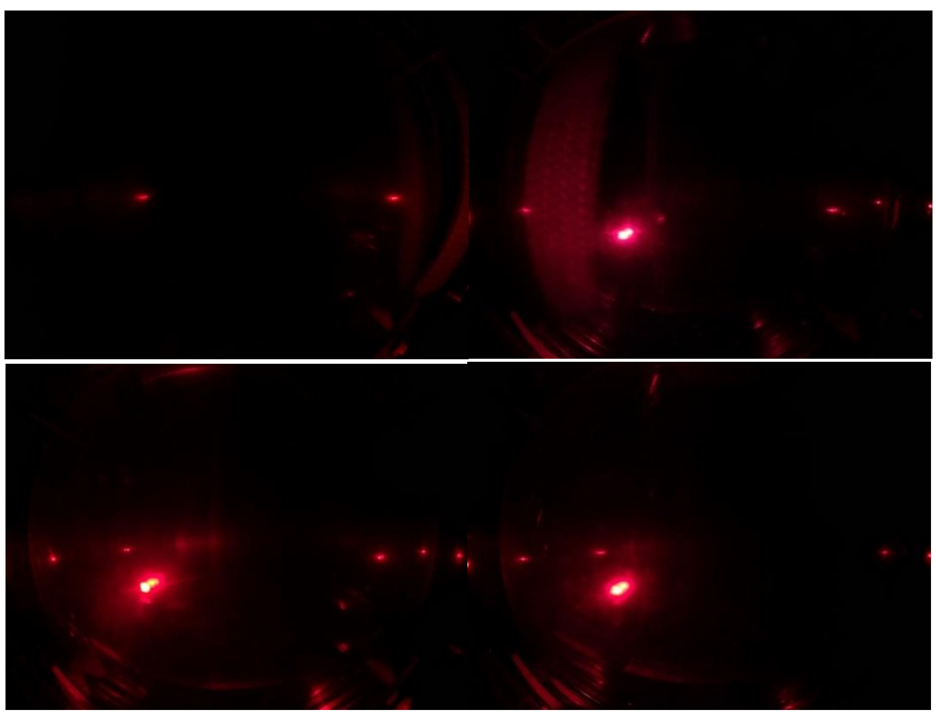

Figure 2-11 Raw POS Images Captured in Flight

After images were captured, the output script indicated via print statements that the POS transmitter was actively sending transmissions. However, these transmissions were not able to be received by the team's ground station. It is likely that this was due to an issue with the SDR receiver, or something within the lower LOPSIDED section preventing transmissions from being broadcasted. Prior to this flight, testing of the POS transmission method has only been conducted with the individual components necessary for its operation, and not as part of the completed LOPSIDED vehicle. Further testing will need to be done to ensure transmissions can be sent within the current vehicle set-up.

3. Vehicle Demonstration Flight Results

3.1 Launch Analysis

The flight was in many respects a success, although a partial failure occurred within the recovery system resulting damage to the main parachute. Figure 3-1 below shows the launch vehicle departing the launch rail.

Figure 3-1 Launch Vehicle departing Launch Rail

A single deviation from the nominal recovery sequence caused a cascading failure within the recovery system. The drogue parachute shroud lines and the base of the parachute were pulled through the attachment hole in the Nomex sheet used to protect the parachute during deployment preventing the drogue parachute from inflating. The cause of this failure is currently unknown, as no changes have been made to the successful drogue recovery harness assembly since the initial, successful vehicle demonstration flight. Currently the team's most plausible theory is that the parachute got jammed into the Nomex sheet during assembly of the drogue parachute. To prevent recurrence of this failure, the sheet will be attached to the drogue quick link. This will securely tether the Nomex sheet to the base of the drogue parachute shroud lines and eliminate any chance of this failure mode occurring again.

Figure 3-2 Drogue Parachute at Field Recovery

As a result of the failure of the drogue parachute to fully inflate, the launch vehicle was not stabilized during the first stage of its descent. This caused the more massive forward assembly to descend below the fin can. Analysis of video taken by team members clearly shows this during the main parachute deployment sequence. When the main parachute deploys from the forward assembly, the fin can continues falling at the drogue descent velocity. Video footage clearly shows the fin can and drogue shock cord impacting the main parachute shroud lines, and the resulting severing of the shroud lines. The field recovery team observed this damage to the main parachute shroud lines upon arrival at the landing site. This can also be seen in Figure 2-2 where the damaged shroud lines are present above the main (black and yellow) parachute canopy. No other damage beyond the damage to the main parachute shroud lines was sustained by the launch vehicle as a result of this failure.

3.1.1 Altimeter Flight Profile Data

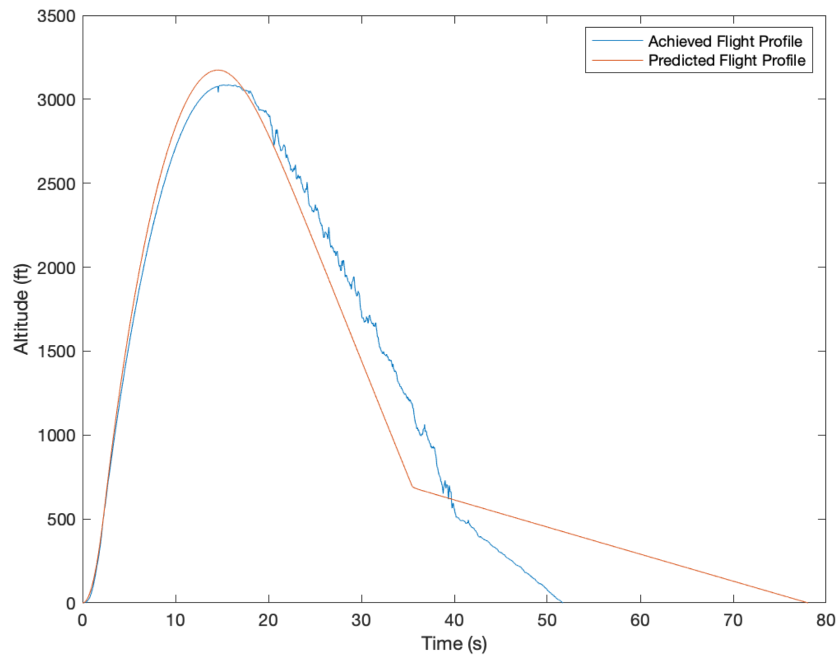

Figure 3-3 Predicted and Achieved Flight Profiles

The achieved apogee was 87 feet below the predicted apogee. The predicted apogee was calculated using the atmospheric conditions from launch day as outlined in Table 1-1, a 5° cant, a 144-inch launch rail, and a CD of 0.634, as was calculated in FRR.

The launch vehicle descent time was 37.4 seconds, which is less than half of the predicted descent time in the prevailing wind conditions of 77 seconds. This is due to the increased main parachute velocity achieved by the launch vehicle under the damaged main parachute. The drogue descent velocity remained close to the predicted drogue velocity. Coordinates of the launch and landing site were recorded, and an actual wind drift of 854 ft. was determined. This is slightly below the predicted wind drift of 1129.5 ft. but is in reasonable agreement with the predicted values since the flight took place during a slight lull in the wind.

3.2 Estimating Launch Vehicle CD

RockSim calculated the CD of the launch vehicle iteratively, but this value can be manually overridden to a determined static value. The CD of the launch vehicle was predicted by adjusting the CD of the launch vehicle in RockSim until an apogee was predicted that was identical to the apogee achieved. Using this method, the CD of the launch vehicle is estimated to be 0.71. The simulated launch profile of the launch vehicle with this adjusted CD is shown in the figure below.

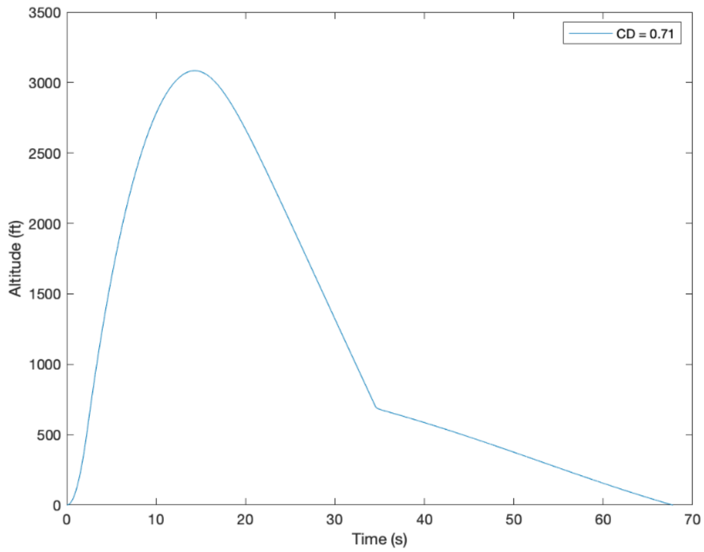

Figure 3-4 Flight Profile with Adjusted CD

3.3 Damaged Hardware

The most significant launch vehicle hardware damage was to the Fruity Chutes 120” Iris UltraCompact main parachute during the main deployment sequence. Several shroud lines were severed as circled in red in Figure 3-2 below.

Figure 3-5 Severed Main Parachute Shroud Lines

The severed shroud lines resulted from the impact with the free-falling fin can described in Section 3.1. This cascading failure did not result in any other damage to the launch vehicle.

The forward rail button fell out of the launch vehicle while it was being erected on the launch pad, causing it to fall and pull the aft rail button out as well. This was deemed to be caused by an excessively large pilot hole being drilled for mounting the rail buttons. The rail buttons were re-installed at the launch field using a smaller pilot hole and performed nominally.

3.4 Lessons Learned

Several critical lessons were learned during this flight. The Nomex sheet will be constrained to the drogue parachute attachment quick link in future flights to prevent this tangling from occurring. This failure point resulted in the loss of the main parachute and a partial recovery system failure. A minor problem encountered at the launch was a difficulty arming screw switches within the launch vehicle body, with the AV sled not remaining aligned with the switch ports in the launch vehicle body tube. Alternatives to this style of switch should be evaluated for future systems. The overall nature of these issues and the team’s confidence in the solution to these issues gives the team confidence in missions success for the competition flight. Most importantly, this flight validated the performance of the extended main parachute bay, shortened forward AV bay coupler, and rearranged components on the main parachute recovery harness discusses in the FRR document.

4. Project Plan Updates

4.1 Testing

4.1.1 Nose Cone Bulkhead Tensile Loading Test

Per TDR 2.2, all critical components of the launch vehicle shall be designed with a minimum factor of safety of 2. This test aims to validate the strength of the nose cone bulkhead and the bolted connection. Sufficient bulkhead strength is critical to the success of the launch vehicle. Should parachute deployment cause a bulkhead to fail, sections of the rocket may descend untethered to a parachute, causing a safety hazard. Success criteria are shown in Table 3-1 below. Should any of the criteria not be met, the bulkheads will need to be redesigned.

Two 3/4-inch bulkheads have been manufactured in the nose cone configuration and inserted into a coupler section as detailed in the FRR document. The piece was tested to a tensile loading of 354 lbf using a universal testing machine, this value gives a factor of safety of 2 with the expected deployment force of 177 lbf.

Table 4-1 Nose Cone Bulkhead Tensile Loading Success Criteria

Success Criteria	Met? (Y/N)
The test sample withstands a load of over 354 lbf	Y
The test sample shows no visible damage under 354 lbf loading	Y

4.1.1.1 Controllable Variables

- Bulkhead material: aircraft-grade birch plywood
- Bulkhead thickness: 3/4 inches
- Applied loading: 354 lbf

4.1.1.2 Procedure

- Ensure everyone in attendance is wearing safety glasses
- Insert the bulkhead u-bolts into each end of the universal testing machine
- Begin increasing the force on the test piece in increments of 50 lbf
- Note the state of the test piece around 354 lbf
- Continue increasing the loading until the test pieces fails or the machine has reached its maximum applied load

4.1.1.3 Results

While setting up the test piece, the zeroed load value was recorded at +2 lbf with an error of ±3 lbf. At a loading of 350 lbf, the test piece showed no visible signs of damage. The loading was continually increased to the machine's maximum loading of 1000 lbf, but the test piece still showed no visible damage when removed. This means the design has a factor of safety of at least 5.65 which far exceeds the value required by TDR 2.2.

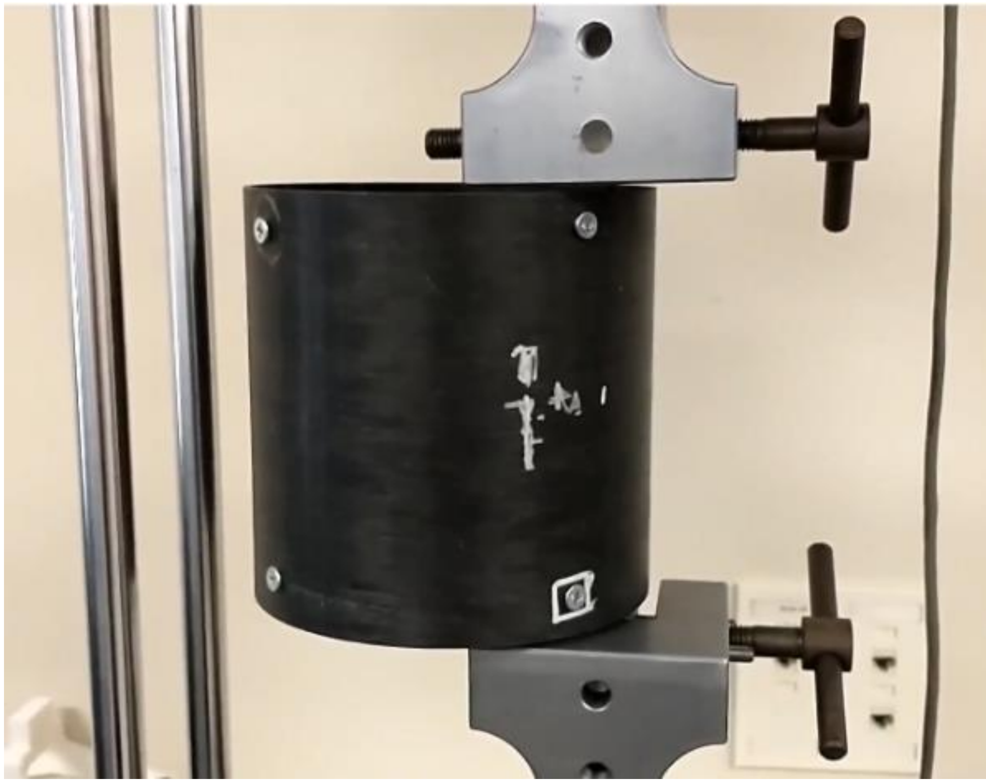

Figure 4-1 Nose Cone Bulkhead Test Setup

4.1.2 AV Bay Bulkhead Tensile Loading Test

Per TDR 2.2, all critical components of the launch vehicle shall be designed with a minimum factor of safety of 2. This test aims to validate the strength of the AV Bay bulkheads and the bolted connection. Sufficient bulkhead strength is critical to the success of the launch vehicle. Should parachute deployment cause a bulkhead to fail, sections of the rocket may descend untethered to a parachute causing a safety hazard. Success criteria are shown in Table 3-2 below. Should any of the criteria not be met, the bulkheads will need to be redesigned.

A test AV Bay has been made using two 3/4-inch AV Bay bulkheads inserted into a coupler section. The piece was tested to a tensile loading of 654 lbf using a universal testing machine, this value gives a factor of safety of 2 with the highest expected deployment force of 327 lbf.

Table 4-2 AV Bulkhead Tensile Loading Success Criteria

Success Criteria	Met? (Y/N)
The test sample withstands a load of over 654 lbf	Y
The test sample shows no visible damage under 654 lbf loading	Y

4.1.2.1 Controllable Variables

- Bulkhead material: aircraft-grade birch plywood
- Bulkhead thickness: 3/4 inches
- Applied loading: 654 lbf

4.1.2.2 Procedure

- Ensure everyone in attendance is wearing safety glasses
- Insert the bulkhead u-bolts into each end of the universal testing machine
- Begin increasing the force on the test piece in increments of 50 lbf
- Note the state of the test piece around 654 lbf
- Continue increasing the loading until the test pieces fails or the machine has reached its maximum applied load

4.1.2.3 Results

While setting up the test piece, the zeroed load value was recorded at 0 lbf with an error of ±3 lbf. At a loading of 650 lbf, the test piece showed no visible signs of damage. The loading was continually increased to the machine's maximum loading of 1000 lbf, but the test piece still showed no visible damage when removed. This means the design has a factor of safety of at least 3.06 which exceeds the value required by TDR 2.2.

Figure 4-2 AV Bulkhead Test Setup

4.1.3 Shear Pin Shear Loading Test

This test is used to ensure the accuracy of the shear strength specified by the shear pin manufacturers. Should the tested shear strength differ from manufacturer specifications, the test strength will be used for recovery calculations. Should the shear pin strength differ from expected values on launch day, the vehicle may fail to separate leading to a ballistic descent, proving the necessity of the test. Success criteria are detailed in Table 3-3 below. Should the criteria not be met the new tested shear strength will be used in calculations.

Two steel plates are used in conjunction with a universal testing machine for shear testing. Each plate has a hole drilled at the end to allow for a quick link connection to the testing machine. Another hole matching the diameter of the shear pins is drilled at the opposite end.

Table 4-3 Shear Pin Loading Success Criteria

Success Criteria	Met? (Y/N)
The shear pins fail within 1 lbf of manufacturer specifications	N

4.1.3.1 Controllable Variables

- Chosen shear pin: 4-40 nylon
- Applied loading: 35 lbf (manufacturer specified)

4.1.3.2 Procedure

- Attach a quick link through the large holes on each plate
- Align the two remaining holes and insert a shear pin
- Insert the quick links into each end of the universal testing machine
- Begin increasing the applied loading in increments of 2 lbf
- Continue increasing the loading until the shear pin fails
- Record the failure point

4.1.3.3 Results

While setting up the shear pin test piece, the zeroed load value was recorded at -8 lbf with an error of ±3 lbf. As the applied loading increased, the shear pin seemed to stretch until it failed at 32 lbf, or 40 lbf including the zeroed load. Because shear pins are typically broken at a high velocity, the team altered the test procedure to reflect this for a second shear pin. This time, the applied force was set to 100 lbf so it could be tested straight to failure and the testing machine's display was recorded to find the point at which it failed. This time the shear pin failed at 34.8 lbf, or 42.8 lbf including the zeroed load. Although the shear pins failed around 40 lbf instead of 35 lbf as expected, this will not be an issue. The force exerted on the shear pins by the expanding gases is far higher than their combined strength meaning that they will still fail even though their strength is slightly higher than expected.

Figure 4-3 Shear Pin Test Setup

4.1.4 Fastener Shear Loading Test

Per TDR 2.2, all critical components of the launch vehicle shall be designed with a minimum factor of safety of 2. This test aims to validate the strength of the chosen bolts for the nose cone bulkhead and the bolted connections between sections. Should parachute deployment cause the bolts to fail, sections of the rocket may descend untethered to a parachute causing a safety hazard. Success criteria are shown in Table 3-4 below. Should any of the criteria not be met, new bolts will need to be chosen.

Two steel plates are used in conjunction with a universal testing machine for shear testing. Each plate has a hole drilled at the end to allow for a quick link connection to the testing machine. Another hole matching the diameter of the bolt is drilled at the opposite end. Due to the off-center location of the U-bolt on the nose cone bulkhead, the bolts closest to the U-bolt will experience a higher loading of 87 lbf based on FEA analysis. Accounting for a factor of safety of 2, the bolt was be tested to a loading of 174 lbf.

Table 4-4 Fastener Shear Loading Success Criteria

Success Criteria	Met? (Y/N)
The fastener withstands a loading of 174 lbf	Y

4.1.4.1 Controllable Variables

- Chosen fastener size: 10-24 machine screws
- Applied loading: 174 lbf

4.1.4.2 Procedure

- Attach a quick link through the 1/4-inch holes on each plate
- Align the two remaining holes and insert a bolt
- Insert the quick links into each end of the universal testing machine
- Begin increasing the applied loading in increments of 20 lbf
- Note the state of the bolt around 174 lbf
- Continue increasing the loading until the bolt fails
- Record the failure point

4.1.4.3 Results

While setting up the fastener test piece, the zeroed load was recorded to be –8 lbf with an error of ±3 lbf. The bolt showed no damage at a loading of 180 lbf so the loading was continually increased. Once it hit 800 lbf, the bolt failed. Since it failed so high above 174 lbf, the second bolt was tested straight to failure. The machine was set to 1000 lbf and the display was recorded to find the exact failure point. The bolt failed at 813 lbf, or 821 lbs including the zeroed load. This gives the bolts a factor of safety of 9.44 which meets TDR 2.2.

Figure 4-4 Fastener Test Setup

4.1.5 POS Transmission Range Re-Test

Due to the geography of the first testing site, the first test of the POS transmitter was not able to reach the 2500-foot maximum transmission distance that needed to be tested. This test was repeated as a different location, where a maximum transmission distance of 2552 feet.

4.1.5.1 Test Design

The POS transmitter sends transmissions to the POS receiver at a variety of different distances. Three team personnel were present to conduct this test – one two experimenters walked with the transmitter in a straight line away from the receiver, while the other experimenter confirmed the successful retrieval of the radio signals. The test is designed to conclude when transmissions are no longer received, or whenever the transmitter reaches a distance of 2500 feet from the receiver. This test was performed at Dorothea Dix park in Raleigh.

4.1.5.2 Required Equipment

- Raspberry Pi
- POS RF transmitter
- Transmitter antenna
- 5V battery pack with USB cord
- Laptop computer with SDRSharp software
- SDR receiver and USB dongle
- Two-way communication devices (i.e., cell phones)
- At least two people

4.1.5.3 Procedure

- Save Radio Test Python script into proper directory on the Raspberry Pi prior to testing.
- In a flat, open area, connect the Raspberry Pi, POS transmitter, and charged battery pack.
- Enable Wi-Fi hotspot on cellular phone and connect laptop and Raspberry Pi
- Establish SSH connection with Raspberry Pi.
- Connect SDR Receiver hardware to laptop and set receiver to 433 MHz.
- Begin test transmission by using nohup command in Raspberry Pi in SSH terminal.
- With POS set-up, move in a straight line away from the SDR receiver in increments of 150 feet.
- With a cell phone, maintain contact with personnel at the ground station to confirm test packets are still being received.
- Repeat steps 4-7 eight times. The ninth transmission should take place at 2500 feet.

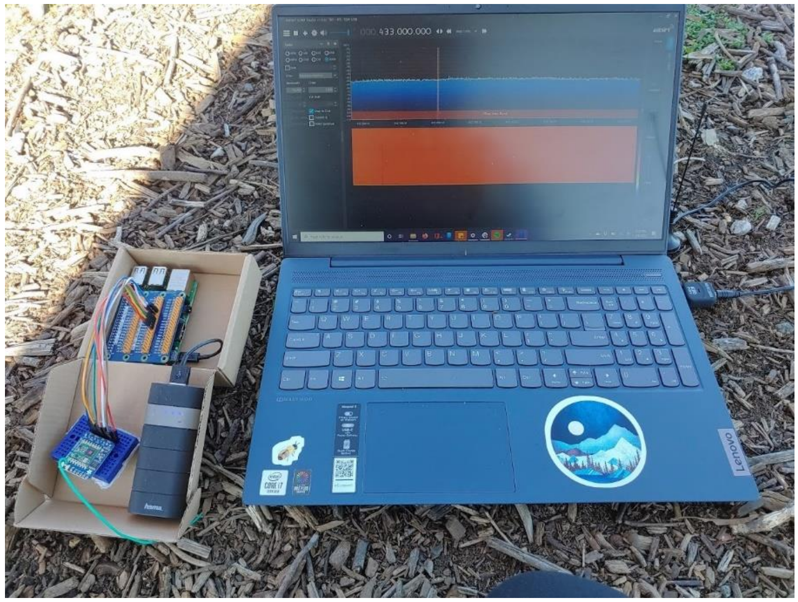

Figure 4-5 POS Range Test Transmitter Equipment

4.1.5.4 Results

For the duration of the test, signal from the POS transmitter was received by the SDR receiver. This was up to and including a distance of 2552 feet.

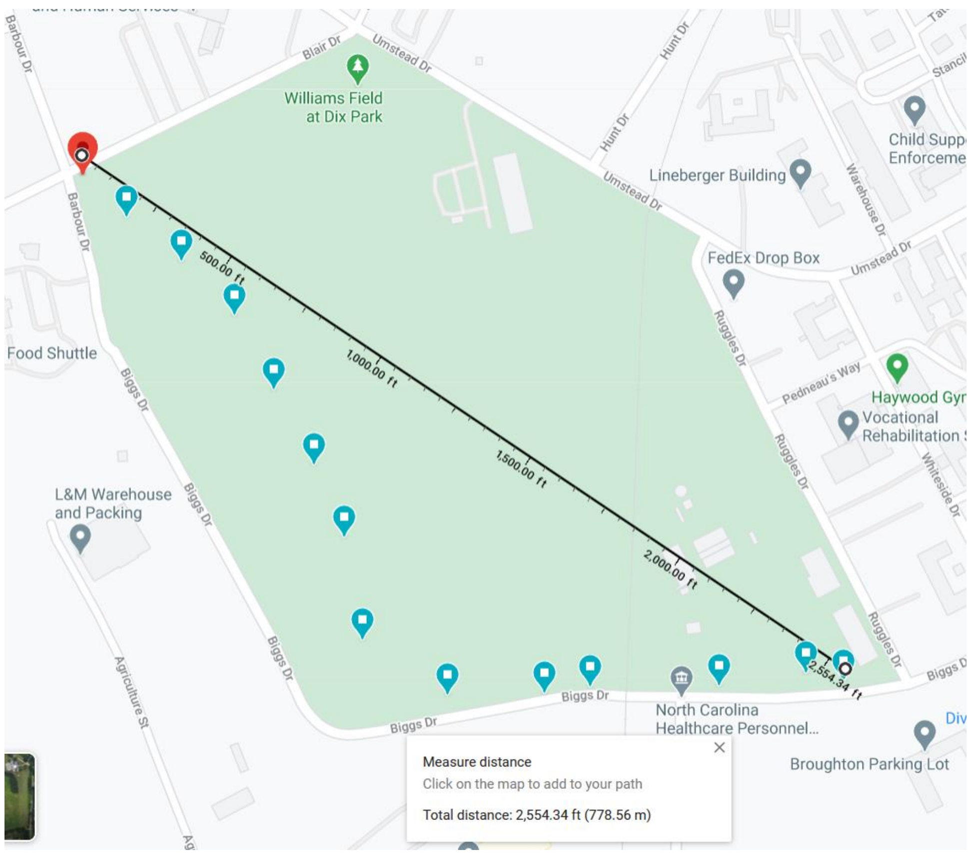

Figure 4-6 Measured Transmission Locations with Linear Distance

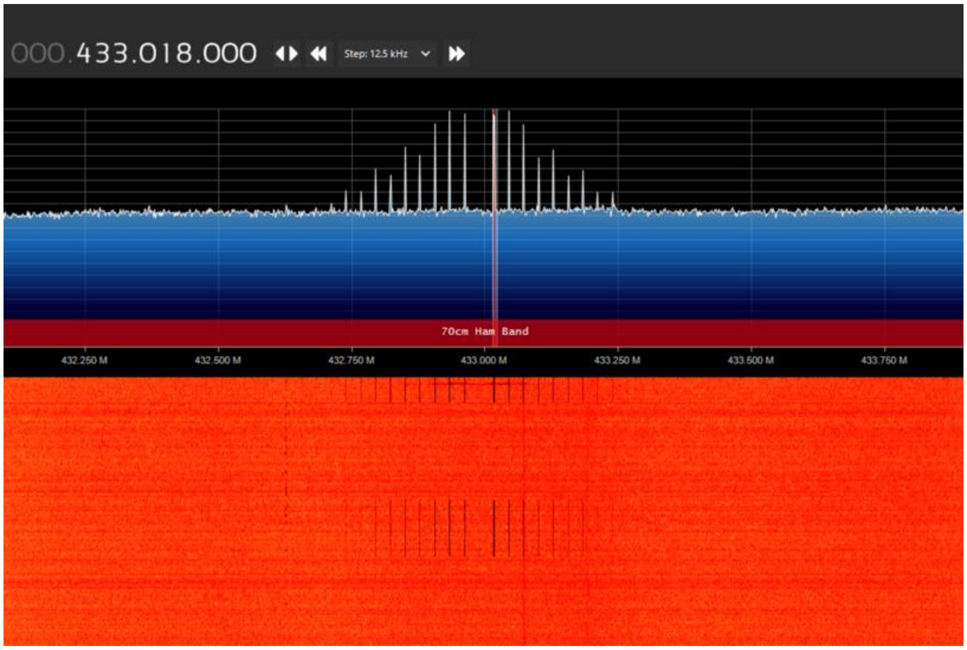

Figure 4-7 Transmission from 200 feet

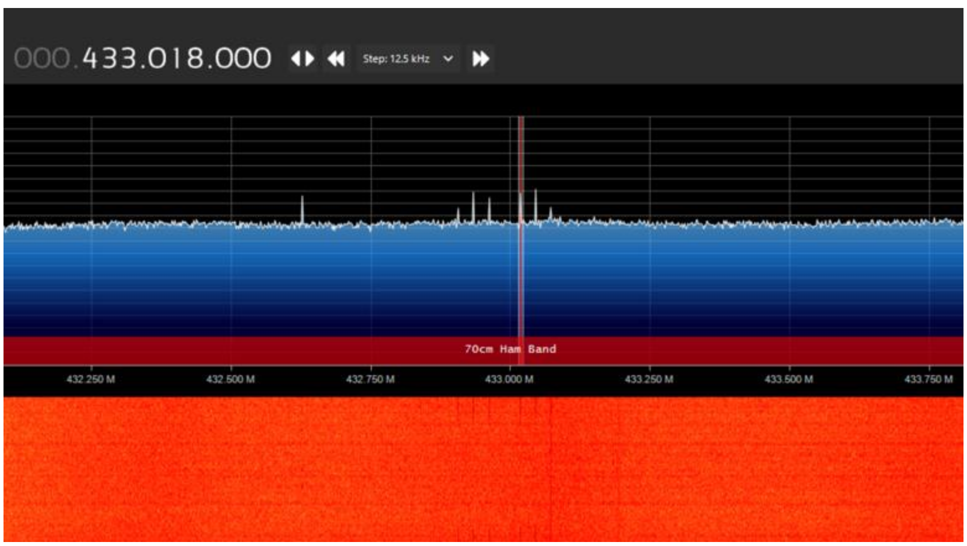

Figure 4-8 Transmission from 2500 feet

While the test packets used in this procedure are much simpler than the audio that will be sent using SSTV, the ability of the POS ground station to receive any form of signal from 2500 feet is promising for the overall transmission range of the final system.

4.1.6 LOPSIDED-POS Battery Capacity Test

This demonstration test is designed to ensure the payload battery can power the POS and other necessary payload components. This includes operating time after the payload lands, as well as the “stand-by” launch pad configuration. Per NASA Requirement 2.7, the payload must be able to maintain launch pad configuration for at least two hours.

4.1.6.1 Test Design

This test requires the incorporation of all necessary on-board electronic payload components. All payload components are wired to the Raspberry Pi and powered as necessary. First, the payload electronics are set to launch pad configuration for two hours. After two hours have passed, the LOPSIDED-POS executes all functions related to payload operation, all of which are listed in the section below. It is crucial that the exact flight components and battery are used for this test, to ensure the results resemble mission performance as closely as possible.

4.1.6.2 Required Equipment

- Payload battery pack
- POS and other payload electronic components
  - Raspberry Pi 3B+
  - Arducam Fisheye Raspberry Pi cameras (x4)
  - POS transmitter
  - Orientation sensor
  - Solenoid latches (x4)
  - Electromagnetic latches (x2)
  - Voltage regulators
- Multimeter

4.1.6.3 Procedure

- Ensure payload battery is fully charged prior to testing.
- Check the battery voltage with a multimeter and ensure it matches battery specifications.
- Wire all POS and other payload electronics to the Raspberry Pi.
- Supply power to the POS and other payload components using the payload battery.
- Leave set-up in launch pad configuration for two hours.
  a. This configuration includes supplying power to the Raspberry Pi, but does not include the actuation or active reading of any latches or sensors
- Using the main flight script on the Raspberry Pi, run the payload electronics through all necessary payload events that require battery use.
  a. The release of parachute latches
  b. The release of solenoid latches
  c. Image capture
  d. POS transmission
- Verify that all payload events occur without loss of power.

4.1.6.4 Results

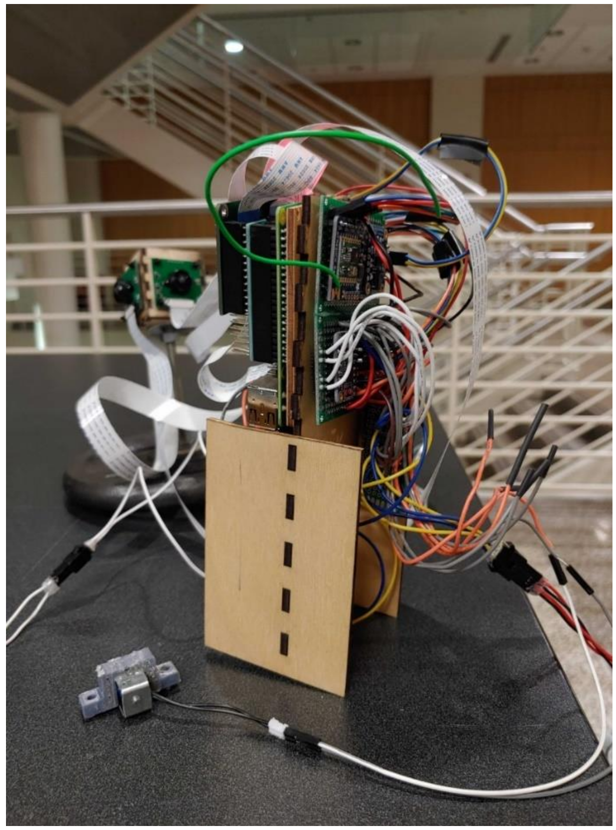

Figure 4-9 LOPSIDED-POS Electronics Sled and Cameras

The initial battery voltage was measured to be 12.88V. After the two hours of idle state, the LOPSIDED-POS launch script was able to run without any difficulty. This includes the actuation of multiple latches, as well as image capture and radio transmission. The final battery voltage was 12.55V.

It should be noted that only one solenoid instead of four was used during this test. This was due to LOPSIDED's changing manufacturing schedule, and the fact that some of the solenoids were already mounted to a part that needed to be left to cure after applying epoxy. To account for this, the single solenoid included in this test was actuated four times. During actual operation, four solenoids are actuated one time each, but the amount of current used by each of these set-ups should be the same.

4.2 Requirements Verification

Table 4-5 and Table 4-6 below show the verification status of requirements that were not verified at the FRR milestone.

Table 4-5 NASA Handbook Requirements Unverified at FRR

Req No.	Shall Statement	Success Criteria	Verification Method	Subsystem Allocation	Status	Status Description
NASA 2.1	The vehicle SHALL deliver the payload to an apogee altitude between 3,500 and 5,500 feet above ground level (AGL).	The aerodynamics lead designs a launch vehicle to reach an apogee between 3,500 and 5,500 feet AGL. The team then constructs the vehicle as designed and the launch vehicle flies between 3,500 at 5,500 feet AGL.	Analysis; Demonstration	Aerodynamics	Not verified	The launch vehicle delivered the payload to an apogee of 2,995 ft AGL during the VDF, and 3,048 ft AGL during the PDF. Therefore, this requirement cannot be verified.
NASA 2.18.2	Payload Demonstration Flight - All teams SHALL successfully launch and recover their full-scale rocket containing the completed payload prior to the Payload Demonstration Flight deadline. The rocket flown SHALL be the same rocket to be flown on Launch Day.	The team completes the PDF prior to the PDF deadline using the same rocket to be flown on Launch Day.	Inspection	Project Management	Verified	The team completed the PDF on March 27, 2021. See Section 2 for flight results.

NASA 2.18.2.1	The payload SHALL be fully retained until the intended point of deployment (if applicable), all retention mechanisms SHALL function as designed, and the retention mechanism SHALL not sustain damage requiring repair.	The payload remains fully retained until the point of intended deployment with each retention mechanism functioning as designed and not sustaining damage requiring repair during the PDF.	Demonstration	Payload Integration	Verified	The payload was fully retained until 700 ft AGL, at which point it was successfully removed from the payload bay by the launch vehicle main parachute. At 500 ft AGL, the ARRD separated the payload from the launch vehicle, and the payload descended under its own parachute to a gentle landing. See Section 2.2 for retention and deployment results.
NASA 2.18.2.2	The payload flown SHALL be the final, active version.	The payload flown on the PDF is the final, active version of the payload.	Inspection	Project Management	Verified	The onboard payload was the final, active version. See Section 2.1 for payload details.
NASA 2.18.2.4	Payload Demonstration Flights SHALL be completed by the FRR Addendum deadline.	The PDF is completed by the FRR Addendum deadline.	Inspection	Project Management	Verified	The PDF was completed on March 27, 2021 which is prior to the FRR Addendum deadline of March 29.
NASA 2.19	An FRR Addendum SHALL be required for any team completing a Payload Demonstration Flight or NASA-required Vehicle Demonstration Re-flight after the submission of the FRR Report.	If the team is completing the PDF or a NASA-required VDF re-flight after the submission of the FRR Report, the team lead submits an FRR Addendum by the FRR Addendum deadline.	Inspection	Project Management	Verified	This FRR Addendum has been submitted following the Payload Demonstration Flight and Vehicle Demonstration Re-Flight.

NASA 2.19.1	If a re-flight is necessary, the team SHALL submit the FRR Addendum by the FRR Addendum deadline.	The team lead submits the FRR Addendum by the FRR Addendum deadline.	Inspection	Project Management	Verified	This FRR Addendum has been submitted before 9 am on March 29, 2021.
NASA 2.19.2	The team SHALL successfully execute a PDF to fly a final competition launch.	The project management team manages the schedule such that a PDF is successfully completed by the FRR Addendum deadline.	Demonstration	Project Management	Verified	The team completed the PDF on March 27, 2021. See Section 2 for flight results.

NASA 4.2	The team SHALL design a planetary landing system to be launched in a high-power rocket. The lander system SHALL be capable of being jettisoned from the rocket during descent, landing in an upright configuration or autonomously uprighting after landing. The system SHALL self-level within a five-degree tolerance from vertical. After autonomously uprighting and self-leveling, it SHALL take a 360-degree panoramic photo of the landing site and transmit the photo to the team.	The payload team designs a planetary landing system to be launched in a high-powered rocket. The payload is capable of being jettisoned from the launch vehicle during descent, landing in an upright configuration or autonomously uprighting after landing, self-levelling within a five-degree tolerance from vertical, and taking a 360-degree panoramic photo of the landing site and transmitting the photo to the team.	Demonstration	Payload vehicle; Payload integration; Payload imaging	Verified	The payload lander was jettisoned from the launch vehicle during descent and landed in an upright configuration. Tipping after landing prevented leveling, though the leveling system was activated. The imaging system captured a 360-degree image and performed the image transmission sequence. See Section 2 for PDF results.

NASA 4.3.1	The landing system SHALL be completely jettisoned from the rocket at an altitude between 500 and 1,000 ft. AGL. The landing system SHALL land within the external borders of the launch field. The landing system SHALL not be tethered to the launch vehicle upon landing.	The payload integration lead designs the payload such that it jettisons from the launch vehicle between 500 and 1,000 AGL, lands within the external border of the launch field, and is not tethered to the launch vehicle.	Demonstration	Payload integration	Verified	The payload was removed from the payload bay at 700 ft AGL. The payload was jettisoned from the launch vehicle at 500 ft AGL. The payload landed within the external borders of the landing field and was not tethered to the launch vehicle at landing. See Section 2.2.1 for PDF results.
NASA 4.3.2	The landing system SHALL land in an upright orientation or SHALL be capable of reorienting itself to an upright configuration after landing. Any system designed to reorient the lander SHALL be completely autonomous.	The payload vehicle lead designs the payload such that it lands in an upright position or reorients itself to an upright configuration after landing using a completely autonomous system.	Demonstration	Payload vehicle	Verified	The lander landed in an upright position. See Section 2.3 for payload landing details.
NASA 4.3.3.1	Any system designed to level the lander SHALL be completely autonomous.	The payload vehicle lead designs a payload leveling system that is completely autonomous.	Demonstration	Payload vehicle	Verified	The leveling system activated autonomously. See Section 2.3 for leveling system performance.

NASA 4.3.3.2	The landing system SHALL record the initial angle after landing, relative to vertical, as well as the final angle, after reorientation and self-levelling. This data SHALL be reported in the Post Launch Assessment Report (PLAR).	The payload vehicle lead designs a payload leveling system which records the initial angle after landing as well as the final angle relative to vertical. The payload vehicle lead reports this data in the PLAR.	Demonstration	Payload vehicle	Verified	The lander recorded its pre- and post-leveling orientation angles. See Section 2.4 for discussion of these values.
NASA 4.3.4	Upon completion of reorientation and self-levelling, the lander SHALL produce a 360-degree panoramic image of the landing site and transmit it to the team.	The payload imaging lead designs an imaging system capable of producing a 360-degree panoramic image and transmitting it to the team following self-levelling of the payload vehicle.	Demonstration	Payload imaging	Verified	A 360-degree panoramic image was captured. See Section 2.4 for imaging details.
NASA 4.3.4.1	The hardware receiving the image SHALL be located within the team’s assigned prep area or the designated viewing area.	The payload imaging lead selects a ground station capable of receiving the image and being located within the team's prep area or designated viewing area.	Inspection	Payload imaging	Verified	The laptop used to receive the lander's image was located in the team's prep area. See Section 2.4.
NASA 4.3.4.4	The image SHALL be included in the team's PLAR.	The payload imaging lead includes the captured image in the PLAR.	Inspection	Payload imaging	Not verified	The team will include the lander's image in the PLAR. This requirement will be verified at the PLAR milestone.

NASA 4.4.2	Teams SHALL abide by all FAA and NAR rules and regulations.	The safety team verifies payload compliance with all FAA and NAR rules and regulations.	Demonstration	Safety	Verified	The team followed all FAA and NAR rules and regulations at the subscale launch, VDF, and PDF.
NASA 5.4	During test flights, the team SHALL abide by the rules and guidance of the local rocketry club's RSO. Teams SHALL communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch.	The safety officer communicates the team's intentions to the local club's President or Prefect and RSO prior to attending any NAR or TRA launch. The safety officer verifies team adherence to the rules and guidance of the local club's RSO.	Demonstration	Safety	Verified	The team abided by the rules and guidance of the local club's RSO at the subscale launch, VDF, and PDF. The team has communicated our intentions for the competition launch to the local club's Prefect.
NASA 5.5	Teams SHALL abide by all rules set forth by the FAA.	The safety officer verifies the team adheres to all rules set forth by the FAA.	Demonstration	Safety	Verified	The team complies with all rules set forth by the FAA.

Table 4-6 Team-Derived Requirements Unverified at FRR

Req No.	Shall Statement	Justification	Success Criteria	Verification Method	Subsystem Allocation	Status	Status Description
TDR 4.6	LOPSIDED SHALL remain locked in its neutral position until after landing and taking its initial orientation measurement.	The payload orientation system must remain locked in order to not damage the launch vehicle, interfere with any deployment mechanisms, and allow for an initial orientation measurement to be recorded.	The gimbal-based leveling system is not allowed to rotate until the initial orientation measurement is recorded.	Test	Payload Vehicle	Verified	Four solenoid latches held LOPSIDED in the level orientation until the initial landing orientation was recorded. See Section 2.3 for leveling system results.
TDR 4.14	The POS SHALL transmit and receive images from up to 2500 feet from the team's ground station.	In the event of excessive wind drift after parachute deployment, image transmissions from the POS will still need to be received.	Images sent by the POS transmitter are successfully received by the ground station from up to 2500 feet away.	Test	Payload Imaging	Verified	The current POS design is capable of transmitting 2552 ft. See Section 4.1.5 for image transmission range test results.

TDR 4.16	LOPSIDED SHALL release the payload parachute upon landing.	Releasing the parachute once LOPSIDED has landed prevents the parachute from interfering with the leveling system if it were to inflate and apply a load.	The parachute detaches completely from LOPSIDED while also not covering POS.	Demonstration	Payload Vehicle, Payload Integration, Payload Imaging	Not verified	LOPSIDED-POS did not release the payload parachute on landing due to issues with the retention latches. See Section 2.2 for parachute release details.