Project Voss

FRR Addendum

Purdue University 2021

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West Lafayette, IN 47906

Purdue Space Program

Table of Contents

Table of Acronyms

Acronym or Abbreviation	Definition
PSP-SL	Purdue Space Program: Student Launch
ASL	Aerospace Sciences Laboratory
BIDC	Bechtel Innovation Design Center
GCS	Ground Control Station
FEA	Finite Element Analysis
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
FDM	Fused Deposition Modeling (3D Printing)
PLS	Planetary Lander System (Lander Team)
ABCS	Aero-Braking Control System (Airbrakes Team)
SOS	Self Orientation Subsystem
LCS	Lander Control Subsystem
PICS	Panoramic Image Capture Subsystem
R&D	Retention and Deployment Subsystem
D&L	Descent and Landing Subsystem
AGL	Above Ground Level
MSL	Mean Sea Level
COTS	Commercial Off-The-Shelf
NAR	National Association of Rocketry
PPE	Personal Protection Equipment
CFR	Code of Federal Regulations
APCP	Ammonium Perchlorate Composite Propellant
OEW	Operating Empty Weight
R&VP	Requirements and Verification Plans
MFSS	Motor and Fin Support Structure
IFVR	In-Flight Video Recording System
CTI	Cesaroni Technology Inc.
VDF	Vehicle Demonstration Flight
FOS	Factor Of Safety
AGL	Above Ground Level
CoM	Center of Mass
VDF	Vehicle Demonstration Flight
PDF	Payload Demonstration Flight
PCB	Printed Circuit Board

1 Summary of FRR Addendum

1.1 Team Summary

Team Name	Purdue Space Program – NASA Student Launch (PSP-SL)
Team Address	500 Allison Road, West Lafayette, IN 47906
Team Mentor Name	Christopher Nilsen
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Team Mentor TRA/NAR Certifications	TRA 12041, Level 3 Certified
Hours Spent on FRR Addendum	100

Table 1.1: PSP-SL Team Summary

1.2 Purpose of Flight

This flight was used as the Payload Demonstration Flight for PSP SL.

1.3 Flight Summary Information

1.3.1 Vehicle Demonstration Flight

Criteria	Outcome
Date of Flight	2/27/2021
Location of Flight	Purdue Dairy Farm
Launch Conditions	48°F, Partly Cloudy, Windspeed SW 6mph
Motor Flown	CTI L1115 4-grain
Ballast Flown	None
Final Payload Flown	Yes, Not Fully Active
Airbrakes Status	Active
Official Target Altitude	4100’
Simulated Altitude	5136’
Measured Altitude	5196’
Off-nominal Events	

Table 1.2: Vehicle Demonstration Flight

1.3.2 Payload Demonstration Flight

Criteria	Outcome
Date of Flight	3/20/2021
Location of Flight	Purdue Dairy Farm
Launch Conditions	45°F, Sunny, Windspeed ESE 5mph
Motor Flown	CTI L1115 4-grain
Ballast Flown	13oz
Final Payload Flown	Yes, Completely Active
Airbrakes Status	Active
Official Target Altitude	4100’
Simulated Altitude	4356’
Measured Altitude	4262’
Off-nominal Events	

Table 1.3: Payload Demonstration Flight

1.4 Changes made since FRR

1.4.1 Changes made to vehicle design

The only structural changes that occurred after the first vehicle demonstration flight were some quality-of-life changes made to the nose cone design. Originally, due to the lack of complexity of the Raspberry Pi Zero computers, the camera system had to be initialized before being integrated into the vehicle. This was inconvenient because it placed a time limit on the team and required assembly at the launch field. To improve this, a new nose cone was 3D printed that included a key switch. This allowed the team to initialize the camera systems on the launch rail, so that the team could maximize the window in which footage could be recorded. Also, in the first nose cone, there were some slight problems with the nuts that fixed the nose cone in place with the attachment plate. Some of the nuts had trouble staying attached to the nose cone after launch, so, in the nose cone redesign, the slots were made much smaller so that friction also contributed to the forces holding these bolts in place.

The printing process for this design began one week before the addendum flight, however, after multiple technical issues with the printer being used, the new nose cone printed only shortly before re-flight, and the team did not have enough time to epoxy the acrylic panes onto the new nose cone. Because of this, the original nose cone was used for the re-flight, and experienced no problems. The new nose cone is now completed, though, and will be used for any and all future flights.

Even though the initial black powder ejection test was a success for both parachutes, the main parachute acquired several burn holes during the Vehicle Demonstration Flight. It also acquired burn holes during the initial black powder ejection test, though these were deemed negligible because it was packed very hastily for the test. The team believes that, even though the parachute was wrapped very carefully with the Nomex blanket for the actual flight, some of the hot gases were still able to sneak around the edges and singe the parachute. Therefore, it was deemed necessary to explore other methods of packing and sizes of ejection charges prior to the Payload Demonstration Flight in an effort to prevent further burn holes and other forms of damage.

After the existing burn holes were repaired with masking tape, a retest of the black powder ejection test for just the main parachute side was conducted on 3/13/2021. The parachute was folded in half twice before rolling up, because this technique allows it to be packed more tightly. Two Nomex blankets were also sewed together on one side to create a larger Nomex blanket, and the parachute was wrapped on all sides by this blanket instead of just on the side facing toward the ejection charges to absolutely ensure complete protection. The tough Kevlar shock cord was packed between the parachute and the charges to provide another layer of protection. Finally, the ejection charge size was reduced from 3g to 2g because another look at the sizing calculations revealed that 3g may have been an overestimation. However, 2g did not result in adequate section separation in the retest, so the ejection charge size was increased back to 3g, and the test subsequently passed. Also, the new packing method had been proven to work, so it was utilized in its entirety for the Payload Demonstration Flight, along with the same ejection charge sizes as in the Vehicle Demonstration Flight.

Figure 1.1: Double Nomex Blanket

1.4.1.1 Primary Payload

The PLS has undergone minimal additional design changes since FRR, but due to time constraints, certain systems have been chosen to be priorities over others. Thanks to the team's aggressive yet "agile" productivity loop, the team made sure that each full achievable build of the system was fully operational before moving on to make modifications.

Due to time and resource constraints, the Lander will no longer attempt to sever its nylon attachment chord through D&L/LCS interaction. This change simply reduces risk of damage and fire but reintroduces performance failure potential due to the chord and connected parachute possibly tangling while on the ground. This system was intended to improve the chances of the Lander to meet its wind-resistance requirement but was deemed unnecessary for the given resource circumstances.

For PDF, software changes were implemented to bring the Lander more in line with the operation of the R&D, with a similar descent detection and activation sequence. This means that while the R&D enables the physical deployment of the Lander, the Lander's electrical system itself will confirm deployment through flight loads and altitude. The SOS system utilized for PDF will be equipped to self-orient but will be unable to employ its desired control system to guarantee that the Lander orients perfectly to its desired angle range consistently. Due to resource constraints, the final implementation of the PICS/GCS system were unable to be fully implemented, though the team has produced a working image stitching code.

1.4.1.2 Secondary Payload

The ABCS has received minimal design changes from the VDF flight. As stated in FRR, the ABCS's power system was disconnected from launch acceleration. This was due to insufficient attachment to the vehicle's coupler bulkhead despite the anticipated load direction. The team found a simple structural fix, more securely adhering the ABCS battery to the bulkhead with an improved mount and zip-ties. The ABCS's battery connector was deemed to not be the cause of the power disconnection.

2 Payload Demonstration Flight Results

2.1 Designed Payload Mission Sequence

2.1.1 Planetary Landing System

This mission is divided into seven essential phases, each with a defining event leading into the action of the next. The system's mission will be considered complete if its status proceeds to the final phase without failure. In the case of a critical failure, additional contingency plans have been considered. The phases of the PLS mission are shown as follows:

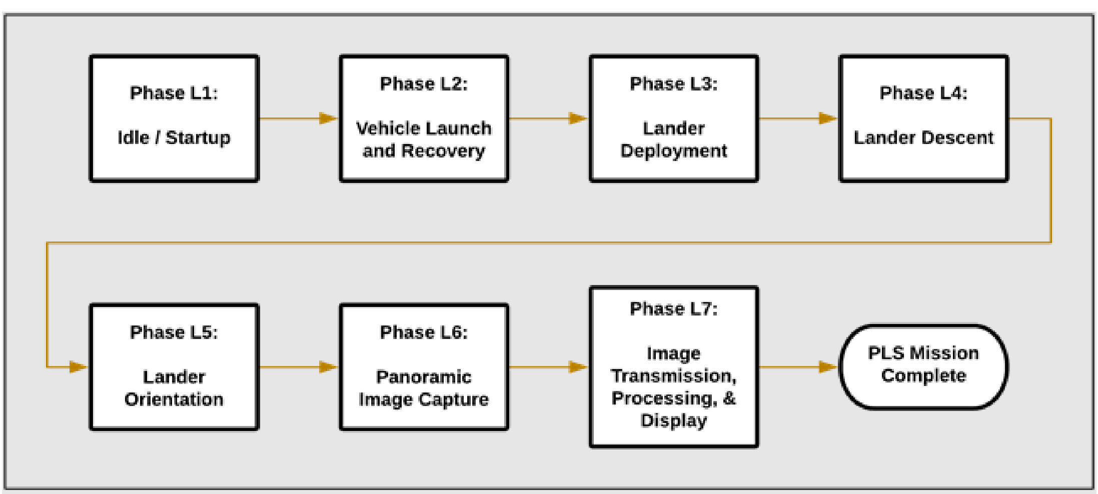

Figure 2.1: Planetary Landing System Mission Overview

L1: Idle / Startup:

The first phase of the mission includes the time between launch vehicle activation and the time of launch. During this time, the R&D will be in an idle but active state in preparation for launch. The Lander will also be in an idle state, awaiting indication form the launch vehicle's flight state to activate. Given that the vehicle is ready to launch, the mission may proceed to Phase L2.

The changes made to the operation procedure of the Lander for PDF include the always-on but idle system of the Lander. The Lander mirrors the functionality of the R&D for the purpose of deployment detection.

L2: Vehicle Launch and Recovery

While the vehicle is in its ascent phase, the R&D will be ensuring that flight loads are transferred around the body of the Lander contained inside. The Lander will not be able to exit the vehicle during this stage due to a mechanical lock, which will not unlock without action from the onboard R&D controller. When the vehicle begins its descent, the load state of the R&D will tend to flip, but the system will still be designed to handle the required loads. The R&D will be capable of withstanding jerk from both the drogue parachute and the main parachute before continuing to Phase L3.

L3: Lander Deployment

After the completed deployment of the vehicle's main parachute by approximately 700' AGL, the R&D will begin to deploy the Lander. The R&D will begin to separate the lock vertically constraining the Payload Bay's nosecone section, allowing the Lander to slide downwards with gravity. Once fully released, the nose cone section will slide downward before hitting stops. The Lander will then be unconstrained in one lateral dimension, allowing it to fall to the side and begin descent. During this time, the Lander's electronic systems will sense its deployment, allowing it to proceed to Phase L4.

If the R&D is unable to deploy the Lander for any reason, the Lander not detect deployment and will remain idle. At that point, the Lander must be carefully deactivated on the ground with the permission of an RSO. With the Lander having exited the vehicle, the R&D system will remain in an open configuration until touchdown, retaining the nose cone of the vehicle.

L4: Lander Descent

The Lander should be clear of the launch vehicle by 500' AGL, by which time a parachute delay method will have disconnected itself from the Lander, allowing the Lander's parachute to open. It should be noted that even if the Lander does not properly awaken, the parachute will still be designed to deploy, ensuring the safety of the Lander and personnel on the ground. The parachute will bring the Lander's terminal velocity to a speed greater than the speed of the launch vehicle (20 fps) to ensure no interference occurs. The Lander will then reach the ground, landing in any orientation. If the active Lander detects a successful return to Earth, it will begin Phase L5.

Repeating a stated change, due to time and resource constraints, the D&L/LCS will no longer attempt to sever its nylon attachment chord and parachute. This action of the Lander Descent phase has been therefore omitted.

L5: Lander Orientation

Now grounded, but with no certainty of landing orientation, the Lander will begin to self-upright by using a motorized Self Orientation Subsystem (SOS). By increasing the Lander's effective support area, the Lander can be assured to bring itself into a stable upright configuration slowly. The SOS will attempt to adjust its final state to ensure that the onboard sensors confirm orientation within 5° of the local gravitational acceleration vector. Once the control system has completed this task, the Lander will proceed to Phase L6. If the Lander cannot complete this phase after a predetermined amount of time, it will deactivate itself to prevent injury to the ground team.

For PDF, the Lander would be unable to fully execute this final accuracy maneuver.

L6: Panoramic Image Capture

Leveled within the desired tolerance, the Lander should now be clear of debris and should have an elevated view of the launch field. The onboard Panoramic Image Capture Subsystem (PICS) cameras will activate and proceed to capture an image of the field. The image will be stored locally until it is ready to be sent to the team's Ground Control Station (GCS), moving the PLS to the final Phase L7.

For PDF, the Lander would be unable to fully execute this image capture functionality.

L7: Image Transmission, Processing, & Display

Once a communication channel is secured between the GCS and the Lander, the PICS will begin to transfer the image data to the GCS via a radio transmitter. Once received, the GCS will store the image data. The Lander Subsystem has now completed its purpose and may be recovered. The GCS will then proceed to process the received image data and convert it into a viewable format. If the PICS utilizes a multi-image capture system, the GCS will need to stitch them together to view at one time. Once converted, the image will be displayed on the GCS's display screen for confirmation by the team, an RSO, and other NASA personnel. Having produced an image, the PLS has completed its mission and may be shut down for recovery by the ground team.

For PDF, the Lander and GCS will be unable to fully execute the full image transmission to display functionality but is capable of image stitching.

PLS Mission Completion

By the end of its mission, the PLS should have produced an unobscured image of the launch vehicle landing site. The system must overcome the challenge of being jettisoned from a high-power rocket during descent and master the elaborate dance of up-righting upon unknown terrain. At the same time, the system must satisfy every functional requirement set forth by the team to be considered ready to fly. If the system can produce these results without succumbing to material failure, inadvertent deployment, or a blocked camera subsystem, then the team will consider the mission a complete success.

2.1.2 Aerobraking Control System

This mission is divided into five essential phases, each with a defining event leading into the action of the next. The system's mission will be considered complete if its status proceeds to the final phase without failure. In the case of a critical failure, additional contingency plans have been considered. The phases of the ABCS mission are shown as follows:

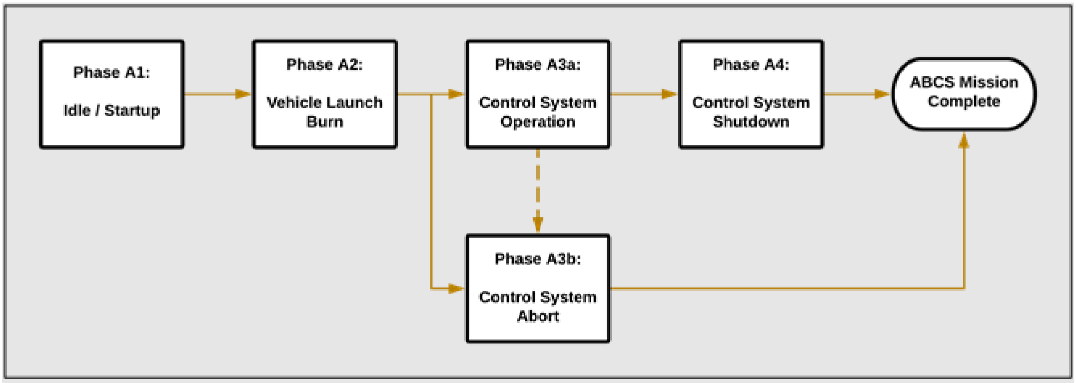

Figure 2.2: AeroBraking Control System Mission Overview

A1: Idle / Startup

The first phase of the mission includes the time between system power-on until the time of launch. During this time, the ABCS is in an idle state waiting for the detection of launch. Once ABCS accelerometers detect the launch burn, the ABCS will transition into phase A2.

A2: Vehicle Launch Burn

The ABCS control system will need to detect the launch vehicle's acceleration state at the start of its burn before it begins its operational stage. The ABCS mechanical system will not be allowed to actuate until the system detects that the launch vehicle's burn has been completed, and the vehicle has reached sufficient altitude, confirming a successful burn. With the ABCS remaining inactive during the boost phase, the vehicle's passive stabilizing fins can operate properly without possible loss of control authority. Once the criteria are met, the ABCS main drag control system loop may be activated, leading to Phase A3a. If the launch burn is not detected to have been completed properly, then the control system will proceed to Phase A3b.

A3a: Control System Operation

Given that the flight conditions are acceptable for the operation of the Airbrakes, the ABCS drag control system loop will begin operation. This control system will employ a suite of sensors to detect the vehicle's current state. Important inputs include the vehicle's linear and angular velocity, acceleration, air pressure, and altitude. A constant set by the team will be the desired final apogee of the launch vehicle. The control system will first predict the vehicle's current apogee error relative to the desired apogee and then determine how much drag would be required to achieve this final apogee. The ABCS will accordingly actuate its Airbrakes, producing this additional drag. An important initial condition of this phase is that the launch vehicle will, without intervention, achieve a final apogee greater than the desired altitude. Without this condition, the ABCS would be unequipped to provide any additional required velocity—it can only act to remove mechanical energy from the system. If at any time during the active phase the control system detects that the launch vehicle has exceeded attitude state or acceleration bounds determined by the team to be within an acceptable range, the control system will immediately switch to Phase A3b to avoid possible loss of stability. If the ABCS continues operation up until apogee, it will transition to Phase A4.

A3b: Control System Abort

The ABCS will be designed to cease its functionality if it detects that it could cause the launch vehicle's instability during ascent. If the ABCS reaches Phase A3b at any time from the beginning to the end of its designated operation time, it will follow a shutdown sequence to ensure that the system does not incur additional change in attitude or velocity. This shutdown sequence will immediately end the apogee optimization drag control system loop and completely retract the Airbrakes Subsystem's drag plates. This contingency plan is essential to allow the launch vehicle's stabilizing fins to return the vehicle's attitude to an acceptable state, avoiding an induced tumble. With all external surfaces now inactive, the ABCS control system will remain inactive for the remainder of descent and touchdown. While the control system could not fully optimize and complete its final calculations and adjustments, the team will still consider this contingency plan as successful as the overall vehicle will still complete its mission.

A4: Control System Shutdown

When the vehicle reaches apogee according to flight sensors, the ABCS will begin a deactivation sequence to reduce the possibility of damage to components. This deactivation sequence will immediately end the apogee optimization drag control system loop and completely retract the Airbrakes Subsystem's drag plates. With all external surfaces now inactive, the ABCS control system's mission will be considered complete and will deactivate for the remainder of descent and touchdown.

ABCS Mission Completion

By the end of its mission, the ABCS will hopefully reduce the error between the vehicle's actual apogee and the desired apogee relative to previous years' vehicles. The system must overcome the challenge of compressible regime aerodynamic loads while also deftly making complex trajectory calculations and executing upon them. Simultaneously, the system must satisfy every functional requirement set forth by the team to be considered ready to fly. If the system can produce these results without succumbing to material failure, having an uncontrolled deployment, or exasperate a hazardous vehicle tumble, then the team will consider the mission a complete success.

2.2 Payload Retention System Design Summary

The R&D electronics and software system underwent only slight changes since VDF. The electronics were unchanged, but there was an additional piece of mounting tape added to hold the R&D battery in the battery holder, since the battery had become dislodged from its socket during VDF. The software did not undergo any changes to the logic or implementation of the data being read, because it worked as expected during VDF. However, the data logged by the system during VDF was missing time stamps due to a bug in the logging code. The bug was fixed for PDF and more logging was added to ensure the team would be able to determine exactly what the R&D system did at certain times.

The R&D PCB was also intended to be added. The team worked to solder components to the PCB, but many of the components, especially the BMP390 pressure sensor, were very tiny and time consuming to solder. Unfortunately, the team could not get that sensor to work properly due to soldering issues. Due to this, the PCB was not used for PDF and the perf board that flew during VDF was used instead to maintain consistency.

The physical side of the R&D system had some changes as well. As stated in FRR, the R&D Pizza Table assembly has gained an additional inch of space to allow for more reliable deployment. To better facilitate the ejection of the Lander, the team decided to add an elastic band across two threaded rods of the Pizza Table, positioned such that they were ~1.5 inches below the top of the lander when the Pizza Table was fully extended. The intent was to provide an actual force to push out the Lander rather than relying on gravity alone. The reason the team thought this was necessary was unreliable track record of the R&D system to date, and the unpredictable nature of the swaying during decent which made relying/accounting for gravity difficult. During repeated tests the addition of the elastic band showed great promise with more reliable ejection that was also more expedient than before. One issue noticed with this addition was the “kinking” of the Pizza Table when the elastic band was not placed in the proper position. When this kinking happened the Pizza Table would fail to fully extend. To prevent this from being an issue for PDF the team secured the elastic band using zip ties.

2.3 Systems which Functioned as Intended

Despite the complications with the drogue parachute, the main parachute deployed successfully and ensured the vehicle touched down safely. One recurring issue with the main parachute was that the ejection charges would burn small holes in the parachute, slowly decreasing its effectiveness. With the use of a double Nomex blanket, this issue was fixed successfully, and the main parachute had minimal damage. Additionally, no major launch hardware was damaged during landing.

The altimeters and ejection charge systems also performed as intended, ejecting both parachutes at their respective times/altitudes in flight. The ejection charges did not damage either parachute, as there were no visible holes or burn marks upon post flight inspection. The charges also had sufficient force to separate the sections of the vehicle, as shown in the flight recording, and the main parachute deployed without any issues. Finally, the brownout and power loss that the StratoLoggerCF altimeter experienced during the Vehicle Demonstration Flight fortunately did not occur again during the Payload Demonstration Flight.

2.3.1 Analysis of ABCS Flight Performance

The target apogee for the flight was 4100’ AGL. During the Payload Demonstration Flight, the rocket apogee was close to the target apogee. This would have eliminated the need for the ABCS to deploy at all. However, this cannot be directly verified due to a lack of foresight and system design; there was no method of logging data during flight for the ABCS system. In a test conducted after the Payload Demonstration flight, the avionics data was streamed to the ABCS system in a “software-in-the-loop” simulation to determine what maximum angle the ABCS would have tried to open to during the flight. This angle was extremely small—only 4 degrees—but it would have been noticed with the aft-cam footage. This was verified by actuating the system to 4 degrees and checking the camera feed post-flight. However, you could not see the Aeroplate, which was in the field of view (FOV) of the aft-cam due to a mechanical jam of that singular Aeroplate at 4 degrees. Additionally, the rail button also distorted the FOV of the aft cam further. This situation is highly unfortunate, but the ABCS team has been able to successfully employ use of the aft-cam footage to analyze the flight, despite the fact that this system was not intended to help do so.

Figure 2.3: POV of the Aft-Cam during Vehicle Coast

While on the pad, the power of ABCS was verified before launch with the observation of a “micro flex” from the system. The ABCS quickly actuates out approximately 4 degrees and returns to its initial configuration, confirming power to both the system and motor. This means that the system did have power during flight. Though, during the micro flex, the Aeroplate aligned with the rail could not be seen to actuate because it was compressed inward by the rail and on the opposite side of the activation switch. This explains why the team could not foresee the jam which occurred during the flight. The question is whether the ABCS prematurely aborted or worked as expected. If the apogee of the launch had been significantly lower than the target apogee, it would have been easily confirmed that the ABCS had prematurely aborted. Unfortunately, the apogee of the launch was extremely close to the target apogee, leaving the team wondering if it was pure coincidence.

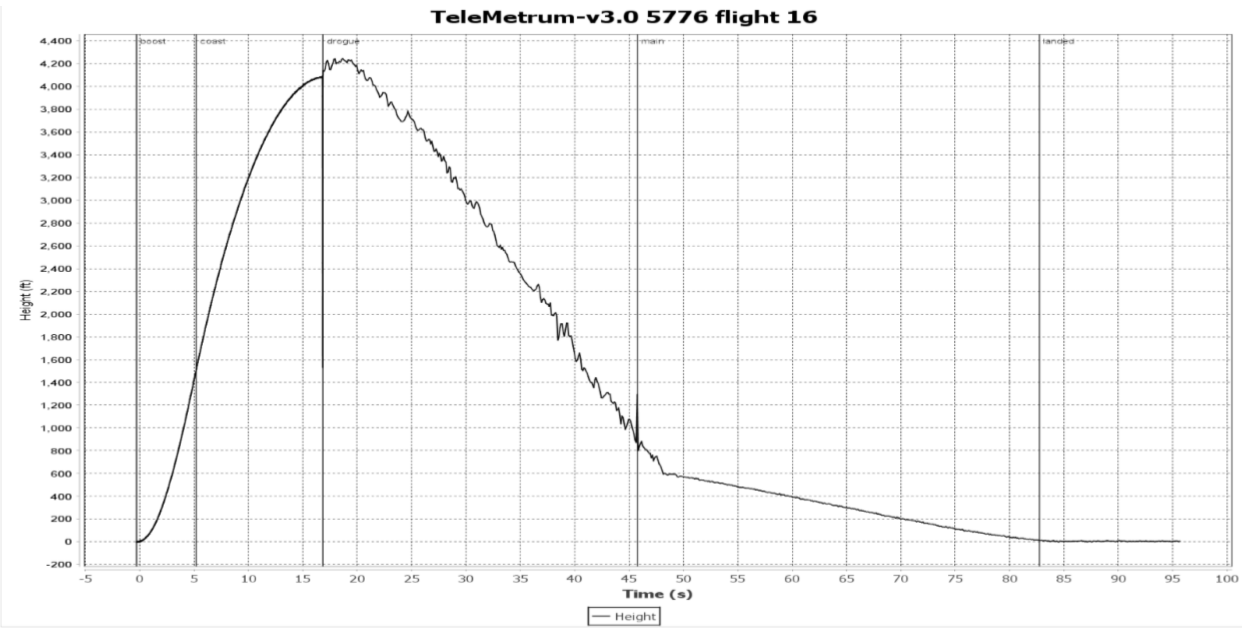

Figure 2.4: Altitude Data Plot of PDF Flight (Courtesy of the Avionics Team)

In contrast with the Vehicle Demonstration Flight, the Payload Demonstration Flight’s launch trajectory was significantly tilted to 16 degrees after the rocket exited the boost phase due to a steep inclination of the pad. This led to the assumption that the ABCS did deploy to 4 degrees, causing a drag force on the side of the rocket opposing the camera providing video feed, possibly explaining the additional turn of the rocket as seen from the aft cam footage. The uneven force distribution is caused by a manufacturing defect in the ABCS, where one pad gets slightly stuck before “popping” out at around 8 degrees. Again, in a series of unfortunate events, the pad that was found to get stuck at 4 degrees happens to be the pad in the line of sight of the camera.

The team has debated whether this is enough evidence to verify that ABCS actuated during flight. To conclude, there is a significant amount of evidence that points to the airbrakes functioning during the Payload Demonstration flight. Considering that the ABCS has successfully satisfied its requirements in both integrity, stability, and altitude accuracy, the team must consider this demonstration a plausible success.

Figure 2.5: ABCS Landed Post-Flight

Figure 2.6: ABCS Post-Flight Actuation Test at 4 degrees

Figure 2.7 ABCS Post-Flight Actuation Test Aft Camera Representation

Figure 2.8: ABCS Post-Flight Actuation Test Aft Camera Optimal Radial Location Representation

As seen in the above images, 2 Aeroplates are visible when actuated at 4 degrees. One of them is not visible due to jamming of the paddle strut with the ABCS coupler caused by insufficient actuation clearance between the two components.

2.4 Systems that Failed to Function as Intended

Upon inspection of the landed vehicle, it was discovered that the drogue parachute was damaged. The parachute was ripped along many of its seams and the shock cord was tangled inside of it. Due to this arrangement, it was presumed that the drogue parachute was ripped by the shock cord due to accidental entanglement during packing, first by wrapping around it and then being pulled apart as the two sections of the vehicle separated. The IFVR footage appears to confirm this, although the camera resolution is insufficient to make a definitive conclusion. The altimeter data shows that the damage occurred during flight, as the descent rate during the period of time between drogue and main parachute deployment was unusually high, and the altitude plot unusually jagged.

Figure 2.9: Torn Drogue Parachute

Figure 2.10: Shock Cord Tangled in Drogue Parachute

While the additional Nomex blanket functioned to protect the main parachute as intended, it failed to remain attached to the original Nomex blanket connected to the shock cord. The main parachute was free of burn marks and holes, confirming two Nomex blankets provide enough protection. The blankets were sewn together using a simple needle and thread, but this was torn apart during flight. Because they did not stay connected, the Nomex blankets failed to function as intended.

The EggFinder tracker located in the booster coupler failed to connect to the receiver and GPS mapping system. This system was given ample time to connect, but failed to do so before launch. While the exact reason for this is unknown, it is assumed to be a result of the various electrical systems in the booster causing signal interference. The EggFinder tracker located in the payload coupler connected to its receiver almost instantly. As this tracker is located away from competing electronic signals, its fast connection supports the theory of signal interference for the booster tracker. Because the booster tracker did not connect before launch, this system was marked as a failure and needs to be reassessed before the next flight.

2.4.1 Summary of PLS Mission Performance

The R&D subsystem was built in its entirety and was active during the flight. To address issues presented during VDF, the team had done informal testing on the deployment of the Lander. The deployment method during PDF differed slightly from the method used in VDF, and the team had success using the new method to deploy the Lander during the informal tests through formal testing. Due to this, the team believed that the R&D subsystem would function as expected. During PDF, there were some unforeseen complications that caused the system to not deploy the Lander. The R&D bay opened partially during the flight, and the impact of the vehicle with the ground caused the Pizza Table assembly to get jostled around, causing the Lander to fall out; however, this was not during in-air flight.

The Lander's software was not in its completed state during PDF. There were numerous challenges that occurred during the development of the software, including very small components that were not soldered on properly, a software environment that not many members had experience with, and a small number of software developers. Due to these issues, the only software that was in its fully finished state was the integration with the pressure sensor, and the ability for the Lander to attempt to stand up on its own, using a "kick" method. An error in the software occurred during PDF, and the Lander did not attempt to stand up.

The PICS subsystem was not integrated in a fully operational state. The team had success implementing much of its Arduino software, but due to the members of the team that worked on it not knowing how to use the software utilized on Lander, it was not able to be integrated into the LCS code.

Additionally, the GCS was not in its active state. Although some of the software was completed for it, such as image stitching, PICS was not completed sufficiently and therefore the GCS was not able to be utilized in the desired manner.

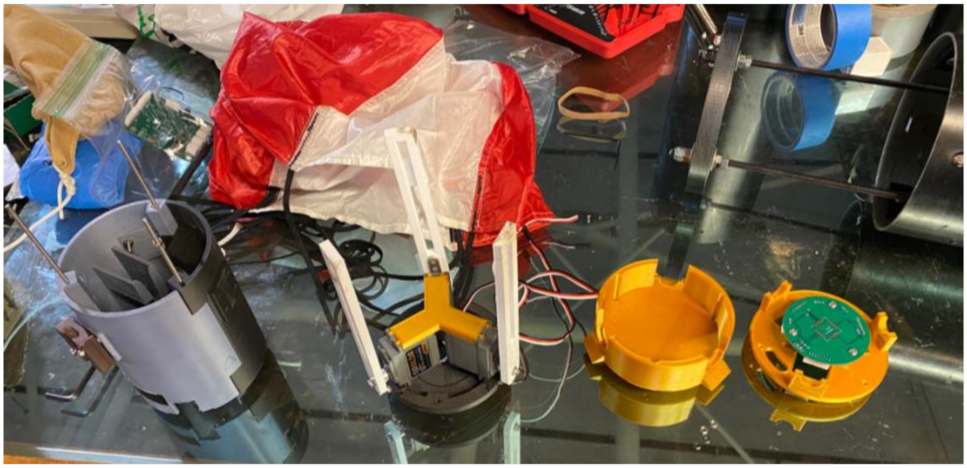

Figure 2.11: PLS Family Photo (Left to Right: Main Body, SOS, Cupola Top, PICS Plate, Pizza Table Assem.)

2.4.1.1 R&D Flight Performance

The R&D software worked as expected during VDF, but not PDF. The reason behind this is that the damaged drogue parachute caused much higher forces to be exerted on the system than expected during descent. For reference, during descent under the drogue parachute, the system logged approximately 2.2g of force. That is over twice the maximum force that the system expected during that period of descent. Due to this, the system believed that the main parachute deployed at that point and began using the RTC and accelerometer of the system to calculate its altitude. The main parachute was projected to exert 2g of force on the system, hence why it thought the main parachute deployed. This was a built-in safety feature in case the altimeter failed during flight. Unfortunately, the safety feature caused the system to attempt to release at an altitude of approximately 2923 feet. To resolve this issue, the code will be reevaluated, and the team will determine the best course of action, potentially removing the safety feature being the altimeter has not failed during any formal or informal test and has worked during both flights so far.

Despite the software misfire, the electronics worked perfectly for PDF. The stepper motor held the lander in the payload bay even though the system was experiencing higher than expected forces. Additionally, the tape held the battery in the holder securely and prevented it from vibrating out as it did in VDF.

The problem that was identified during VDF for the R&D system was the logging issue. After analyzing the data logged after the launch, the issue is resolved. The team was able to recover all the necessary data and timestamps from the flight.

Mechanically, the R&D bay failed to fully extend which prevented the deployment of the lander while descending. The team believes that the R&D pizza table experienced unexpected forces during descent, primarily from the increased load from the main parachute due to the drogue not deploying correctly. It is also possible that the addition of the elastic band could have caused the failure to fully extend. Unfortunately, the onboard cameras didn’t provide enough information to accurately determine the exact reason the Pizza Table failed to fully extend.

Figure 2.12: Post-Flight Payload Bay with R&D Bay Open

2.4.1.2 D&L Flight Performance

Unfortunately, as the R&D failed to fully deploy the Lander, no meaningful results can be determined according to the operation of the D&L System. The Lander fell with the rocket, so recording the descent time would not determine the functionality of the Lander's parachute. Because the Lander did not leave the R&D Bay, the parachute stayed in the deployment bag as intended. Of note, the Lander was found approximately 11' from the nearest element of the launch vehicle.

Figure 2.13: Lander Deployed after Dragging Post-Flight

2.4.1.3 LCS Flight Summary

Due to several circumstances, including delayed orders and the loss of critical personnel resources, the LCS was not able to be fully completed in the desired state. There were several features of the LCS that were not implemented and several last-minute modifications that needed to be made. First, the PCBs arrived, but the team ran into several problems assembling components onto the PCBs. The critical BNO085 and BMP390L sensors were the primary issue. Both sensors proved to be extremely difficult to solder on despite using equipment available from the BIDC electronics lab. Ultimately, the BMP390L was not functioning at the time of launch and the team believes this is a result of a hardware issue that the team did not have time to debug. The team improvised and soldered a BMP388 breakout board to the primary board to use in place of the BMP390L. The BMP388 uses the same API as the BMP390L so this change did not require any changes to code, in fact much of the code was developed using the BMP388.

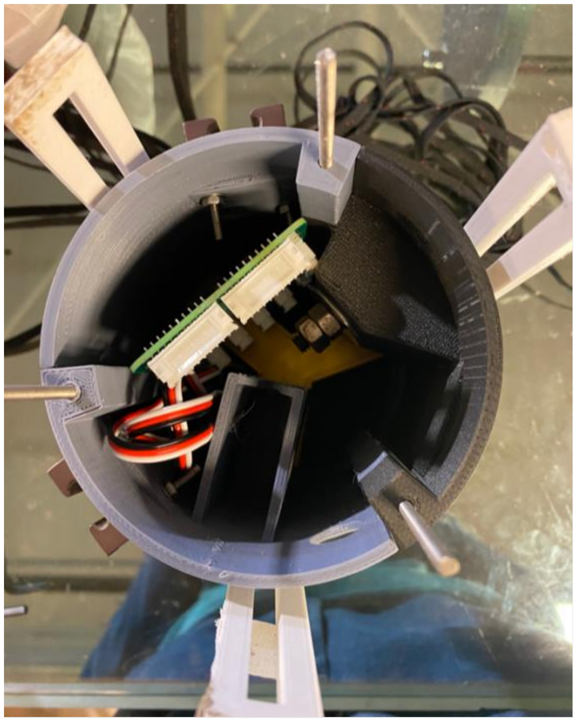

Figure 2.14: Final Lander LCS Overhead View (No Battery Installed)

The BNO085 also was not functioning prior to launch. It has yet to be determined if this is a hardware or software issue. The team did not attempt to replace the BNO085 due to a lack of resources and time. The team implemented several changes to software detailed in the SOS section.

Since the team did not have an IMU it would be impossible to implement the originally imagined triple redundancy deployment of the nichrome parachute release system with the same procedure. To ensure the safety of team members and bystanders, it was determined that the team would not attempt to sever the parachute. Since the team was unable to test this system in this launch, and with the limited time before the next launch, the team no longer expects to use the nichrome system at any point this competition. The team will test to see if the Lander can still meet requirement S.P.19, without severing the parachute. Requirement S.P.19 specifies that the Lander will be able to remain stable in 10mph winds. After some post-flight experimentation, the team believes that the system will still meet this requirement.

The final piece of the LCS that was not operational during flight was the transmitter. A purchase order for necessary components was delayed, preventing the XBee transceivers from being properly installed. In addition, other problems specified above took up too much time that the software to use the transceivers was not developed enough to be integrated.

Due to the IMU being non-functional, an alternative route was used to determine if the Lander had landed. The altimeter in conjunction with the RTC was used. The altimeter was used to determine the appropriate stages of flight by reading the altitude. This allowed the lander to detect when it should have been deployed and when it landed. The RTC attempted to keep track of the time since the lander was projected to be deployed. The timer was set to be much longer than the expected landing took (approximately 20 minutes), so that the lander wouldn't start moving too soon in case of a fault somewhere in the code. The failure of the system to accurately detect landing would result in the lander attempting to open inside the payload bay, or while it was falling. The team determined that these potential failure modes posed no threat to the integrity of the rocket or to the safety of the team, so the software was implemented.

On launch day, the Lander experienced an initialization error. The cause of this error is unknown at this point. As a result of the error and the fact that the R&D system did not successfully deploy the Lander it is impossible to determine if the Lander would have been able to determine if it had landed and triggered the SOS at the right time. The software for the basic SOS system was developed and basic tests were done prior to launch. The SOS section contains more information on software specific to the SOS system.

2.4.1.4 SOS Mission Summary

Upon landing, the Lander initializes all legs to 0 degrees and allows 5 seconds to pass before triggering the next sequence. However, due to complications with interfacing the IMU, the ability of the final detection of orientation and self-correcting procedure was unable to be completed. Without the ability to detect if the Lander has fallen into an unfavorable orientation, the team decided that the Lander would continue to perform a "kick" function with each of its legs, one by one, to allow the Lander to roll down any hill or slope it is potentially positioned on. After each kick is performed, the Lander would actuate all three legs to the same angle and stand itself upright. Should the Lander be positioned on a flat surface after performing the kicking sequence, this sequence would stand the Lander up perfectly vertical and has been tested and proven to be effective at transitioning the Lander to a stable initial standing position. Future additions to this sequence will involve correcting from the stood-up position to 5 degrees from vertical.

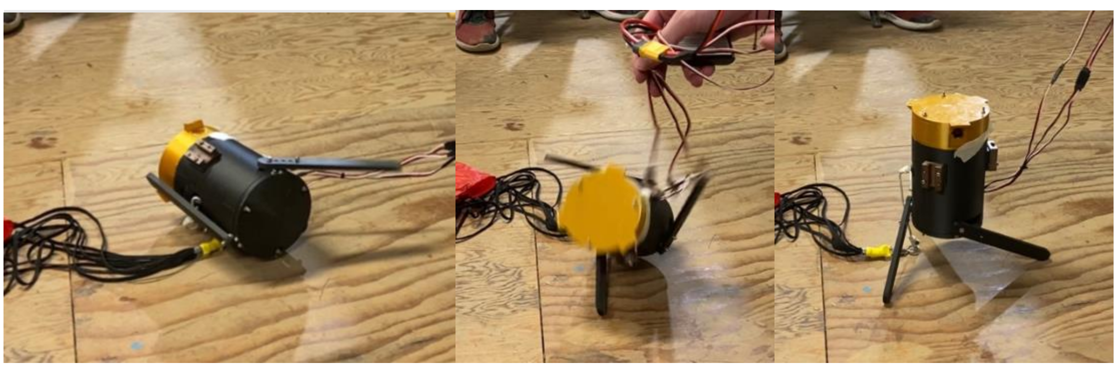

Figure 2.15: Successful Test of the SOS Stand-Up Procedure (Left to Right: Kick, Stand-Up, Standing)

2.4.1.5 PICS/GCS Mission Summary

The image stitching that was to be done on the GCS was completed by the team. Due to other aspects of the software that it depended on not being fully completed, the image stitching wasn't implemented during PDF.

The PICS system was not in a fully operational state for this launch. When distributing limited team resources, it was decided that PICS would take the lowest priority as it provided no safety concerns. In addition, PICS system can be fully tested without having to go in flight. All PICS components were present and connected in the Lander during flight. This way, the team could verify that the PICS components would not sustain any damage from flight. The team believes that this particular aspect was a success, seeing as there was no damage to any PICS system components despite abnormal loads from the drogue malfunction and being dragged out of the bay after Landing. The team has not made any changes to the PICS system since FRR and will continue to work on the system in the coming weeks.

As stated in the LCS section the Lander did not have a transmitter in flight nor was the PICS operational. This made it impossible to fully test the GCS's ability to receive and stitch the images automatically. However, the software to stitch the images has been completed but still needs additional testing to verify it functions properly.

2.5 Damaged Hardware in Need of Replacement

As mentioned above and confirmed by altimeter data, the drogue parachute was destroyed during deployment and will not be usable for future launches. In preparation for the next launch, the original plan was to purchase the same parachute as a replacement. It is currently out of stock however, so the next launch will use the 24" SkyAngle CERT-3 Drogue parachute, which offers comparable performance. This decision was backed by the ability to use it immediately, since it was available from a launch during a previous year.

One of the Nomex blankets needs to be replaced after it was torn from the original Nomex during flight. Because it was unclear when the extended Nomex tore from the original section, there was a low chance of recovering it from the launch field. Additionally, the color of the Nomex material blended in with the crops scattered throughout the launch area. This system needs to be replaced because the two-Nomex system prevented the VDF problem of parachute burn holes, but one Nomex was not recovered from the launch field.

2.6 Lessons Learned from the Flight

The drogue parachute was damaged due to interaction with the shock chord. It was tangled around the loose shock chord, which tore the parachute apart once it became taut. Despite the normal careful and meticulous packing of both parachutes, the drogue parachute was destroyed. This necessitates a more thoughtful parachute packing approach for the drogue parachute, with extra care as to avoid any further shock chord related damage in the future. Additionally, all future launces will ensure that all components of the recovery system are secured in place without the ability to move around and arrange themselves in a manner that caused the destruction of the drogue parachute.

The extended Nomex blanket successfully protected the main parachute from burn holes, solving a problem presented in VDF. However, the connection method between the two Nomex blankets was not strong enough, causing one to be lost during flight (they were loosely hand-sewed together). This will be mitigated in the future by using a more secure sewing method to attach the two blankets. Specifically, a mechanical sewing machine will be used to securely fasten the two blankets with two lines of stitching. It is unlikely the forces of flight will tear through one of these more secure lines, let alone both.

The failure of the booster section EggFinder tracker is likely due to signal interference from surrounding electronic systems. Another possible explanation for this failure is the increase in carbon fiber components in the vehicle, as this material is known to block electronic signals. To solve this problem in the future, a shielding plan will be implemented to protect the booster tracker signal. This shielding is likely to include a slight repositioning of the EggFinder itself and a reevaluation of carbon fiber materials located in the vehicle. It is noted however that this material is used sparingly, and it is unlikely that any carbon fiber will be removed from the design. Finally, before the next flight, this will be tested to ensure that the tracker can connect to the receiver in launch configuration.

3 Updated Project Plan

3.1 Payload Testing & Flight Reliability

The below testing plans and results should serve as overriding documentation of ID-matched verification tests on FRR. These tests have been further reviewed or completed since FRR.

3.1.1 Weight Testing — VT.P.0.1, VT.P.0.2, VT.P.0.3, VT.P.0.4

Test Objective: Fulfill requirements S.P.0: The overall mass of the payload systems shall not exceed 16lbm, S.P.0.1: The overall mass of the lander subsystem shall not exceed 3lbm, S.P.0.2: The overall mass of the retention and deployment subsystem shall not exceed 5lbm, and S.P.0.3: The overall mass of the ABCS shall not exceed 8lbm.

Testing Variables: The testing variables are the mass of each system of the Payload in pound-mass, determined through measuring pound-force.

Success Criteria: Mass of the Payload systems including Lander subsystem, Retention and Deployment subsystem, and ABCS properly fulfill set weight requirements.

Why it is Necessary: A smaller total weight is necessary to obtain the required minimum thrust-to-weight ratio of 5:1, as defined by S.V.9. Additionally, properly coordinated weight is essential to achieving the desired apogee.

Methodology:

1) Assemble individual components in flight configuration.
2) Measure the mass of each system with a scale.
    a) Measure the combined mass of the Payload.
    b) Measure the individual mass of the Lander Subsystem.
    c) Measure the individual mass of the Retention and Deployment Subsystem, subtracting the mass of the vehicle airframe.
    d) Measure the individual mass of the ABCS, its couplers, and attachment fasteners, subtracting the mass of the lower airframe (including all motor components).

Impact of Results: Should any system exceed weight requirements, further work would be required to optimize the materials used in construction of components, whether that be design changes or other relevant compromises. Should each system meet weight requirements, no further modifications would be necessary.

Results and Conclusions:

Item	Weight	Maximum	Status
Lander	1lbm 8oz	3lbm	Pass
R&D (w/ Nosecone)	4lbm 1.2oz	5lbm	Pass
ABCS	5lbm	8lbm	Pass
Overall	10lbm 9.2oz	16lbm	Pass

Table 3.1: Weight testing

The weights of all elements of the Payload are below their required quantities. In fact, additional weight has been added to particular systems such as the R&D coupler (1lbm 13oz) at the request of Construction. Overall, the resultant weight of all systems are far within bounds.

3.1.2 PLS R&D Deployment Testing — VT.P.1.1

Test Objective: Determine whether requirements: S.P.1.4, S.P.1.18, S.P.1.19, and S.P.1.21 will be fulfilled or not.

Success criteria: The Lander analogue stays nearly immobile in the payload bay while it is suspended and while it is suspended and shaking/swaying. The team can switch the R&D electronics from pre-flight to flight ready without disassembling the payload bay during the test. Finally, the Lander Analogue deploys under 5 seconds during both the static test and the swaying test.

Why it is necessary: The test ensures the payload bay and R&D system protect and deploy the Lander as designed.

Methodology:

1) Fully assemble the payload bay and insert Lander Analogue into the bay. Visually inspect fit of Lander Analogue.

2) Close payload bay and attempt to switch R&D electronics from pre-flight status to flight ready status.
3) Suspend the payload bay from the test stand.
4) Induce both vibration and swaying of the payload bay to simulate flight conditions and inspect Lander Analogue for movement or damage.
5) Signal the R&D electronics to deploy the Lander Analogue and time the process from signal sent to full deployment (Lander exits cylindrical confines of R&D).
6) Perform the previous step under various swaying condition, both different intensities and different direction of sway.

Impact of Results: If the payload bay assembly perform as expected no action is necessary. If significant movement or any damage of the Lander Analogue is observed during the test modification of the payload bay will be necessary to better secure the Lander. If the deployment time is observed to be over 5 seconds during any of the tests the team will determine whether it is feasible to start the deployment process earlier in the flight so that Lander ejection occur in the correct altitude range. Additionally, the times recorded will be used to determine how much earlier to begin the deployment. If the Lander Analogue fails to deploy in any of the test's significant modifications to the ejection method might be necessary. This is also true for if the R&D electronics prove impossible to switch from pre-flight to flight ready during the test.

Results and Conclusions: This test has not yet been conducted for FRR but was be done before PDF.

Trial	Difference	Time to Deploy (s)	Time to Unscrew (s)
1	No sway, Parachute Bottom	No Deploy	2.5
2	No sway, Parachute Bottom	No Deploy	2.5
3	No sway, Parachute Ramped	~2.6	2.49
4	No sway, Parachute Top	No Deploy	*-
5	No sway, Parachute Ramped	Deployed	-
6	No sway, Parachute Ramped	No Deploy	-
7	Sway, Parachute Below, Ramp Added	Deployed	-
8	No Sway, Parachute Below, Ramp Added	Deployed	-

Table 3.2 PLS Deployment Testing

*Times to unscrew marked with "-" were not measured.

This test has been deemed successful. The R&D system was proven to open up and release the Lander in far under 5 seconds when the mechanism properly functions. Observing footage taken of the test, the Lander exits almost concurrently with the opening of the R&D bay.

The primary concern after extensive and vigorous experimental testing was whether the R&D release mechanism could reliably release the Lander for the purposes of PDF. Many small adjustments were made to the R&D bay before executing this test in an attempt to increase this reliability. Some of these modifications can be seen in the "Difference" column above. The final configuration tested and used on PDF included a small ramp beneath the parachute in order to better assist the Lander's fall out of the bay.

3.1.3 ABCS Battery Testing — VT.P.2.2

Test Objective: Fulfill requirement S.P.2.7: The battery powering the ABCS must be able to withstand idle operation for a minimum of 2 hours.

Success criteria: The ABCS would be able to receive adequate power from the battery for 2 hours powered on.

Why it is necessary: This test will ensure that the ABCS will be able to function when necessary during the flight of the vehicle.

Methodology:

1. The motor assembly system will be connected to a multimeter and the battery. As the motor is deployed, the current will be measured which will then be used to calculate how long the battery can support active motor usage.
2. To test the idle operation of the motor assembly it will be connected to the battery and multimeter and left turned on in the idle position. The voltage will be recorded every 0.25 hours until at least the 2 hour mark is reached. The voltage drop will then be analyzed in order to determine if it adequately meets the voltage needs of the system.

Impact of Results: If the test goes as expected, the battery and motor combination is adequate and is ready to be fully integrated into the launch vehicle. If the battery will not be able to withstand the idle operation for the full 2 hours, then modifications will be made and further tests will be made until this is able to be accomplished.

Calculations:
Battery voltage and capacity: 3300mAh at 12.1V
System current draw (at 5V):

Component	Teensy 4.0	BMP280	BNO085	Motor Driver (Idle)	Total
Max Current Draw	120mA	5mA	10mA	50mA	185mA

Table 3.3: ABCS Component Current Draw

Hours of idle operation: 3300mAh / 185mA = ~17 hours

These calculations suggest that the system, when in idle state, could last for up to and possibly longer than 17 hours of operation. The motor driver is put into idle mode while the launch vehicle is on the pad to conserve power. Once the IMU detects the upward force from the motor being fired, it switches the motor driver into an active state where more power is drawn but the motor has holding torque.

Based off the theoretical calculations, the ABCS system should be able to stay in a powered-on state for well over the 2-hour requirement on the pad. This is mainly because the motor can be enabled or disabled to allow the use of holding torque at the cost of higher power consumption.

Results and Conclusions:

Time	Voltage
15min	12.2V
30 min	12.1V
45 min	12.1V
60 min	12.1V
75 min	12.1V
90 min	12.1V
105 min	12.0V
120 min	12.0V

Table 3.4: ABCS Battery Testing

The ABCS was shown to be fully operable after the completion of this this test. Therefore, the power supply capabilities of the ABCS battery successfully meets the two hour operation requirement.

3.1.4 ABCS Activation Testing — VT.P.2.4

Test Objective: Fulfill requirement S.P.2.6: The ABCS must be able to fully activate or deactivate control surfaces in under 5 seconds.

Success Criteria: The ABCS can actuate fully within the allotted time of 5 seconds.

Why it is necessary: This will ensure that the system is able to operate as quickly as necessary during flight.

Methodology:

1. An analysis will be done in order to determine how long it should take for the aeroplates to be fully deployed.
2. In order to fully test the activation/deactivation time, the plates will be loaded with 45 kg of tension evenly split between the three plates. The system will then be timed as it activates and deactivates in order to verify that it is within the allotted time of 5 seconds.

Impact of Results: If the test goes as expected no changes to the ABCS are necessary. If the activation and deactivation are not each able to be completed in the allotted time, modifications to the software and/or hardware will be made, and testing will continue until the requirement is met.

Results and Conclusions: The ABCS system was actuated successfully in 4 seconds under load, well within the 5 second requirement. This means that the ABCS will be able to perform its function within reasonable to help with achieving the target apogee.