NASA Student Launch

2017-2018 Flight Readiness Review (FRR)

March 5th, 2018

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1 General Information

1.1 School Information/Project Title

School Name:	University of Louisville
Organization:	River City Rocketry
Location:	J.B. Speed School of Engineering 132 Eastern Parkway Louisville, KY 40292
Project Title:	River City Rocketry 2017-2018

1.2 Team Officials

Advisor Name: Dr. Yongsheng Lian
Contact Information: y0lian05@louisville.edu **or** (502) 852-0804

Dr. Lian serves as a faculty member at the Department of Mechanical Engineering at the University of Louisville. He worked at the Ohio Aerospace Institute as a Senior Researcher from 2003 to 2005 and as a Research Scientist at the Aerospace Engineering Department of the University of Michigan from 2005 to 2008. He joined the University of Louisville in 2008. He has 21 years of experience in computational fluid dynamics. He developed algorithms to study fluid/structure interaction, laminar-to-turbulent flow transition, low Reynolds number aerodynamics, and its application to micro air vehicle, two-phase flow, and design optimization.

Team Captain/Safety Officer
Name: Maria Exeler
Contact Information: msexel01@louisville.edu **or** (859) 912-3547

Maria is currently a senior mechanical engineering student at the University of Louisville's J.B. Speed School of Engineering. This is Maria's second year in NSL and her first year as co-captain of River City Rocketry. After contributing to last year's successful season, Maria is looking forward towards improving on the team's safety while continuing to lead the team through new challenges. Maria plans to bring her experiences from working at GE Aviation to her position as co-captain and as safety officer. Throughout last year Maria gained valuable knowledge in fabrication, integration, and problem solving, and she hopes to both pass this knowledge down and employ these skills at GE Aviation following graduation.

Team Captain/Outreach Lead
Name: Gabriel Collins
Contact Information: gdcoll01@gmail.com **or** (502) 457-8829

Gabriel is currently a senior mechanical engineering student at the University of Louisville's J.B. Speed School of Engineering. This is Gabriel's third year in NSL and his first year as co-captain of River City Rocketry. After contributing to last year's success, Gabriel is looking forward towards improving on the team's integration while continuing to take the team to new heights. Gabriel plans to bring his experiences from working at PIA to his position as co-captain and Outreach Lead. Throughout this experience Gabriel has gained valuable knowledge in design, communication, and project optimization, and he hopes to both pass this knowledge down along with employing these skills in the aerospace industry following graduation.

1.3 Tripoli Rocketry Association Mentor

Name: Darryl Hankes
Certification: Level 3 Tripoli Rocketry Association
Contact Information: nocturnalknightrocketry@yahoo.com **or** (270) 823-4225

Darryl Hankes engaged himself in rocketry in February of 2003. In 2004, he joined Tripoli Indiana and where he received his Level 1 TRA certification. In 2006 at Southern Thunder, Hankes received his Level 2 TRA certification. A year later, in 2007, Hankes successfully attempted his Level 3 TRA Certification at Mid-West Power. Over the years, Hankes has flown an R10,000 twice in a team project along with countless M-R projects with clusters, staging, and air starts. He is the former prefect for the Tripoli Rocketry Association, Bluegrass Rocket Society (TRA #130), which provides launch support during test launches. Hankes has mentored the team through all seasons that River City Rocketry has participated in NASA's student launch competitions. The team is pleased to see his return for this year's competition.

2 Summary of FRR Report

2.1 Vehicle Summary

A summary of key launch vehicle parameters is shown below in Table 1.

Length (in.)	139
Diameter (in.)	6.25
Mass (lbs.)	49.3
Motor Selection	Aerotech L2200-G
Recovery System	Cruciform Drogue and Toroidal Main (4 sections)
Rail Size	1515, 144in.

Table 1: Summary of launch vehicle parameters.

The launch vehicle has been designed to allow adequate room for all payload and recovery hardware. A length of 133 in. and a diameter of 6 in. was found to provide adequate space for all flight controls, payload, and recovery subsystems. To safely launch the vehicle and provide a margin of error for mass assumptions of various components, an AeroTech L2200-G solid ammonium perchlorate motor was chosen. A Variable Drag System will allow the launch vehicle to reach 5,280 feet with accuracy within ±23 feet.

The launch vehicle will be recovered in four independent sections. The vehicle will utilize two cruciform drogue parachutes, and two toroidal main parachutes. At apogee the launch vehicle will split into two sections, ejecting a drogue from the nose cone, and another drogue from the payload recovery coupler. The two sections will fall under drogue independently until releasing their main parachutes at the designated altitude. The payload section will use an ARRD to release the main bag and use the nose cone parachute to pull the main from the payload recovery bay. The booster main parachute bag will be connected to the bottom of the payload recovery coupler and the booster drogue will pull the booster main parachute from the booster recovery bay. The nose cone will then recover under the original drogue, and the same for the payload recovery coupler.

2.2 Recovery Summary

A separation event at apogee will decouple the vehicle into two independent sections: the payload segment, and the booster segment. Both the nosecone and the coupler will separate from their respective airframe counterparts during main deployment and be recovered under the drogue parachutes as independent sections. These two drogues will also act as pilot parachutes for each respective main parachute. These four independent segments are displayed below in Figure 1.

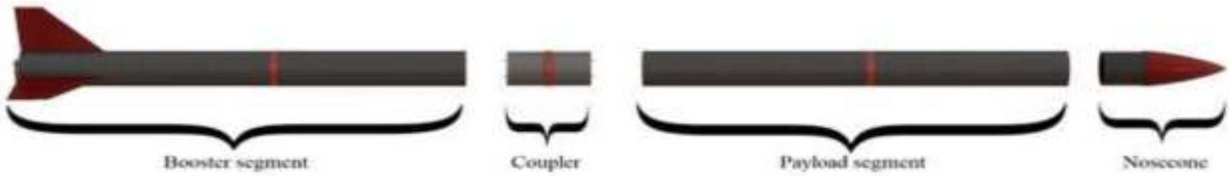

Figure 1: Independent sections of the launch vehicle upon descent.

2.3 Payload Summary

This year's payload is designed to accomplish the deployable rover challenge of the NASA Student Launch Competition. The payload consists of an autonomous rover vehicle carrying a foldable solar array and an orientation correction system to ensure upright orientation of the rover prior to deployment. Deployment will be remotely activated using a unique deployment signal sent to the vehicle by a team member after receiving RSO permission to proceed. For the remainder of this document, "the payload" will refer to all subsystems and subassemblies of the entire experimental payload onboard the launch vehicle while "the rover" will solely refer to the autonomous rover vehicle and onboard rover systems and assemblies.

3 Changes since CDR

1.1. Vehicle Design Changes Since CDR

Change	Justification
VDS bottom plate design changed so that mass reduction slots were removed so that the plate was solid aluminum.	Following the results of the first test flight, it was deemed that making the bottom plate of the VDS solid aluminum could protect the VDS in the event of a motor CATO.
VDS spacers were changed from machined aluminum parts to 3D printed PLA plastic parts.	Following the results of the first test flight, the VDS spacers were destroyed and due to time constraints, new spacers were 3D printed.
Booster recovery bay tube length changed from 23 in. to 24 in.	After final manufacturing of all recovery hardware, a 24 in. tube was deemed necessary to stow the booster recovery hardware.
Payload Recovery bay tube length changed from 25 in. to 30 in.	After final manufacturing of all recovery hardware, a 30 in. tube was deemed necessary to stow the payload recovery hardware.
Fin material was changed from a custom carbon fiber sheet to a store bought DragonPlate carbon fiber sheet.	After the results of the first test flight, the custom fins suffered damage. Due to time constraints, it was deemed necessary to change materials to a readily available material.

1.2. Recovery

Following testing of the recovery system, it was concluded that stability during descent could be increased by modifying the cruciform design while retaining the surface area. This modification is discussed in Section 4.2.1.4.

1.1 Changes since CDR

Change	Justification
Updated from Beaglebone Green microcomputer to Teensy 3.6 microcontroller for main VDS control system.	Microcomputer is not viable for the needs of the variable drag system, nor is it compatible with the VN-100 sensor. See 4.1.2.1.1_Changes in hardwareChanges since CDRChanges in hardware
Switched from VN-100 IMU to bmp280/BNO055 combination for DAQ.	Not compatible with the type of serial communication used in VDS programming architecture. See 4.1.2.1.1_Changes in hardware
Updated PCB design.	Changed to accommodate updated sensors and microcontroller. 4.1.2.1.2_Manufacturing
Updated Simulation Parameters.	Changed in order to meet the updated parameters of the rocket, and create an updated fully dynamic simulation of an actuating VDS during flight

Added function in Drag Blades class in program.	To add motor movement testing functionality. See **Error! Reference source not found._Error! Reference source not found.**

3.1 Changes to Payload

Change	Justification
Attached bearings to inside wall of the rover body.	Mitigate deflection in the bearing housing.
Thickened rover latch and changed material	Lower stress concentrations and improved chance of successful deployment
Replaced mounting holes with slots	Aid in sub-assembly alignment.
T-slot relocated	Mitigate risk of snagging on ROCS during deployment
Passive wheel material change	Lighter than Delrin, easy to manufacture.
Redesign drive shaft spacer	Reduce number of parts, increase durability, and improve surface finish.
Replaced open bearings with shielded bearings	Protect bearings from FOD and retain lubrication.
Drive shaft bracket material change	Reduce friction between the drive shaft and bracket.
Added control electronics power switches	Maximize pad, flight, and payload mission times by turning power on after payload integration.
Added RGB LED indicator	Indicate the state of the rover
Added transistor to CES	Directly power the solar tower locking motor using the controller battery
Bolt and screw added to each panel support arm	Increased security of solar panel mounting.
Shortened panel support arm length	Increased clearance between Rover and ROCS and probability of mission success.

4 Launch Vehicle

4.1 Design and Construction of Launch Vehicle

4.1.1 Launch Vehicle Overview

The launch vehicle has been designed to safely deliver a rover payload to an apogee altitude of 5,280ft. The launch vehicle consists of five sections: the booster, booster recovery bay, payload bay, payload recovery bay, and the nose cone. The vehicle will feature a rover payload as well as a Variable Drag System (VDS) that will be discussed in detail in later sections. A rendering of the fully assembled launch vehicle is shown below in Figure 2.

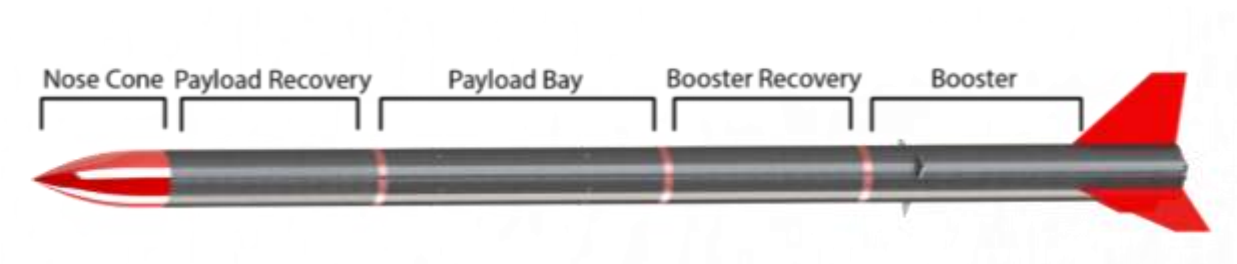

Figure 2: Rendering of the fully assembled launch vehicle.

4.1.1.1 Launch Vehicle Dimensions

The launch vehicle is approximately 6.25 inches in diameter, and 139 inches in length. The dimensions of the vehicle were dictated by the size of the motor selected, the rover payload size, and the size of the as built recovery equipment. The recovery bay dimensions changed slightly since CDR as discussed in 1.1. The size of the fins and nose cone were determined using software, further discussed in 4.1.3.2 and 4.1.3.7 respectively. The length of each section of the as built launch vehicle, including witness rings, is shown below in Table 2.

Section	Length (in.)
Booster	37
Booster Recovery Bay	25
Payload Bay	33
Payload Recovery Bay	29
Nose Cone	15
Total Length	139

Table 2: Launch Vehicle Dimensions.

4.1.2 Variable Drag System (VDS)

The Variable Drag System (VDS) has been fully manufactured and ground tested. It has verified all its safety, integration and breaking power requirements. Shown in Figure 7 are the motor configuration, the printed circuit boards, and the coupler pre-integration.

Figure 3: Full VDS (disassembled)

4.1.2.1 Hardware

4.1.2.1.1 Changes in hardware

Initially, the VDS was designed to incorporate a VN-100 Inertial measurement unit with a BeagleBone Green computer as its primary data acquisition system by which the VDS performs it's drag analysis in flight. The system now consists of a Teensy 3.6 microcontroller, and two IMUs; an Adafruit BMP280 altimeter and n Adafruit the BNO055 9 Degrees-of-freedom sensor and accelerometer. The team is confident that this electronic system will be viable, as it has been tested extensively in the past, and has been proven to provide the level of accuracy desired for this system.

The change was due to complications in integration of the VN-100 with the BeagleBone green computer. This IMU sensor is not compatible with the BeagleBone via SPI serial communication to the degree that is necessary for the accuracy of the VDS this incompatibility could not have been predicted. Additionally, the microcomputer has an operating system which has additionally been proven to be incompatible with our software architecture, or the adjacent VN-100 sensor. To more clearly refer to this previous configuration, the VN-100/BeagleBone design will be referred to as the electronics v1.

4.1.2.1.2 Manufacturing

The electronics design has been finalized and manufactured in several iterations. The progression of manufacturing consists of the process as shown in Figure 4.

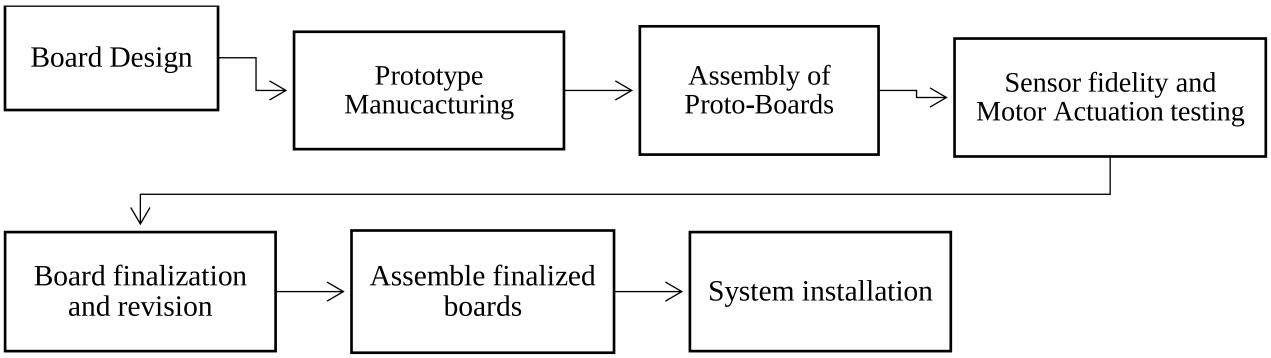

Figure 4: Board manufacturing process

The printed circuits boards (PCBs) initially went through a prototyping process consisting of the electronics v1 design. These PCBs were two layer, FR-4 copper plated boards manufactured by Advanced Circuits.

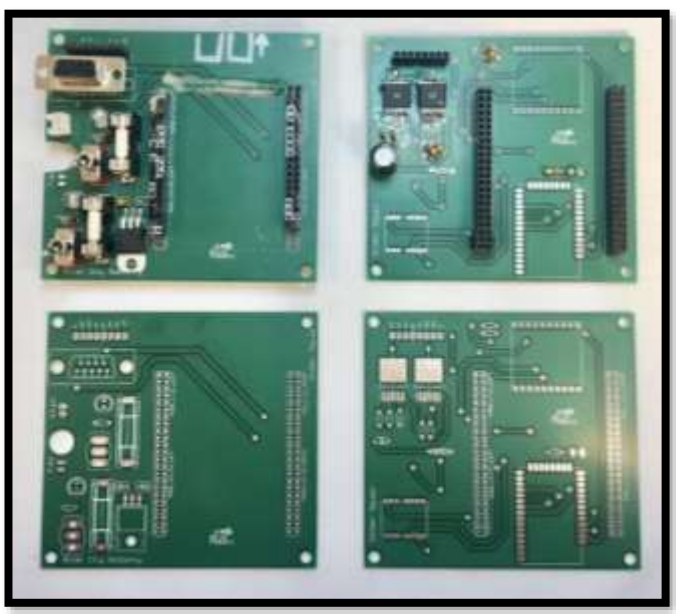

Figure 5: Electronics v1 boards, assembled and disassembled.

This board was produced for use in the full scale control and full break launches, however due to the aforementioned circumstances, alternative boards were designed. The revised boards also consist of two copper plated layers, having been manufactured by a local LPKF PCB milling machine. This board has been used to test functionality of the VDS and all of its components, and has served as the flight board for the completed full scale launches. These hand created boards are shown assembled in Figure 6.

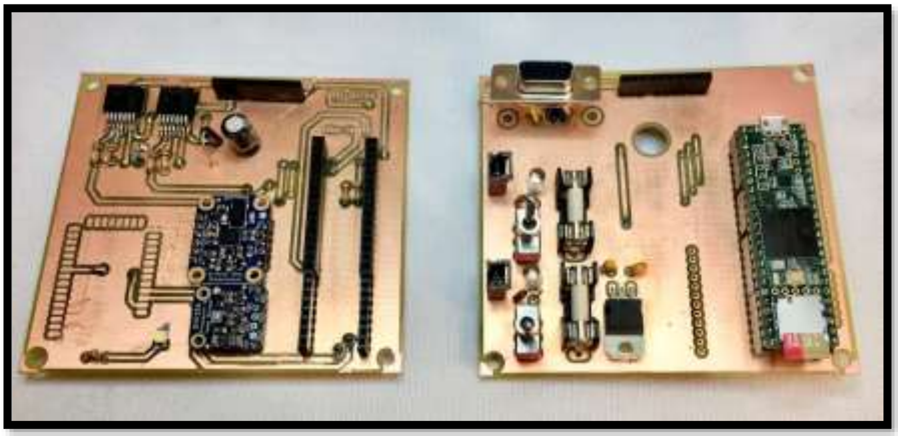

Figure 6: Assembled, updated VDS printed circuit boards.

The updated PCB will be remanufactured by advanced circuits to provide optimal performance quality which will eliminate error that could potentially stem from the hand manufactured and assembled boards.

The full installation and demonstration of the hardware configuration is vital to verification of the functionality of the circuit components. The major components of the system include; the BMP280 altimeter, the BNO055 9DOF and accelerometer, BTN7960 H-bridge motor controls circuit, limit switches, and a motor encoder. The components that required verification are the BMP280 and the BTN7960 motor circuit. The BMP280 pressure sensor has been verified by recording its altimeter data at different pressure points and comparing them to the actual altitude above sea level value. The motor circuit was verified through giving various commands to the blades utilizing the assembled PCB connected to the software. In all of these tests, the VDS preformed nominally and performed successfully, as anticipated, qualifying it for launch testing.

The system installation consists of connecting all the system components together. System installation verifies that the dimensions and lengths are correct. The installation demonstrates the full in-flight configuration of the system. A figure of the installed system is shown in Figure 7.

Figure 7: Exploded installed VDS

When integrated, the blade motor configuration is connected through a 9 pin male-to-female D-sub connection mounted into a wooden bulk plate. The corresponding end is plugged into another D-sub connection mounted onto the PCBs, which is fed through the electronics sled. This system is able to be tested independently from full insertion into the booster section of the rocket, as well as when it is placed and secured into the booster section.

4.1.2.1.3 Radio Telemetry

The radio telemetry system utilizes two Xbee SX pro's, one of which is integrated into the PCBs and the other which connected to a Yagi Antenna at the ground station. The test integrations can be seen in **Error! Reference source not found.** and **Error! Reference source not found.**.

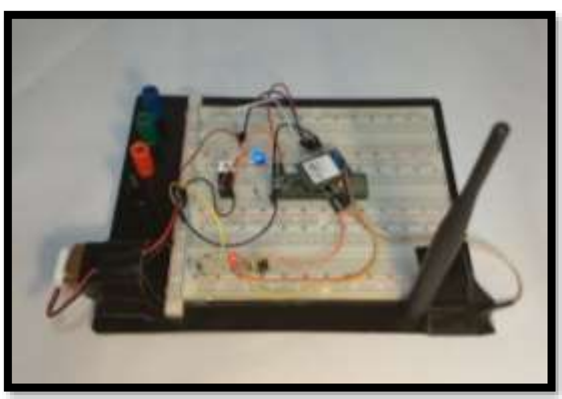

Figure 8: Launch Vehicle Telemetry Test Setup

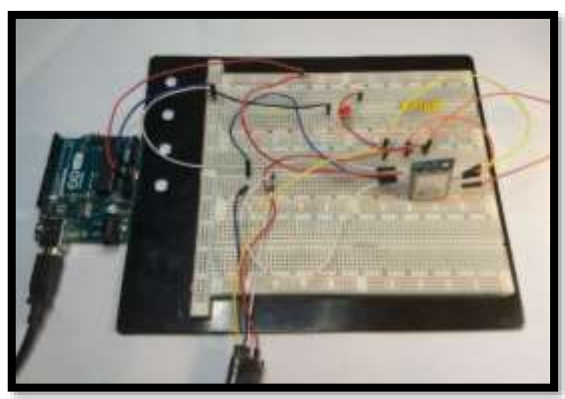

Figure 9: Ground Station Telemetry Test Setup

The telemetry testing setup consists of two XBee SX Pro’s connected to an Arduino Uno (Figure 10) and a TEENSY 3.6 (Figure 10) respectively, which assist in powering the various components and recording the data. A red Lumex LED is used to visually verify data transfer between the XBee SX Pro's.


Figure 10: Arduino Uno and TEENSY 3.6

The intrinsic specifications of the XBee SX Pro can be seen in Table 3: XBee SX Pro Specifications

XBee SX Pro Relevant Specifications	
Characteristics	
Operation	
Supply Voltage (VDC)	2.6 to 3.6
Current (mA) : VCC = 3.3V	40
Transmit Current (mA) : VCC = 3.3V	900 @ 30 dBm; 640 @ 27 dBm; 330 @ 20 dBm
Parasitic Drain (μA) : VCC = 3.3V	2.5
Performance	
Frequency Range (Mhz)	902 to 928
Transmit Power (dBm)	0 to 30
Channels	10 Hopping Sequences share 50 Frequencies
Max Data Throughput (kb/s)	120
Rural Range LOS (Miles)	65
Urban Range LOS (Miles)	11
Network Topology	Peer To Peer, Point to Point, Point to Multipoint, mesh

Table 3: XBee SX Pro Specifications

The intrinsic specifications of the Laird Tech PC906 Antenna can be seen in Table 2:

Laird Tech PC906 Antenna Specifications	
Characteristics	
Dimensions	
Antenna Type	Yagi
Element Number	6
Height (in)	25
Max Element Width (in)	7
Performance	
Frequency Range (Mhz)	896 to 940
Gain (dBi)	11.1
Frequency Group (MHz)	UHF (300 to 1000)
Termination	Connector, N-Female

Table 4: Laird Tech PC906 Antenna Specifications

The intrinsic specifications of the Digi International A09-HBMM-P5I can be seen in Table 5

Digi International A09-HBMM-P5I Specifications	
Characteristics	
Operation	
Supply Voltage (VDC)	2.8 to 5.5
RX Current (mA) : VCC = 3.3V	40
Transmit Current (mA) : VCC = 3.3V	900 @ 30 dBm; 55 @ 13 dBm
Cyclic Sleep (mA) : (Idle Current)	.8 (16 sec cyclic sleep)
Performance	
Frequency Range (Mhz)	902 to 928
Transmit Power (dBm)	20 to 30 (For 100mW – 1W)
Interface Data Rate (bps)	1,200 to 230,400
Receiver Sensitivity (dBm) : 1%	-110 @9,600 bps : -100 dBm @115,200 bps
RF Data Rate (kbps)	10 to 125
Rural Range LOS (Miles)	40
Urban Range LOS (Miles)	1
Termination	MMCX Male
Dimensions	
Antenna Type	Half Wave Dipole Whip
Height (in)	7
Gain (dBi)	2.1
Impedance (Ohms)	50
Power Rating (mW)	1000

Table 5: Digi International A09-HBMM-P5I Specifications

The XBee communicates with the TEENSY through UART interface and a 3.3V power line. The XBee’s integrated position on the boards is shown in Figure 11.

Figure 11: Xbee integrated into PCBs.

On the launch vehicle side of the telemetry system, an XBee SX Pro will be powered by a 7.5V LiPo battery which will pass through a voltage regulator and be converted down to 5V which will go into the TEENSY, this is turn will regulate the voltage down to 3.3V and output it through its VCC port which will power the XBee SX Pro. The TEENSY receives data from the Skytraq (Section 4.1.2.1.4) and outputs that data to the XBee SX Pro which in turn broadcasts that data from the Digi International A09-HBMM-P5I. This bitsteam (At a baud rate of 9,600 bps) is received by the Laird Tech PC906, transfers the data through its XBee SX Pro and then to the Arduino Uno which allows us to track the rocket using XCTU.

Thorough range testing of the telemetry system has been completed at one mile and the results show a 97% packet reception rate as seen in **Error! Reference source not found.** and Figure 13.

Figure 12: Telemetry Testing - Signal Strength

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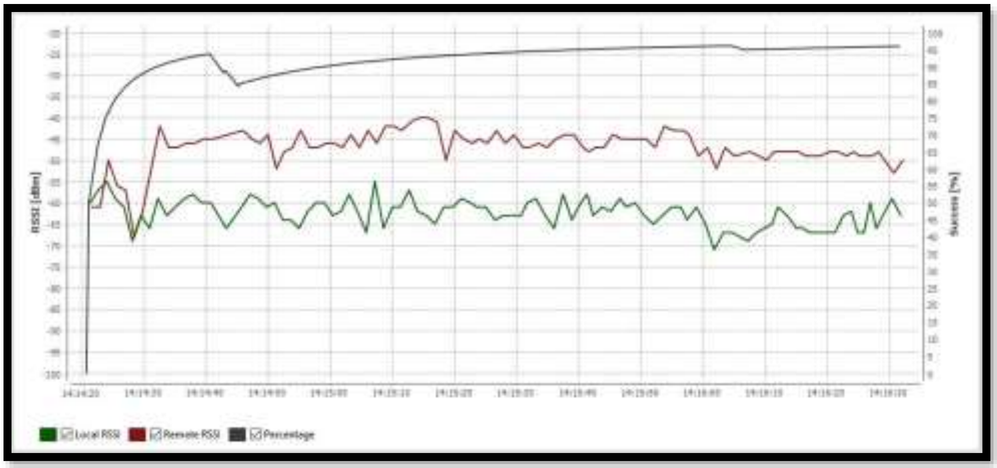


Figure 13: Telemetry Testing - 1 Mile LOS

The two anomalies in package reception rate, at times, 14:14:20 and 14:14:45 are due to the near-mono-directional nature of the Yagi antenna used for the ground station. During testing, the antenna was intentionally pointed at the ground when testing began and was accidently pointed towards the ground during a moment of muscular instability. Without these anomalies, it is very likely that the reception rate would have been 100% despite the one-mile distance, high density of nearby buildings and significant external noise

4.1.2.1.4 GPS

The GPS system that will be utilized for the booster section of the rocket will be integrated into the VDS boards. It is the S1216F8-GL GLONASS until manufactured by Skytraq. This unit can track up to 12 satellite signals to triangulate its position, and it's -148dBm cold start sensitivity feature allows the unit to acquire, track, and fix onto any signal autonomously in weak signal environments. The positioning data from the Skytraq will be transmitted through the radio telemetry system, whose transition and usage details are referred to in section 4.1.2.1.3. This unit will allow the team to monitor the position of this unit throughout the flight and upon recovery. The GPS unit communicates through UART with the teensy 3.6 and powered via the shared 5V line between the two.

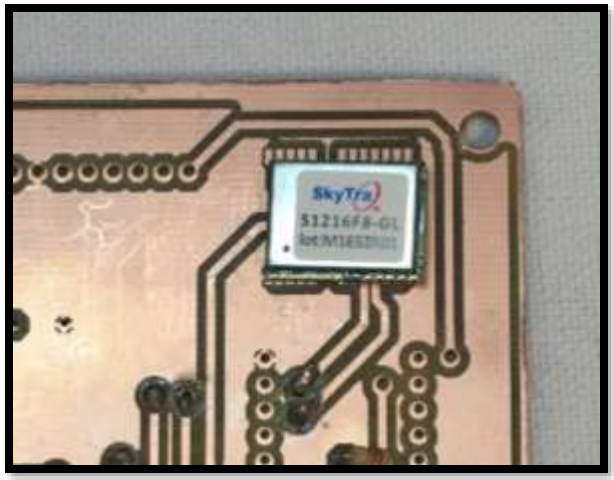


Figure 14: GPS placement on PCB.

The GPS communicates to the ground through receiving its position, and transmitting it to the teensy, which in turn communicates it to the Xbee SX for transmission to the ground station. It is through this method that the position of the booster is known at all times throughout the flight. The position of the GPS on the boards is shown in Figure 14.

4.1.2.2 Software

The (VDS) program contains six necessary classes tackling six different aspects of the system. These classes are the data acquisition, the data log, the graphical user interface (GUI), the drag blades, the proportional–integral–derivative (PID controller), and the main loop. They operate as shown in Figure 15.

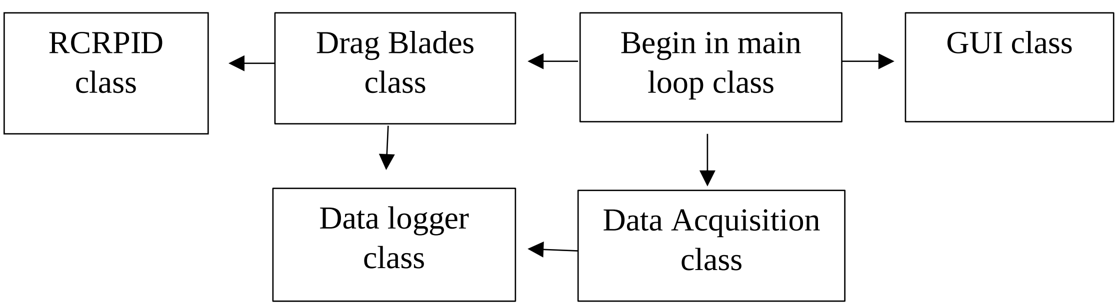


Figure 15: Flow chart of VDS program structure.

1. The data acquisition (DAQ) class' main purpose is to obtain data from the onboard sensors. Using the altitude data and an internal clock, the velocity of the rocket is calculated. Together, the collected data enable the VDS system to know its position, velocity, acceleration, tilt, pitch, yaw and roll. This information is relayed to the main loop class for analysis and execution. This code segment is the first to be executed and includes a calibration step to validate the nominal performance of the sensors. The calibration step includes rotating the BNO550 sensors

ninety degrees in the x, y and z direction to ensure that all ranges of motion are accounted for. It also includes a check that the altimeter is reading a nominal value and that the velocity is zero. When the sensor calibration is completed, the VDS system acknowledges that the data acquisition is performing nominally.

2. The data log class ensures that all aspects of the flight are recorded onto an SD card on the Teensy. This data analyzed after flight and used to optimize performance for future launches. Rather than each code block containing its own data logging setup, the data log code segment allows the centralized setup of the SD card and its services can be easily accessed by both the acquisition code block and the drag blades code block.
3. The GUI class provides the serial text interface for the user to initialize the rocket launch. Working with the main loop of the program, the GUI allows the user to navigate the initial setup before a launch. It also handles the printing of calibration data obtained from the DAQ as the user validates the nominal performance of the sensors. Furthermore, the GUI code block prints out the statistics of the rocket which includes its name, dry mass, wet mass, thrust rating etc.
4. The drag blades class is responsible for writing commands to the DC motor which actuates the drag blades Using pulse width modulation (PWM) to send signals to the physical motor controllers, the drag blades class receives speed instructions from the PID class to execute. One of the challenges that must be taken into account is the use of DC motors, not servo motors, to control the drag blades. Therefore, actuating the blades in and out requires the reverse of polarity on the power pins of the motor. The logic to actuate in a certain direction is done in this class. This class also includes a calibration function which tests the range of motion of the drag blades from zero percent actuation to one hundred percent actuation. Once this calibration is complete, the main loop receives the confirmation that the drag blades are operating nominally.
5. The PID class is necessary to control the DC motor as if it was a servo motor. Using the set point dictated by the drag blades class and the current position provided by an encoder on the DC motor, the PID class provides an output speed for the drag blades class. As the blades reach its desired position, the speed output is dialed down to zero. This speed is the raw input which the drag blades class uses to write PWM signals to the motor as described above. Using basic control theory, the PID class ensures that the set point is achieved quickly and remains there stably.
6. The main loop is the first class that the program steps into, therefore it is also the loop which calls on the calibration of first the sensors and then the calibration of the motor. Only after the calibration of the sensors and motor and the confirmation of the data logger will the main loop continue to execute. With this class there are two modes that can be chosen. The mode is flight mode which allows onboard systems to determine the actuation of the drag blades. This is the mode that will fly during competition. The main loop also includes a full brakes test mode which extends the drag blades just after burn and retracts them after apogee. These classes, with their methods and fields, are shown in a class diagram in Figure 16.

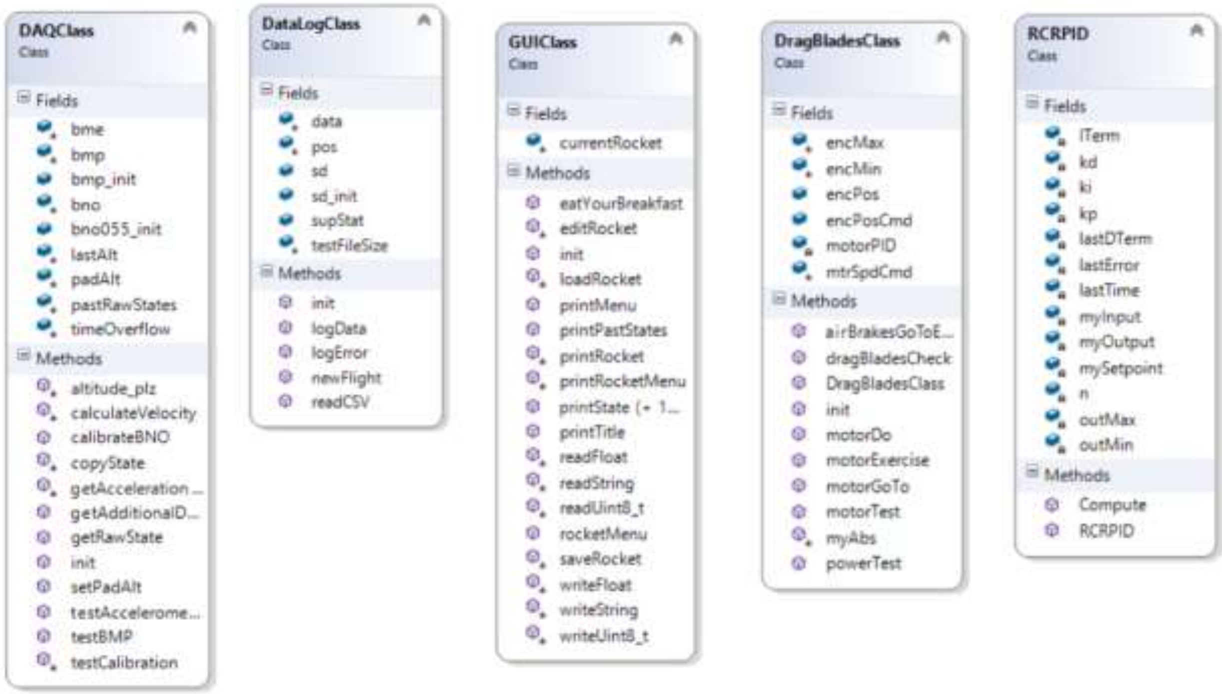


Figure 16: Class diagram of VDS program structure.

In the case that the VDS is running through a “full break test” (in comparison with a full performance mode launch) the program evaluates 3 conditions; whether the acceleration is negative, in order to affirm that the vehicle has left burn phase, that the altitude is above 150 m., to account that it does not actuate prematurely, and that velocity is less than 0, to add that the rocket is in fact moving (for redundancy). At apogee, these three conditions are no longer met, and the blades retract to provide for a safe recovery.

4.1.2.2.1 Mechanical Hardware

The VDS’s three drag blades were cut from 0.125 in. thick 6061-T6 Aluminum using a Maxiem 450 Water Jet. Each blade has a set of radial gear teeth designed to mesh with a 0.125 in. mild carbon steel central spur gear. The design of the drag blades optimizes the projected area for a radially actuated braking system, and the flat plate shape of the blades provide a high coefficient of drag.

A 0.125 in. Delrin plate is placed on both the top and bottom side of the blade configuration. The Delrin plates provide a low coefficient of friction with the aluminum drag blades. This reduces the friction force that the motor must overcome to actuate the blades, allowing for faster actuation speed, lower overall mass, and less power consumption by the system. Three custom designed spacers were 3D printed using PLA, and are placed between the Delrin plates to ensure proper alignment of the system and prevent overtightening on the drag blades.

The drag blade configuration and Delrin bearing plates sit between two 0.125 in. 6061-T6 aluminum support plates. The aluminum support plates were also cut using a Maxiem 450 Water

Jet. The support plates take much of the drag force acting on the VDS. Aluminum was chosen as the material for both the drag blades and the support plates because of its light weight, machinability, and rigidity. The completed variable drag system is shown below in Figure.

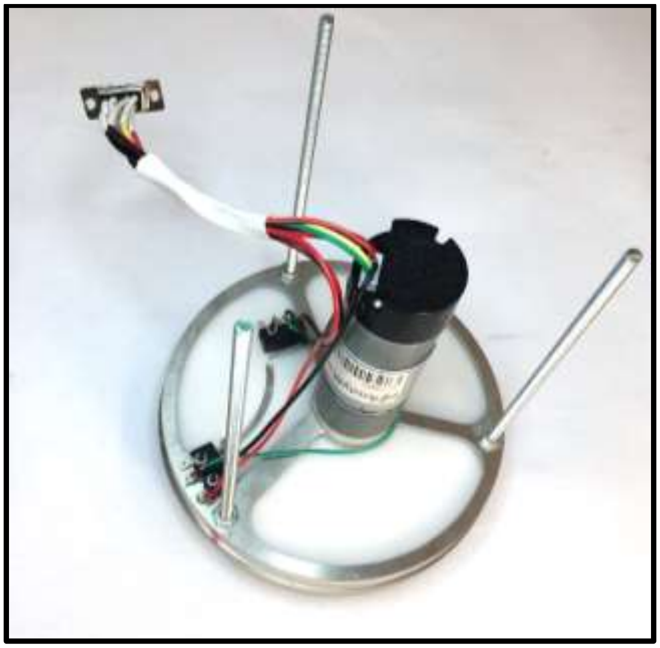


Figure 17: Variable Drag System assembled mechanical componenets.

To ensure that the design will be robust enough to withstand the maximum in flight forces with a minimum acceptable factor of safety of 2.0, the mechanical components of the VDS V3 were analyzed using ANSYS Workbench 17.2. Due to uncertainties in the drag force calculation and possible changes in the maximum velocity of the launch vehicle, each drag blade of the VDS was tested to withstand a full drag force of approximately 20 lbs. multiplied by a factor of two. A minimum factor of safety of 6.51 was determined for each drag blade. The results of the analysis conducted on the drag blades are shown below in Figure 18.

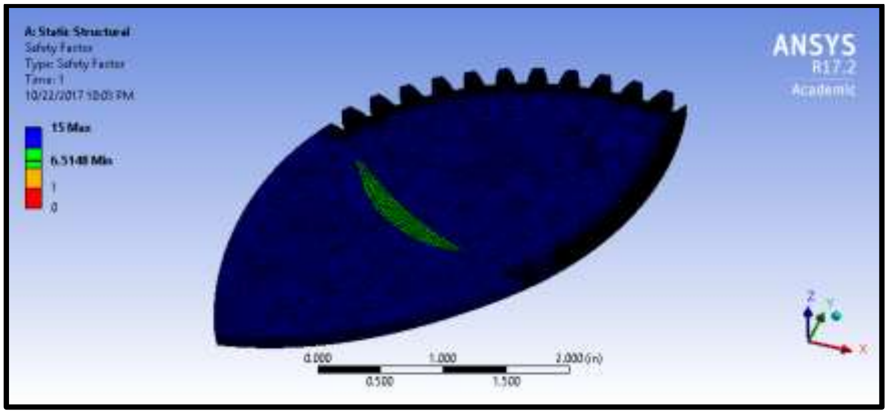


Figure 18: Drag blade factor of safety plot under maximum braking force.

The gear teeth of both the drag blades and the central spur gear were tested to ensure that they would perform safely under loading equivalent to the maximum stall torque of the NeveRest 40 DC motor applied to a single drag blade. The results of the study showed a minimum factor of safety of 1.68 for the gear design on the drag blade and 1.73 for the gear design on the central spur gear. The results of the Finite Element Analysis are shown below in

Figure **19** and Figure 20.

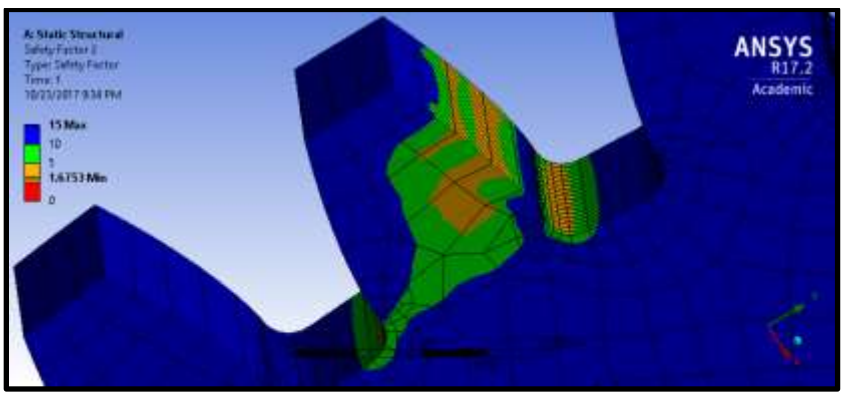


Figure 19: Drag blade gear tooth factor of safety plot.

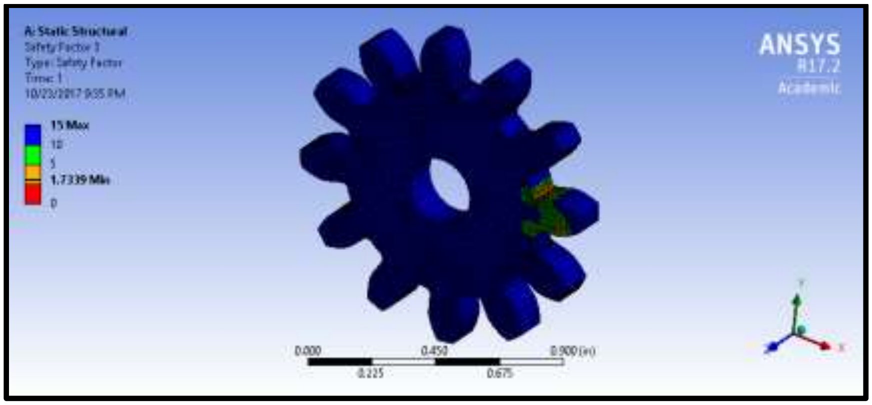


Figure 20: Central spur gear tooth factor of safety plot.

4.1.2.3 Verifications

The VDS has undergone demonstrative testing in order to verify the team derived requirements set in place. Table 6 displays each of these requirements, and how they have been verified.

Requirement number	Requirement	Method of Verification	Verification Status
V.1.1**	The VDS will autonomously actuate it's drag blades, and alter the drag of the rocket to achieve an altitude of ±23 feet of the target altitude.	**Test:** The actuation method will be tested independently of the launch vehicle, as well as through several test launches to verify the system.	**Incomplete:** The actuation method has been tested independently of the launch vehicle, however it must also be tested in the 3-17-18 re-flight addendum launch.
V.1.1.1	The VDS actuation method must provide continuous control over actuation and retraction of the drag blades.	**Demonstration:** Three drag inducing blades set with radial gear teeth that mesh with a central spur gear will allow for continuous control by a single DC motor.	**Verified:** Using the DragBlades.Cpp class as shown in 1.2.1.4_DragBlades_class, the program will utilize a motorGoTo function to maintain a consistent control over the blades. The blades will be connected to the avionics via a D-sub connection port as shown in **Error! Reference source not found._Error! Reference source not found.**_avionivs to manintain a physical connection with the blades.

V.1.1.2	The drag inducing blades must fully actuate in less than 1.4 seconds.	**Analysis:** An actuation device which provides the fastest actuation speed will be chosen.	**Verified**. The motor configuration has been timed with full bearing load, to have an average actuation time of 1.2 seconds with a standard deviation of 0.233 s as shown in 1.1.1.1.1_Brake_timing
V.1.1.3	The DC motor shall not experience a torque greater than 388 oz-in during the actuation of the drag blades.	**Analysis:** The friction force between the drag blades and support plates will be calculated to determine the required torque to actuate the drag blades.	**Verified:** The blades maximum torque limits have not been exceeded as shown in the 4.1.2.5.3_Flight Configuration Test. Additionally, the blades were put to actuation in a high-stress environment as shown in 1.1.1.1.2_Requirement V.1.1.1.3 – Torque where they continued the programmed motor test while hitting peak force of 376 oz-in.
V.1.1.3.1	The coefficient of friction between the drag blades and the support surface must be lower than 0.5 to provide a bearing surface for the drag blades.	**Demonstration:** Delrin Acetal Resin was chosen for the bearing surface because it has a coefficient of friction of approximately 0.3 with Aluminum.	**Verified.** The manufacturer provided dynamic coefficient of friction of the delrin plates is 0.35, which meets the requirement of less than 0.5 for a low friction bearing surface.
V.1.1.4	The actuation method must provide simultaneous actuation of all three drag blades.	**Test:** A prototype of the VDS V3 gear assembly will be manufactured to test verify that the design will provide a simultaneous actuation.	**Verified**. The central gear/pivot design of the blades allows actuation if and only if all three blades are moved simultaneously. This design is shown in **Error! Reference source not found.**.2_**Error! Reference source not found.**_Actuation, which

			shows the method of gear fitting.
V.1.1.5	The drag blades shall not over-actuate beyond their mechanical limit.	**Demonstration:** Two limit switches will be fastened to the top VDS aluminum support plate, and communicate with the DC motor to prevent over actuation.	**Verified.** Normally open limit switches are used to define the outer and inner limits of blade actuation. During the testing shown in 4.1.2.5.3_Flight Configuration Test, the blades were able to recognize the limits, in turn, altering the direction of blade actuation to retraction.
V.1.1.6	No component of the actuation device may be damaged as a result of the actuation.	**Analysis:** Finite Element Analysis was performed using ANSYS Workbench to verify the structural integrity of the gear mesh and drag blades.	**Verified.** In nominal operation, the VDS is not damaged by any portion of its design and is considered a full reusable system. This is shown in the testing from 4.1.2.5.3_Flight Configuration Test, where a mock set-up of an actual launch is tested to ensure that no components are damaged in integration or de-assembly from the rocket.

Table 6: Verification of Team derived requirements for VDS (1).

1.1.1.1.1 Requirement V.1.1.2:

The verification of this requirements was determined through timing full actuation and retraction of the blades for 10 iterations - the average time of these iterations was calculated to be 1.25 s with a standard deviation of 0.233 s.

1.1.1.1.2 Requirement V.1.1.1.3 – Torque

As an addendum to the testing shown in 4.1.2.5.3_Flight Configuration Test, the motor was additionally strained by placing a load weighing ~1.9 kg on each the blades, while increasing the coefficient of friction by tightening the nuts around the all threads keeping the VDS configuration together. In this instance, the VDS was still capable of completing its motor test running with a cumulative torque of 376 oz-in. This is indicative that even with a load very close to the threshold, the motor is able to continue running at nominal performance.

As shown in Table 7, requirements V.1.3 throughV.1.6.2 are regarding the integration of the VDS intro the full scale vehicle. Specific details regarding these verifications and their implementation can be found in section **Error! Reference source not found.**.

Requirement number	Requirement	Method of Verification	Verification Status
V.1.2**	The VDS will telemetrically communicate its current state to a ground station during flight, without altering the path of the vehicle.	**Test:** This requirement will be verified in sub scale flight testing. The tests will verify whether the range and data transmission rates are of acceptable standards for the needs of the VDS.	**Incomplete as of 3/4/18:** This requirement willg be verified in addendum re-flight on 3-17-18. The tests will verify whether the range and data transmission rates are of acceptable standards for the needs of the VDS.
V.1.3**	The VDS shall have access to power controls externally from the vehicle.	**Demonstration:** The VDS bay will contain a port which grants access to the power source of the VDS in order to prevent power depletion during integration.	**Incomplete as of 3/4/18:** This verification will be met through installing a port large enough for a power cable's insertion into the avionics bay into the re-flight rocket on 3-17-28.
V.1.4	The VDS shall be capable of determining the state of the vehicle (i.e. altitude and velocity) with noise limits of no more than ± 5.0 m and ± 5.0 m/s respectively.	**Demonstration:** The VDS will take data points and employ the use of a built in sensory Kalman filter in order to reduce noise in data intake.	**Verified:** Through pressure and movement ground testing, the VDS was able to actuate based on external conditions as read by the sensors. Noise graphs as shown in 4.1.2.5.2_Sensor Noise Verification testing with upper limits of 3.5 m and lower limits of 3.7 m with the altimeter, and noise upper/lower limits of 4.8 m/s and 3.5 m/s (respectively) for the 9DOF accelerometer and speed sensor.
V.1.5**	The VDS shall be capable of performing a minimum of 39,600 ft-lbs of work to reduce the apogee of the	**Test:** Multiple launches will be conducted to verify that the VDS is capable of performing the required amount of	**Incomplete:** Will be evaluated during 3-17-18 re-flight addendum launch with criteria as described in 4.1.2.5.5_Full scale flight – full break.

	launch vehicle from a maximum projected apogee of 5600ft. to within ±23ft of 5280ft.	work on the launch vehicle.	
V.1.5.1	The VDS shall be capable of increasing the projected frontal area of the launch vehicle by at least 29%.	**Inspection:** Computer aided design software was used to verify that the VDS V3 will increase the projected area of the rocket by at least 29%	**Verified.** The cross sectional area of the VDS has been found in comparison with the cross sectional area of the vehicle. It was found that the cumulative area of the blades increased the overall fontal area by 30%. This analysis was completed on an ANYS simulation as shown in **Error! Reference source not found.**.1_**Error! Reference source not found.**
V.1.6	The VDS shall be integrated into the vehicle as a single removable entity.	**Test:** Multiple launches will be conducted to verify that the VDS is capable of performing the required amount of work on the launch vehicle.	**Verified**. Both the Motor configuration and the electronics are able to be removed and integrated into the vehicle separately via integration utilizing all-thread, and a durable electronics sled. These are shown in **Error! Reference source not found.**.2_**Error! Reference source not found.**_integration
V.1.6.1	The VDS electronics will be accessible after being secured within the launch vehicle via a connection mounted to the vehicle's airframe directly outside of the VDS avionics sled to provide a constant power supply as required by V.1.3.	**Test:** An audible signal will be produced by the VDS avionics when connected to a power supply.	**Verified.** The VDS has a custom designed integration sled used to accessibly house the electronics within the launch vehicle. This sled includes a port designed for access to the microcontroller to provide both power and data communication. The integration design has been both modelled and manufactured, as shown in **Error! Reference source not found.**.2_**Error! Reference source not found.**_integration

V.1.6.2	All electronics will be securely harnessed within the VDS avionics sled to prevent disconnection during flight.	**Inspection:** All components will be visually inspected to ensure that all fasteners have been set in place before inserting the VDS into the launch vehicle.	**Verified.** A custom designed and 3D printed electronics sled is used to house and harness the VDS avionics throughout flight. This design and physical manufacture is shown in **Error! Reference source not found.**.2_**Error! Reference source not found.**_integration.

Table 7: .Verification of team derived requrements for VDS (2).

**Due to the unexpected catastrophe at takeoff, and launch anomaly, requirements V.1.1, and V.1.2, yielded ambiguous or otherwise nonexistent results that are not adequate to say that these have been verified. These will be verified before the submission of an approved re-flight via the addendu

4.1.2.4 Flight results

Figure 21: Remains of VDS after 2-17-18 CATO.

Figure 22: VDS remains after 3-4-14 anomaly flight

Due to the rocket having experienced a Catastrophe at Take Off on February 17th, the VDS was unable to perform the planned full brake test required to verify the practicality, safety, and overall performance of the system during this flight. The resultant remains of the VDS are shown in Figure 21 and Figure 22. The system however, has been fully ground tested in various scenarios, and has met all of its safety requirements. Through the use of the integrated simulation as seen in Figure 23, the team has been able to predict the blade actuation timing and performance using the data recoded from the system while integrated into the rocket on the ground.

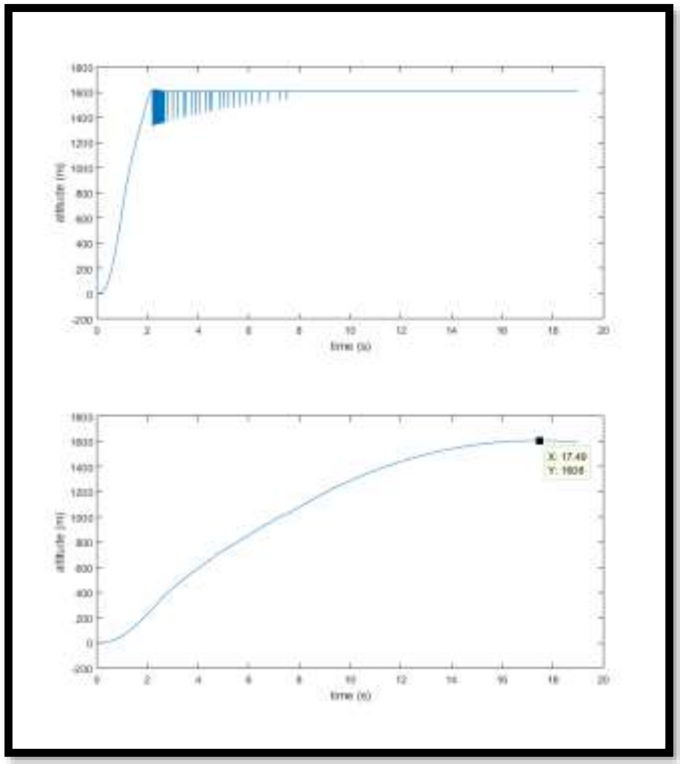


Figure 23: Predicted VDS performance. (Top) Blade actuation, (Bottom) actuation effects on altitude.

Additionally, due to the unsuccessful outcome of the secondary full scale, full break launch on March 3rd, all of the data recording devices set in place, such as a 32GB SD card, and several internal external cameras, were destroyed or unusable. It is for this reason that the results regarding the full brake, full scale VDS test are inconclusive. Although the apogee was found to be 5,114 ft., this value could be attributed to other drag factors, and therefore it cannot be determined whether the VDS blades actuated or not. The VDS will be tested and conclusive upon submission of the submission of the addendum during the re-flight on March 17th.

4.1.2.5 Testing Procedure

4.1.2.5.1 Xbee distance testing

The purpose of the Xbee distance testing is to verify that the telemetry signal s viable at distances up to and exceeding one mile, through high interference areas, and with varying types of antennas. On the Xbee test taking place on March 2nd, 2018 a Yagi Laird Tech PC906 Antenna was used as the receiving antenna, while a Digi International A09-HBMM-P5I was used as the transmitting antenna.

<u>Items to be tested</u>

- Signal vitality and clarity in static and dynamic ranges of +/- 5280 feet, in both high interference and low interference areas.
    - High interference is defined in this instance as one with high vehicular traffic, buildings with potentially interfering antennas, or otherwise non line-of-sight factors.
- Voltage loss and from the transmitting side, as well as current drain in comparison with various packet sizes, and transmission lengths.

Pass/Fail Criteria

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria
Xbee distance testing	V1.2, V 1.4	This test will be considered passed if the battery has negligible power loss after extended use, and is able to transmit data at distances up to 5,280 ft.

Table 8: Pass/Fail criteria of Xbee testing

Pre-Test

Setup and Procedure

1. Assemly of antenna and circuitry on test board as seen in Figure 8: Launch Vehicle Telemetry Test SetupFigure 8 and Figure 9.
2. Set up of both Xbee units on XCTU testing software
    a. The requirements of this set up include desired range, packet size, and MAC addresses of both parties.
    b. In this instance, the desired range is the maximum as shown in Table 3, the packet size is the maximum allowed character, and the MAC addresses are manually inputted.
3. Verify connection between both Xbee parties. This connection can be verified through the XCTU software.
    a. Once both parties are verified, the XCTU software isput into “Range test mode” where the number of data packets reieved and transmitted between both parties are analyzed.
4. Place receiving unit at static point, gradually move transmitting unit further at a constant rate.
    a. The Transmission area is shown in Figure 24, with a total static transmission area of 1.11 miles.

Figure 24: Telemetry testing points – total hypotenuse of 1.11 mi.

<u>Equipment</u>

- 2 Xbee Pro SX units
- 2 full sized breadboards
- Breadboard wiring
- Digi International A09-HBMM-P5I antenna
- BeagleBone Computer
- Li-Po battery
- 5V and 3.3V voltage regulators
- Yagi Laird Tech PC906 Antenna

<u>Results</u>

Thorough range testing of the telemetry system has been completed at one mile and the results show a 97% packet reception rate as seen in **Error! Reference source not found.** and Figure 13. Specific details regarding this testing can be found in 4.1.2.1.3 Radio Telemetry. The ground test as mentioned in V.1.4 was able to be completed, however V.1.2 still remains, as an in-flight test was not verified to the CATO occurrence during launch.

4.1.2.5.2 Sensor Noise Verification testing

The purpose of this testing is to verify that the sensors will have adequate noise limits of +/-5m/s in its velocity and +/- 15m in it's positioning. By doing so, the team will gain a greater understanding of the abilities of the VDS to perform and reach the desired target apogee.

<u>Items to be tested</u>

- Sensor noise limits in velocity DAQ as well as positional DAQ

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria
Sensor Noise test	V.1.4 (in addition to all sensor necessary tests)	This test will be considered passed if the noise limits of +/- 5m/s in its velocity and +/- 15m in its positioning.

Figure 25: Pass/fail critera of sensor noise.

Setup

1. Connect sensors (BMP 280/BNO055) to teensy 3.6 via SPI connection.
    a. Assure that the teensy's SD card is initialized taking data
2. Run corresponding "Sensory_test_program.ino".
    a. Verify that teensy is actively recording data via the serial monitor.
3. Record the begin time, and all concurrent times where setting is changed with sensors active.
4. Begin on known altitude and pressure from sea level.
    a. Gradually move up to a higher elevation via elevator, stair, or hill.
    b. Record each time where the destination trek has begun and where it ends
5. Test velocity while placing sensor in a moving vehicle.
    a. Again, record all times as accurately as possible.

Equipment

- BMP 280
- BNO055
- Stopwatch
- Teensy 3.6
- Breadboard configuration
- Moving Vehicle

Results

As shown in Figure 26, the noise margins were within the team mandated limits of +/- 15m. As can be seen around the 5-8 minute mark, the testing party changed altitude and the graph displayed very little noise throughout this movement.

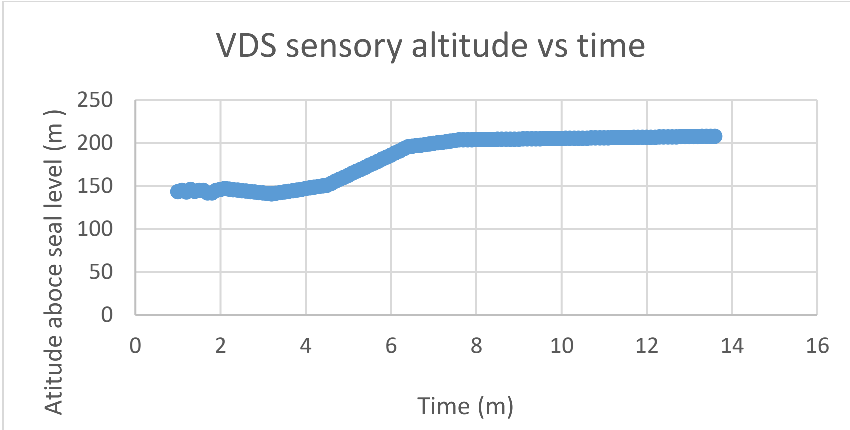


Figure 26: Data derived from sensor noise testing.

4.1.2.5.3 Flight Configuration Test

The purpose of flight configuration testing is to emulate the set up and motor actuation as if the VDS were undergoing an actual full break or full performance launch. This test includes thorough integration, assembly, avionic connection, and motor calibration in the order and procedure that it would be done on a flight day. From this testing, various vital pieces of information can be derived, such as torque on the motor, drag blade, area, actuation speed, integration success and procedures as well as several others.

<u>Items to be tested</u>

- Blade Actuation and limit switch functionality – verifying that the normally open limit switches are being activated adequately
- Program and electronics check - verifying that the VDS controls are operating nominally and without issue
- Verify torque strain on the brushless DC motor
- Measure actual drag blade area
- Time average actuation speed, and evaluate smoothness of blade actuation and retraction
- Practice integration procedure

<u>Pass/Fail Criteria</u>

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria
Flight Configuration Test	V.1.1.4, V.1.1.5, V.1.1.6	This test will be considered passed if the blades are able to actuate fully without issue or strain, and retract autonomously with the full use of the limit switches.

Table 9: Pass/Fail criteria of flight configuration

<u>Setup</u>

1. Assemble blade configuration with wiring into electronics sled.
    a. Blade configuration consists of three all thread pieces which are screwed in from both the bottom of the blades, as well as in their corresponding holes within the bulk plate.
    b. Blade configuration must be sturdily plugged into mounted D-sub 9-pin connector mounted in bulk plate. Avionics will connect to corresponding side of D-sub connector
2. Validate that electronics are operational by sending test commands found in MotorDo function and in motor calibration settings of VDS controls program.
    a. Move blades in increments of 25%, until limit switches are pressed fimly.
    b. Verify maximum and minimum of blade limits

Equipment

- Full scale launch vehicle
- VDS and VDS electronics
- VDS motor configuration
- Measuring devices
- Multimeter
- Booster main
- VDS coupler and connecting Dsub extenstion.

Safety Notes

All parties will be aware of hot power lines and will keep at least 1 foot from moving drag blades to prevent pinching or blocking.

Results

This test was proven to have been successful in actuating the blades, and showing that the gears are viable and able to move freely, the limit switches are operational, the electronics are functioning properly, and the code is able to be transmitted to the Teensy 3.6 without issue. Additionally, all relevant requirements were able to be derived from this test, as it was success ful in providing verifications in all areas.

4.1.2.5.4 Full scale flight – control launch

The purpose of this test is to find the rocket's true apogee, and to determine the amount of work required of the VDS. By doing so, the VDS blades remain dormant throughout the duration of the flight however the sensors take data regarding the altitude, pressure, acceleration, velocity, roll, pitch, and yaw.

Items to be tested

- Find the vehicle's max apogee without drag effects from the VDS

- Verify the ability of the sensors to take data in high stress conditions. The sensors also act as a backup to the AIM and stratologgers in verifying the vehicle's path.

Pass/Fail Criteria

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria
Control Vehicle Flight Test	2.2, 2.6, 2.9, 2.19, 2.19.1, 2.19.2	The launch vehicle control test flight shall be considered a pass if the vehicle ascends stably, does not exceed 5,600ft. AGL, is +/- 10% of the expected apogee altitude, takes adequate data to use in future simulations, and recovers safely within the predicted drift radius.

Table 10: Pass/Fail criteria of Control Launch

Setup

Hardware:

1. Verify that all traces have correct continuity and are not shorted to any grounds.
2. Verify Battery Charge of both 7.4 and 11.1 li-Po batteries. If more than .2V below specified voltage, charge.
3. Plug in Teensy 3.6 into top board.
4. Plug top board into bottom board, assure that al header pins are making adequate contact with bottom female headers.
5. Assemble stand offs into boards. The top board should have nuts screwed into them, and the bottom will be screwed in after assembly into sled.
6. Insert boards into sled with Teensy in the direction of cable insert hole. Place screws into bottom stand offs.
7. Verify that both batteries are inserted into the correct places. Plug in batteries **with correct polarity.**
8. **Fl**ip switches on to verify that LEDs are illuminated.
9. Insert sled into coupler with correct Allthread orientation
10. Keep Motor configuration disconnected from electronics to prevent any accidental actuation or otherwise any interference from the VDS

(REFER TO SOFTWARE SECTION AT THIS POINT)

11. Remove USB cable when launch ready.

Software

1. Begin by booting up VDS_Software_V2. Load program, and verify that it is "built" onto Teensy 3.6.
2. Open serial port
3. Begin program in Serial monitor with "s" command
4. Verify the bmp is "GO"
5. Calibrate BNO by rotating at 25 degree angles until sensors reads all "3s
6. Verify that the BNO280 is taking data accurately
7. If all components are "GO", confirm assembly in rocket. Install coupler and keep VDS Powered until flight readiness.

Equipment

- Full scale launch vehicle
- Four PerfectFlite Stratologger CF altimeters
- Steel ballasts to simulate the weight of the payload, or actual payload body
- VDS and VDS electronics
- Ejection charges
- AeroTech L2200-G motor
- 12-foot rail and launch pad
- Launch system
- ARRD
- Booster Main and Drogue
- Booster Main and Drogue shock cords
- Fins
- Multimeter

Safety Notes

All parties will be respectful of all flight safety procedures as outlined in the safety handbook. All electrical team members will be aware of hot power lines and will be aware of any potential hazards associated with operation the VDS and its electronics.

Results

This flight took place on 2-17-18, however, as described in 4.1.2.4_Flight results, the apogee altitude was not able to be determined by the flight due to a CATO upon burn phase. For this reason, the test was unsuccessful and a determination was unable to be made.

4.1.2.5.5 Full scale flight – full break

The purpose of this test is to verify the lowest possible apogee that the VDS is able to bring the vehicle to. By doing so, the VDS is able to better tune it's algorithm to adjust for the level of sensitivity necessary for actuation, the amount of work that needs to be done by the motor, and to finalize the coefficient of drag for both the rocket and the VDS.

Items to be tested

- Determine vehicle minimum height with full drag effects from the VDS
- Determine coefficient of drag for both the rocket and the VDS
- Determine if it is necessary for the vehicle to add weight, or lose weight for the intended target apogee.

Pass/Fail Criteria

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria
Full Break test	2.2, 2.6, 2.9, 2.19, 2.19.1, 2.19.2, V.1.1	This test will be considered passed if the vehicle ascends stably, does not exceed 5,200ft. AGL, is +/- 10% of the expected apogee altitude, takes adequate data to use in future simulations, and recovers safely within the predicted drift radius.

Table 11: Pass/Fail criteria of full break test.

Setup

Hardware:

8. Verify that all traces have correct continuity and are not shorted to any grounds.
9. Verify Battery Charge of both 7.4 and 11.1 li-Po batteries. If more than .2V below specified voltage, charge.
10. Plug in Teensy 3.6 into top board.
11. Plug top board into bottom board, assure that al header pins are making adequate contact with bottom female headers.
12. Assemble stand offs into boards. The top board should have nuts screwed into them, and the bottom will be screwed in after assembly into sled.
13. Insert boards into sled with Teensy in the direction of cable insert hole. Place screws into bottom stand offs.
14. Verify that both batteries are inserted into the correct places. Plug in batteries **with correct polarity.**
15. **Fl**ip switches on to verify that LEDs are illuminated.
16. Insert sled into coupler with correct Allthread orientation
17. Plug in motor D-sub, and feed through USB wire for Teensy computer connectivity, and intermittent charging.

(REFER TO SOFTWARE SECTION AT THIS POINT)

18. Remove USB cable when launch ready.

Software

19. Begin by booting up VDS_Software_V2. Load program, and verify that it is "built" onto Teensy 3.6.
20. Open serial port
21. Begin program in Serial monitor with "s" command
22. Verify the bmp is "GO"
23. Calibrate BNO by rotating at 25 degree angles until sensors reads all "3s"
24. Perform preemptive motor test with "M" command.
25. Check status of all components with "D" command
26. If all components are "GO", confirm assembly in rocket. Install coupler and keep VDS Powered until flight readiness.
27. When flight is ready to begin, put electronics into "Full break test flight mode" by selecting "F" in GUI. The program will verify whether all sensors and motor are calibrated, if so, the VDS will be armed and ready for flight.

Equipment

- Full scale launch vehicle
- Four PerfectFlite Stratologger CF altimeters
- 12-foot rail and launch pad
- Launch system
- ARRD

- Steel ballasts to simulate the weight of the payload
- VDS and VDS electronics
- Ejection charges
- AeroTech L2200-G motor
- Booster Main and Drogue
- Booster Main and Drogue shock cords
- Fins
- Multimeter

Safety Notes

All parties will be respectful of all flight safety procedures as outlined in the safety handbook. All electrical team members will be aware of hot power lines and will be aware of any potential hazards associated with operation the VDS and its electronics.

Results

This flight took place on 3-3-17, however, as described in 4.1.2.4_Flight results, the apogee altitude was not able to be determined by the flight due to an anomaly on flight recovery. During this test, the rocket fell balisticaly without parachute, and all data recording devices, in addition to the VDS itself, were destroyed upon landing. For this reason, the test was unsuccessful and a determination was unable to be made as the team could not make a solid determination as to whether the blades actuated on ascent.

4.1.2.5.6 Full scale flight – full actuation

This test will serve as the first 'full run' of the VDS with full use of altitude correction software and telemetry system. The purpose is to gain a full understanding of the capabilities of the VDS in various weather conditions and with the final competition weight. This configuration will serve as the final competition configuration for the VDS, and will be tested at least one time to gather the necessary data to update the software for peak accuracy.

Items to be tested

- Verify VDS drag blade actuation ability and drag blade effectiveness.
- Test and verify that the sensors on the VDS electronics have a high enough DAQ rate
- Employ the full telemetry system
- Determine the accuracy of the VDS in its apogee altitude
- Test and verify the competition configuration of the VDS.

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria

Full Actuation test	2.2, 2.6, 2.9, 2.19, 2.19.1, 2.19.2, V.1.1	This test will be considered passed if the vehicle ascends stably, does not exceed 5,300ft. AGL, is +/- 10% of the expected apogee altitude, takes adequate data to use in future simulations, and recovers safely within the predicted drift radius.

Table 12: Pass/Fail criteria of Full performance launch

Setup

Hardware:

28. Verify that all traces have correct continuity and are not shorted to any grounds.
29. Verify Battery Charge of both 7.4 and 11.1 li-Po batteries. If more than .2V below specified voltage, charge.
30. Plug in Teensy 3.6 into top board.
31. Plug top board into bottom board, assure that al header pins are making adequate contact with bottom female headers.
32. Assemble stand offs into boards. The top board should have nuts screwed into them, and the bottom will be screwed in after assembly into sled.
33. Insert boards into sled with Teensy in the direction of cable insert hole. Place screws into bottom stand offs.
34. Verify that both batteries are inserted into the correct places. Plug in batteries **with correct polarity.**
35. **Fl**ip switches on to verify that LEDs are illuminated.
36. Insert sled into coupler with correct Allthread orientation
37. Plug in motor D-sub, and feed through USB wire for Teensy computer connectivity, and intermittent charging.

(REFER TO SOFTWARE SECTION AT THIS POINT)

38. Remove USB cable when launch ready.

Software

39. Begin by booting up VDS_Software_V2. Load program, and verify that it is “built” onto Teensy 3.6.
40. Open serial port
41. Begin program in Serial monitor with “s” command
42. Verify the bmp is “GO”
43. Calibrate BNO by rotating at 25 degree angles until sensors reads all “3s”
44. Perform preemptive motor test with “M” command.
45. Check status of all components with “D” command
46. If all components are “GO”, confirm assembly in rocket. Install coupler and keep VDS Powered until flight readiness.
47. When flight is ready to begin, put electronics into “Full flight mode” by selecting “F” in GUI, and the “n” to designate that this is a full flight and not a test flight. The program will verify whether all sensors and motor are calibrated, if so, the VDS will be armed and ready for flight.

Equipment

- Full scale launch vehicle
- 12-foot rail and launch pad
- Launch system

- Four PerfectFlite Stratologger CF altimeters
- Steel ballasts to simulate the weight of the payload
- VDS and VDS electronics
- Ejection charges
- AeroTech L2200-G motor
- ARRD
- Booster Main and Drogue
- Booster Main and Drogue shock cords
- Fins
- Multimeter

Results

This flight, as well as an anticipated secondary full performance flight will take place on a reflight date prior to competition.

4.1.2.5.7 Actuation

Before the March 3rd full scale test launch, the actuation of the VDS drag blades was tested in two different settings. The actuation was tested while removed from the launch vehicle airframe to verify that there were no issues with gear binding, and the VDS was tested while secured in the VDS coupler and placed inside the launch vehicle airframe to ensure that there was no blockage due to the sizing of the VDS slots cut into the airframe. In each instance, the VDS successfully actuated its blades. A picture of the VDS during the actuation testing with the blades fully actuated is shown below in Figure 27.

Figure 27: VDS blade actuation testing with blades fully actuated.

4.1.2.5.8 Integration

The VDS avionics are secured inside a custom designed harness that is fastened within the top side of the VDS coupler during flight. The harness was 3D printed to allow for a unique geometry that can secure the VDS printed circuit boards as well as the batteries used to power the VDS avionics. An port is cut into the launch vehicle airframe to provide external power to the VDS avionics. This prevents the batteries from being drained during vehicle assembly, and can provide power in the case that the vehicle must wait on the launch pad for an extended time before launch. The completed avionics sled is shown below in Figure 28.

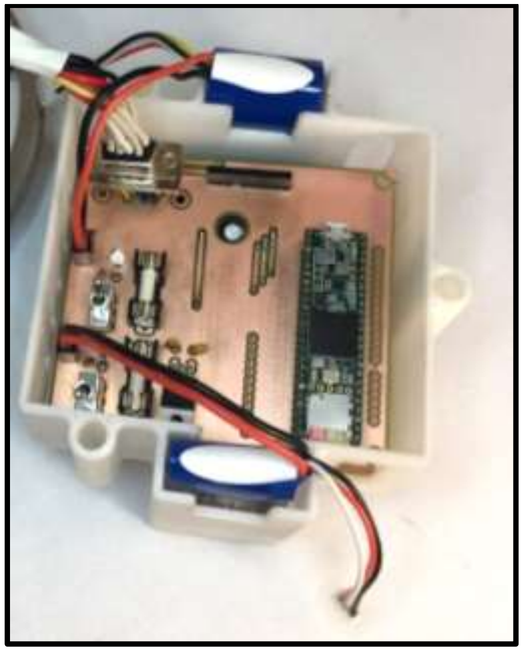


Figure 28: VDS avionics sled.

All components of the variable drag system are shown removed from the VDS coupler in

Figure 29.

Figure 29: Variable Drag System coupler disassembled.

4.1.3 Vehicle Structural Components

4.1.3.1 Airframe

The launch vehicle airframe consists of four 6.25 in. outer diameter sections, which are 37, 24, 32, and 28 inches in length. Each section of the airframe was constructed in-house using a proven fiber layup method. Quasi-isotropic carbon fiber fabric was cut to the length of each respective vehicle section and saturated with Aeropoxy PR2032 resin and PH3660 hardener before being laid onto a 6-inch diameter aluminum mandrel. All sections were manufactured to be five layers thick to ensure adequate strength and low mass.

All separating sections of the vehicle are mechanically fastened to the coupler that joins the two sections of airframe using #4-40 nylon 6-6 shear pins. All non-shearing connection points of airframe utilize 3 #6-32 stainless steel button head cap screws to connect the airframe to the coupler. Both the #4-40 nylon 6-6 shear pins and the #6-32 stainless steel screws will be threaded into a nut epoxied to the interior of the coupler. This method allows for a secure connection between the airframe and coupler and is shown below in Figure 30, where the coupler is highlighted in yellow, and the airframe in red.

Figure 30: Non-shear pin rendering.

To allow for quick and easy integration of the couplers with the airframe, witness rings were epoxied to the coupler at the couplers mid-point. Witness rings are also equipped with witness triangles to allow for quick and easy alignment of screw holes during assembly. The VDS coupler with a witness ring and triangle epoxied to its midpoint is shown below in Figure 31.

Figure 31: Witness ring and witness triangle.

All bulkplates and centering rings are secured to the launch vehicle airframe using Glenmarc G5000 two-component filled epoxy. This epoxy was chosen for its high strength properties as well as its working and cure times. The Glenmarc epoxy is black in appearance and the centering ring epoxying process is further discussed in 4.1.3.5.1. The material properties of Glenmark G5000 epoxy are shown below in Table 13.

Tensile Strength	7,600 psi
Compression Strength	14,800 psi
Elongation	6.30%
Shore "D" Hardness	85

Table 13: Glenmarc G5000 epoxy material properties.

Aeropoxy PR2032 and PH3660 was chosen as the epoxy resin for the launch vehicle as it is the most practical option for the team. Aeropoxy features a one hour working time with a medium viscosity, making it practical to remove excess epoxy via a heat shrink tape method. Another advantage to using Aeropoxy epoxy is that unlike other epoxies used in composite manufacturing, Aeropoxy can cure at room temperature. This is important for the team as we currently do not have access to the tooling or an oven that would be needed for epoxies used in traditional industrial applications. Material properties for Aeropoxy PR2032/PH3660 epoxy are shown below in Table 14, and were supplied by the manufacturer.

Property	Value
Cured Hardness	88 Shore D
Viscosity at 77˚F	800-875 cps
Density (in.^{3}/lb.)	0.0420
Tensile Strength (ksi)	45.35
Modulus of Elasticity (ksi)	2,800
Elongation at Break	1.91%
Flexural Modulus (ksi)	2,770

Table 14: Material properties for Aeropoxy PR2032/PH3660.

Each tube of the launch vehicle's airframe was manufactured following a common composite fabrication method known as "lay-up". First, the aluminum mandrel was wiped clean using Acetone. Next, a layer of lubricant was applied to the length of the mandrel covering a slightly larger surface area than the carbon fiber fabric will cover during the lay-up process. A thin plastic sheet was then wrapped around the mandrel to prevent the Aeropoxy from curing to the mandrel. This signifies the completion of the mandrel preparation process, and the aluminum mandrel is then mounted to the X-Winder desktop filament winder. The X-Winder was used to rotate the mandrel during the lay-up process.

The quasi-isotropic carbon fiber fabric was then cut to the desired length and diameter of each section of airframe. Next, each layer of quasi-isotropic carbon fiber fabric was saturated with Aeropoxy PR2032 resin and PH3660 hardener as shown below in Figure 32.

Figure 32: Saturation of quasi-isotropic carbon fiber sheets with epoxy.

After prepping each carbon fiber sheet, the fabric was wrapped around the aluminum mandrel as shown below in Figure 33.

Figure 33: Lay-up of individual carbon fiber sheets onto aluminum madrel.

To complete the lay-up process, the uncured airframe tubes were wrapped with heat shrink tape. A heat gun was used to apply heat to the tape, and the tape shrinks by up to 4%. This process compressed the carbon fiber fabric to remove excess epoxy and reduced the overall mass of the finished airframe tube. The heat shrink process is shown below in Figure 34.

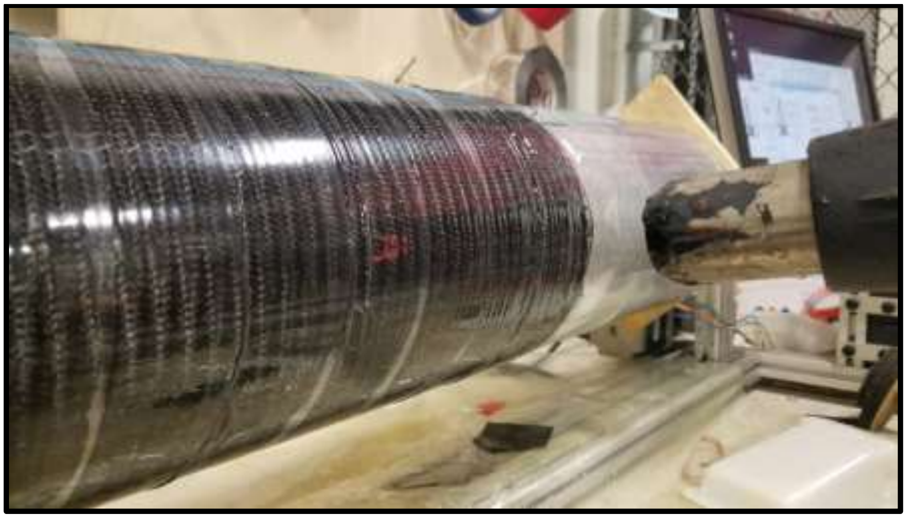


Figure 34: Removal of excess epoxy using a combination of heat shrink tape and heat supplied using a heat gun.

The airframe tube was allowed to cure for at least twenty-four hours before the tube was freed from the mandrel. The team uses a custom process to remove all sections of airframe. For clarity, the fully assembled airframe removal tool is shown below in Figure 35.

Figure 35: Fully assembled airframe removal tool.

The airframe removal tool consists of two main subassemblies that are described in detail below.

The first subassembly of the removal tool was used to pull the mandrel away from the airframe tube. A single five-foot-long 0.5-inch steel threaded rod was mechanically fastened on one side to a five-inch long 1-inch stainless steel eye bolt using 0.5-inch x 2-inch female hex standoff and two 0.5-inch hex nuts. A 1-inch diameter stainless steel quick link was used to fasten the eye bolt to a five-foot-long 0.5-inch stainless steel chain, and the chain was attached to a turnbuckle at the other end using a second 0.5-inch diameter quick link. Both the threaded rod and the chain were fed through the mandrel, and the turnbuckle was fastened to the car using a third 1-inch diameter quick link. Attached to the other side of the threaded rod was one 1-inch thick aluminum bulkplate that is dimensioned to fit inside the aluminum mandrel, as well as one 0.5-inch thick wooden bulkplate, two 0.25-inch aluminum bulkplates, and one 0.5-inch aluminum bulkplate all dimensioned to be slightly larger than the outer diameter of the aluminum mandrel. The inner bulkplate provided stability during the removal process, while the four outer bulkplates provided a leverage point to assist in pulling the mandrel away from the airframe tube. The components of the first main subassembly of the removal tool are shown below in Figure 36 and Figure 37.

Figure 36: Threaded rod and attached components used during airframe removal process.

Figure 37: Chain and turnbuckle attached to threaded rod during airframe removal process.

The second main subassembly of the removal tool was used to push the airframe tube off the aluminum mandrel while the first subassembly pulls the mandrel away. One 11-inch square 0.25-inch thick aluminum plate was set between one 11-inch square 0.25-inch thick steel plate and one 12-inch square 0.25-inch thick steel plate. A hole was cut using a Maxiem-450 water jet from the center of each plate to tightly fit around the outer diameter of the aluminum mandrel. Three plates were used to increase the strength of the tool. The plates were mechanically fastened using four ¾-inch stainless steel eyebolts placed at the four corners of each plate. A shackle was placed at each eyebolt to provide a point of an attachment for two 20-ft. long 0.5-inch chains. Each chain was wrapped around a concrete barrier column. One chain is attached to the top two shackles, while the other is attached to the bottom two shackles. While the car pulled the mandrel away, the concrete barrier column pulled back on the chains, and the plates pushed the airframe tube off of the mandrel. The components of the second main subassembly of the removal tool are shown below in Figure 38.

Figure 38: Plates and chains used to push the airframe off of the mandrel.

Following the removal process, each tube was cut to the precise length of the needed airframe section using a band saw and sanded for precision.

4.1.3.2 Fins

The fins were constructed using a BMS 8-276 Toray carbon fiber prepreg composite in a quasi-isotropic manner. The material was constructed by first cutting 20 layers from a unidirectional roll of the fabric. The layers were cut at angles of 0˚, ±45˚, and 90˚ relative to the horizontal. The fabric being cut at a 45˚ angle is shown below in Figure 39.

Figure 39: Fin material being cut.

The sheet was cured using a heated vacuum press, then cut to the fin dimensions using an OMAX waterjet. The finished fins were flown during the first full scale test flight, further discussed in 4.4.1, and unfortunately suffered significant damage. Due to time constraints, it was determined that the team could not remanufacture the fin material in time and that a material change was necessary. The new fins were constructed from a DragonPlate carbon fiber sheet the team has used on previous launch vehicles of this size. In the past, this material has withstood flights seeing greater maximum velocities and harsh landings without failing. The DragonPlate fin material properties are shown below in Table 15.

Property	Value
Young's Modulus	5 Msi
Tensile Strength	50 Ksi

Table 15: DragonPlate material propertires.

The DragonPlate fins are shown below in Figure 40.

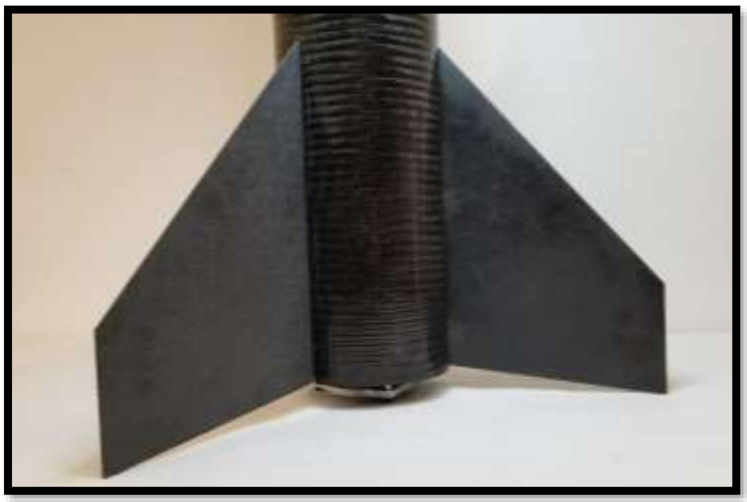


Figure 40: DragonPlate fins.

4.1.3.3 Bulkplates

All bulkplates in the launch vehicle are made of birch plywood or carbon fiber sheet. The booster and payload bay bulkplates, which take the load experienced during main parachute opening, are shown below in Figure 41 and Figure 42.

Figure 41: Booster Recovery Bulkplate and U Bolt.

Figure 42: Payload Recovery Upper Bulkplate

The payload and booster section recovery attachment points are black-oxide steel U-bolts rated for 600 lbf. and 1075 lbf. respectively. Using the predicted opening forces from CDR, FEA was run on the bulkplate design to verify the design would suffice for flight. The results of the FEA are shown below in

Figure 43 and

Figure 44.

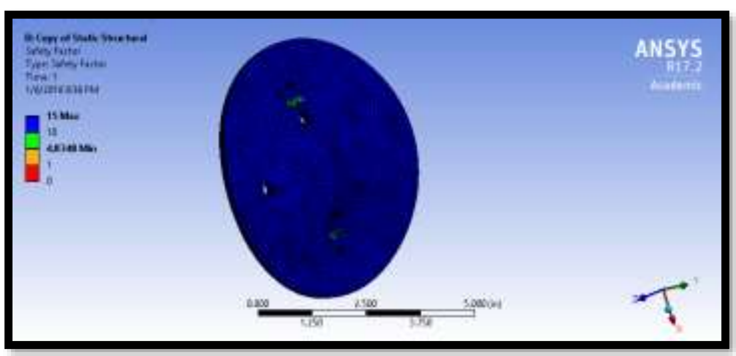


Figure 43: Payload bay bulkplate assembly factor of safety plot.

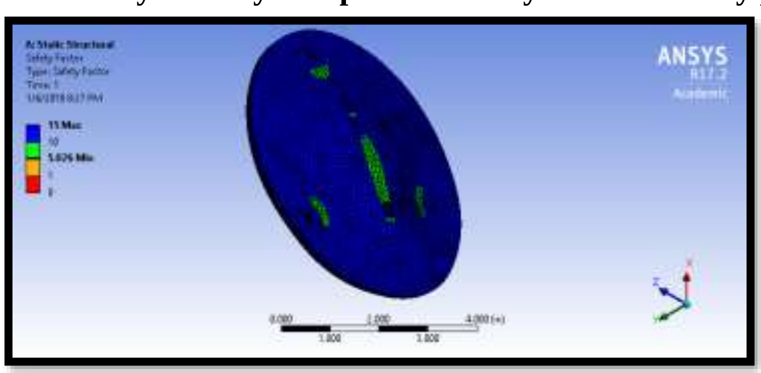


Figure 44: Booster bulkplate assembly factor of safety plot.

The carbon fiber / birch bulkplates were each epoxied together using Glenmarc G5000 two component filled epoxy. The lone coupler aft and fore bulkplates are shown below in Figure 45 and Figure 46.

Figure 45: Lone coupler aft bulkplate.

Figure 46: Lone coupler fore bulkplate.

The eye bolts utilized by the launch vehicle are only used to retain light recovery hardware, such as parachute deployment bags, and do not support any substantial weight. A custom-made eye nut, shown above in Figure 45, is used to pull the Booster main parachute out of the booster recovery bay and does not see any load. The U-bolt on the fore bulkplate of the lone coupler sees minimal load under drogue parachute. Each of the above bulkplates is 0.5 inches in thickness and is manufactured from birch plywood.

4.1.3.4 Launch Rail Interface

The launch vehicle will launch from a 12 ft., 1515 size, 8020 aluminum rail. The vehicle will utilize a pair of 0.625 in. diameter Delrin rail buttons that are rated for use on rockets weighing up to 150lbs. Delrin was chosen as the material for the rail buttons due to its high strength to weight ratio and low coefficient of friction. The rail button interface with the airframe and launch rail, is shown below in Figure 47.

Figure 47: Launch rail interface with Delrin rail buttons.

4.1.3.5 Booster Section

The booster section of the launch vehicle is responsible for securing the motor hardware and fins and consists of three centering rings, a removeable fin system, three fins, motor mount tube, and a motor retainer. The airframe of the booster section will be 36 inches in length to accommodate the motor hardware and VDS. The fully assembled booster section is shown below in Figure 5.

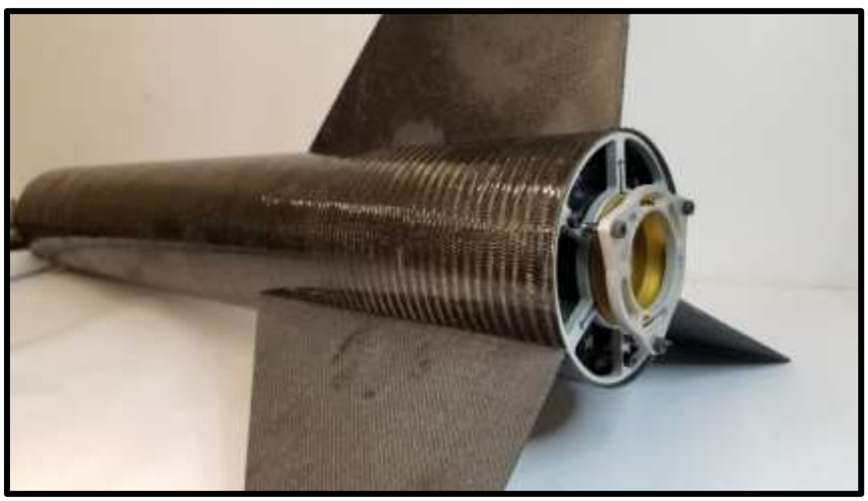


Figure 48: Fully Assembled Booster Section

4.1.3.5.1 Centering Rings

The launch vehicle utilizes three, 0.25 in. thick, 6061-T6 grade aluminum centering rings to transfer the thrust from the motor to the rest of the launch vehicle. The centering rings were cut from a 0.25 in. thick sheet of 6061-T6 aluminum using a Maxiem 450 water jet. Dimensional drawings of the centering ring designs are shown in Figure 49 and Figure 50.

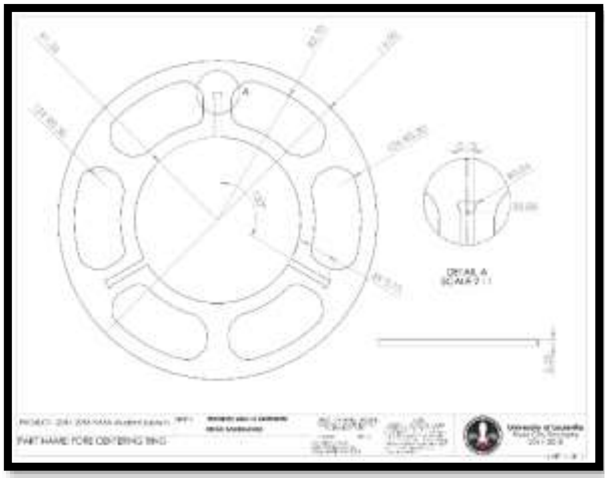


Figure 49: Dimensional drawing of the fore centering ring.

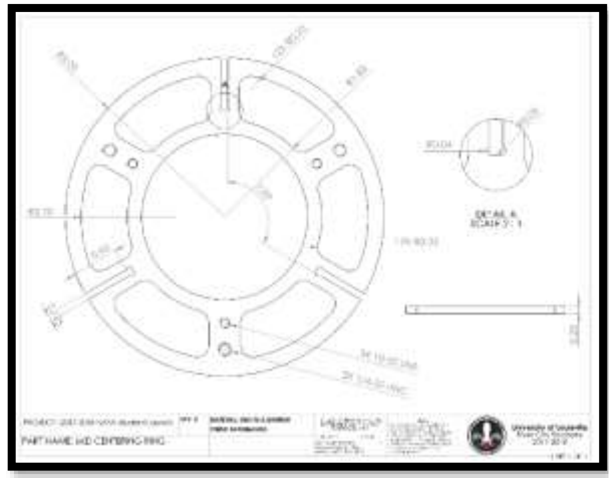


Figure 50: Dimensional drawing of the mid centering ring.

To ensure that the centering rings will withstand the forces exerted on them during motor burn, FEA was run on the fore and mid centering rings. As an additional safety measure, the centering rings were designed so that even if one fails, the remaining two centering rings could support the max load produced by the motor with a minimum factor of safety of 2.0. The centering rings were set to be fixed along their outer rim replicating how they will be once epoxied into the booster airframe. A force of 350 lbs. was applied to the inner rim of the centering rings, where the ring will be epoxied to the motor mount tube. This load is one half the expected maximum thrust we will see produced by the motor, further discussed in 4.3.3.2. The results of the FEA simulations showed that the minimum factor of safety of each centering ring design is greater than 2.0, as shown below in Figure 51 and Figure 52.

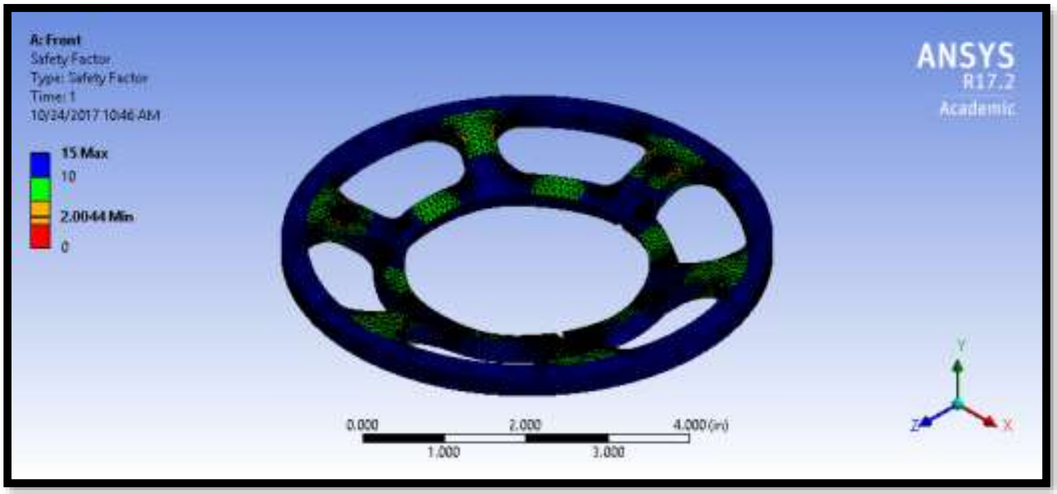


Figure 51: Fore centering ring FEA results.

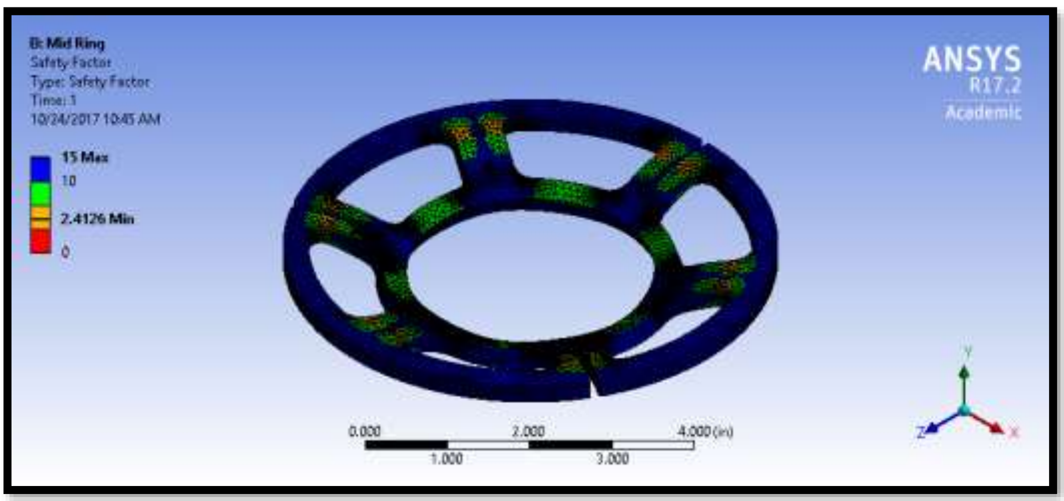


Figure 52: Mid centering ring FEA results.

The centering rings were positioned for epoxying to the motor mount tube using a centering ring alignment jig shown below in Figure 53.

Figure 53: Centering ring alignment jig.

The jig was cut using a CNC laser cutter allowing for precise dimensioning. The centering rings were slid onto the motor mount tube and then placed in the gaps between the wooden plates on the jig. The jig was designed so that the centering rings can slide in and fin alignment plates can slide into the fin slots in each centering ring, thus ensuring proper alignment. Once placed in the jig, the centering rings were epoxied to the motor mount tube as shown below in Figure 54.

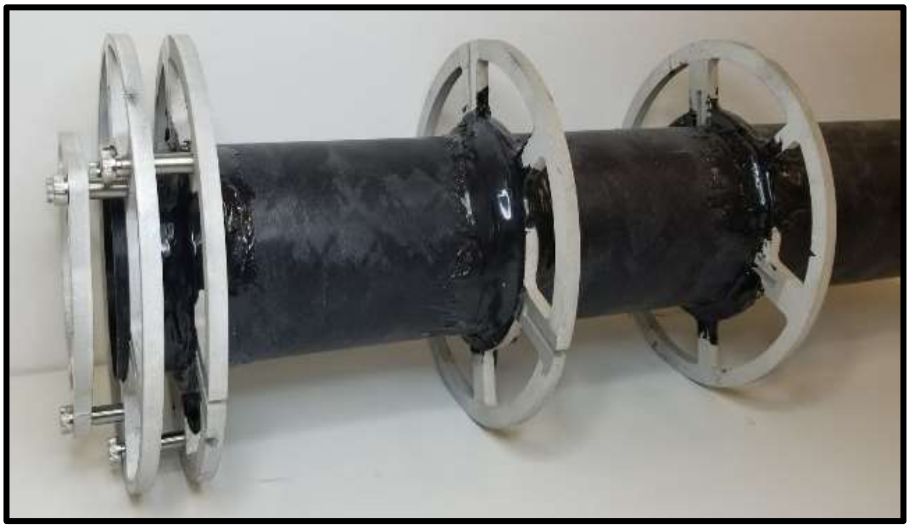


Figure 54: Centering rings expoxied onto the motor mount tube.

4.1.3.5.2 Removable Fin System

The launch vehicle utilizes a custom designed Removable Fin System (RFS) that allows for easy installation and removal of the launch vehicle's fins. The RFS consists of one fore centering ring, two mid centering rings, and a fin retainer. To insert the fins into the RFS, first the fore fin tab was inserted into the fore centering ring fin slot. The rest of the fin falls into the two remaining centering ring fin slots, then the fin retainer is placed over the aft fin tab. The fin retainer was then secured to the aft centering ring with three #10-24 stainless steel shoulder bolts. Upon installation of the motor casing, the motor retainer was then secured to the fin retainer using three #10-32 stainless steel shoulder bolts. A schematic of the RFS assembly process is shown below in Figure 55.

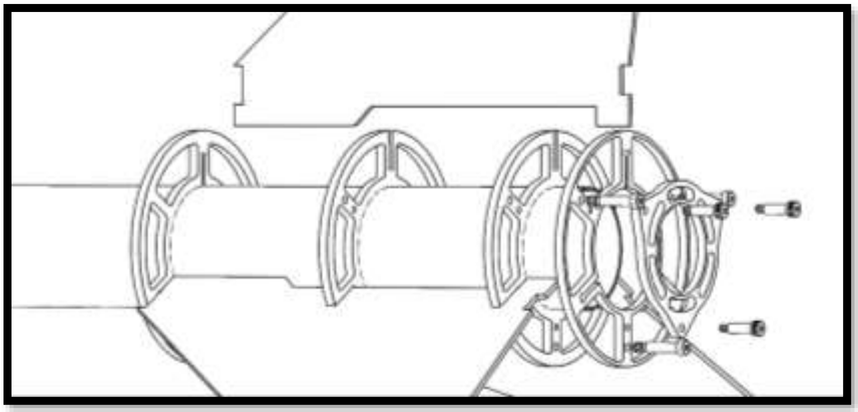


Figure 55: Schematic of RFS assembly process.

A fin slot jig was designed and manufactured to allow for precise alignment of the fin slots. The booster section of the launch vehicle was inserted into the jig and baffles were used to mark where the fin slots needed to be cut. The jig was cut using a CNC laser cutter allowing for precise dimensioning. The manufactured fin slot jig accompanied with the booster section of the launch vehicle is displayed in Figure 56.

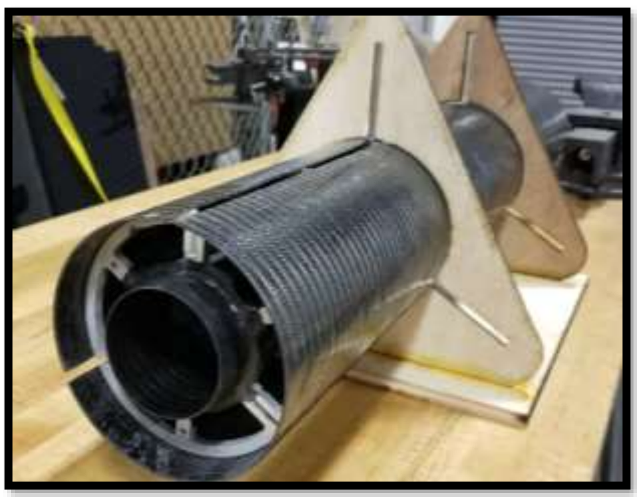


Figure 56: Fin slot alignment jig in use.

The locations of the fin slots were marked on the booster airframe using baffles and then cut using a Dremel as shown below in Figure 57.

Figure 57: Cutting of the fin slots in the booster airframe.

An interior and exterior photo of the fully assembled RFS is shown below in Figure 58 and

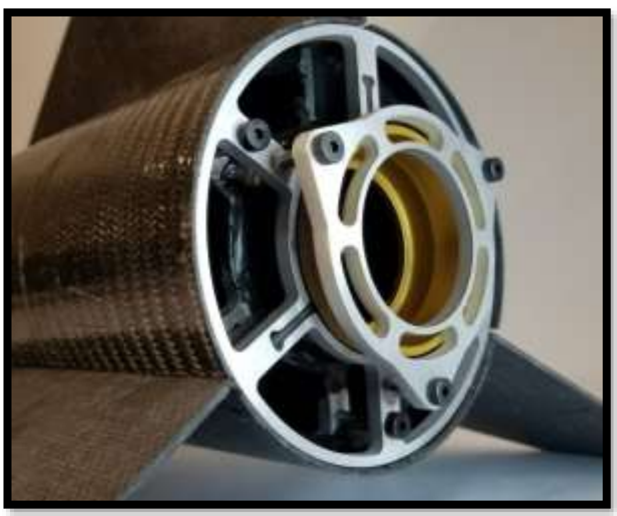


Figure 59.

Figure 58: Interior view of mid centering ring and fore centering ring with fin installed.

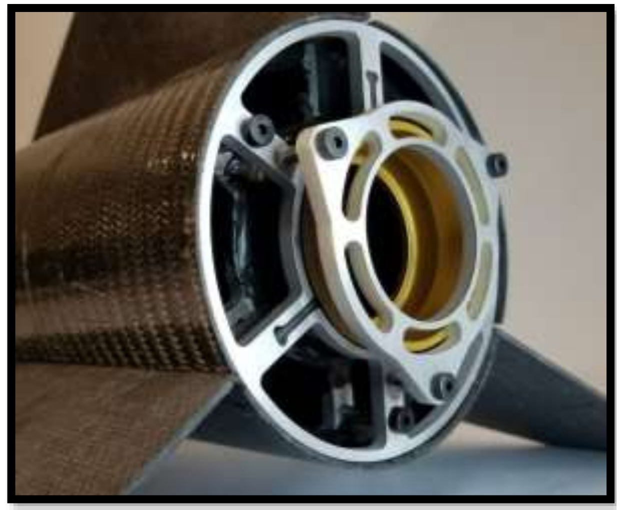


Figure 59: Fully assembled RFS.

4.1.3.5.3 Motor Retainer

A custom motor retainer was designed to ensure that the motor is secured within the motor mount tube during flight. The force that the motor retainer will have to withstand during flight was calculated using

$$F_m = m_m a_m \quad \textbf{(1)}$$

where m_m is the mass of the motor casing after burnout and a_m is the acceleration experienced during the opening of the main parachute. The force the motor retainer would need to withstand was calculated to be approximately 120 lbs. FEA was conducted on the motor retainer design to verify that it could withstand this force. The results of the FEA, shown below in Figure 14, show that the motor retainer design can withstand the expected opening force with a minimum factor of safety of 3.65.

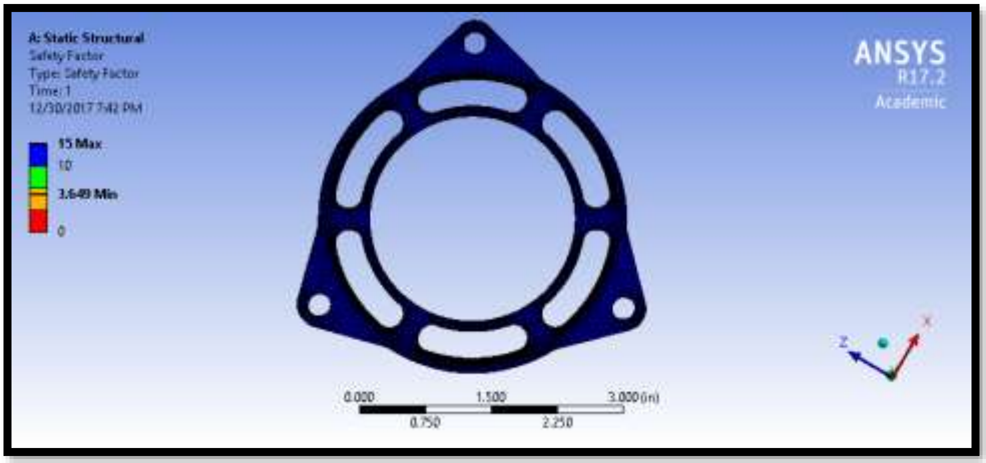


Figure 60: Motor retainer FEA simulations.

The motor retainer was machined from 0.25 in. thick, 6061-T6 grade aluminum, using a Maxiem 450 water jet. The manufactured motor retainer is pictured in Figure 61.

Figure 61: Manufactured motor retainer.

Prior to motor installation the fins and the fin retainer must be installed. Then, the motor retainer will be attached to the fin retainer via three #10-32 stainless steel shoulder bolts. The fin retainer is shown below in Figure 62.

Figure 62: Manufacted fin retainer.

4.1.3.6 Payload Bay

The payload bay of the launch vehicle is responsible for securing the rover payload further discussed in 5.2. To secure the payload to the payload bay airframe, 20 #10 clearance holes were drilled radially around the airframe. #10-24 steel screws were used to fasten the payload to the airframe as shown below in Figure 63.

Figure 63: Screws fastening the payload to the payload bay airframe.

4.1.3.7 Nose Cone

The launch vehicle utilizes a 12 in. long parabolic nose cone design with a 3 in. transition section. This design was chosen for its minimal drag and low mass. The nose cone carries a StratoLogger altimeter and an AIM XTRA GPS device within a coupler epoxied into the nose cone. A rendering of the nose cone design is shown below in Figure 64.

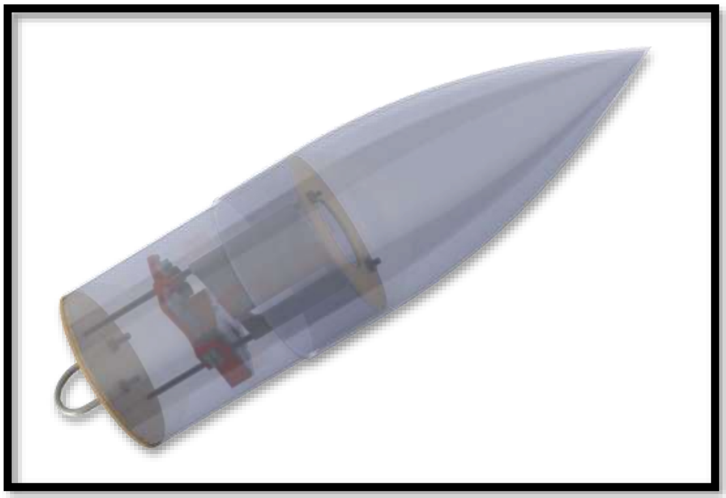


Figure 64: Parabolic nose cone with clear walls for clarity.

The nose cone has been additively manufactured from Nylon 12 using a SinterStation 2500+ machine shown below in Figure 65.

Figure 65: SinterStation 2500+ machine used to additively manufacture the nose cone.

This manufacturing method was chosen because of Nylon 12’s low mass and the ease of manufacturing. After manufacturing imperfections in the nose cone’s surface were filled in using Bondo All Purpose Putty and sanded down for a smooth finish. The completed nose cone is shown below in Figure 66.

Figure 66: Additively manufactured parabolic nose cone following successful drop dest.

The additively manufactured nose cone underwent drop testing to verify the strength of the Nylon 12 material and passed. Nylon 12's material properties are shown below in Table 16.

Mechanical Property	Value
Elongation at Break	15%
Tensile Modulus (ksi)	246
Tensile Strength (Psi)	6,815
Density (lb/in^3)	0.034

Table 16: Mechanical properties of Nylon 12.

4.1.3.8 Avionics

To reliably separate the launch vehicle in flight, two StratoLogger CF altimeters are used to initiate each separation event redundantly. The StratoLogger CF, shown below in Figure 67, is programmed prior to launch day to detonate a pyrotechnic charge within each separation section that causes the launch vehicle to separate and deploy a parachute.

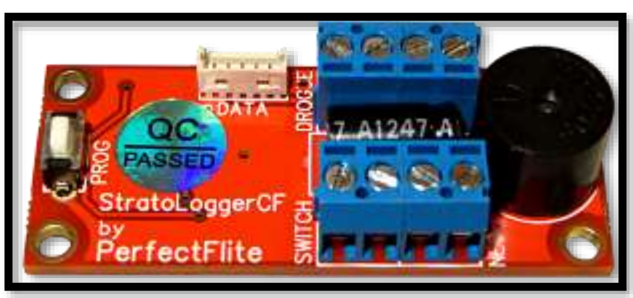


Figure 67: StratoLoggerCF altimeter.

To prevent over pressurization of the airframe, the secondary StratoLogger CF is programmed to detonate either 1 second (for the drogue) or 50 feet (for the booster main) later than the primary.

In the case of the Payload section main parachute, the separation event is initiated by an Advanced Retention Release Device (ARRD) instead of a pyrotechnic charge. The StratoLogger CF is reliable and has been found to be accurate to ± 1 feet. Each pair of StratoLogger CF altimeters are secured in flight via a custom designed 3D printed sled. The sleds have been printed from PLA plastic using a MONOPRICE Maker Select 3D printer as shown in Figure 68.

Figure 68: MONOPRICE Maker Select 3D Printer.

The launch vehicle carries five StratoLogger altimeters: one in the nose cone for altitude scoring, two in the Payload coupler, and two in the lone coupler between the booster recovery and Payload bays. Their locations are shown below in Figure 69.

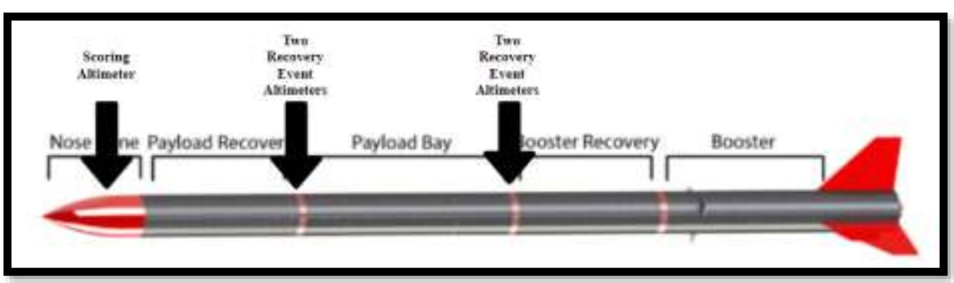


Figure 69: Illustration of altimeter locations.

The StratoLogger CF altimeters are secured to the sleds using four #4-40 nylon 6-6 screws. The altimeters are each powered by a Duracell 9-volt battery. The batteries are secured inside the battery cavity of sled by a battery cover made of acrylic, which is mounted to the sled using a single #4-40 nylon 6-6 screw on one end, and the coupler's all thread on the other. Each altimeter utilizes a Featherweight screw switch for arming and disarming from the exterior of the airframe. The two altimeters and two Duracell 9-volt batteries on the sleds, shown below in Figure 70, are secured within the coupler by two 10-32 all thread rods.

Figure 70: StratoLogger CF sled.

24 AWG wiring runs from the altimeter sleds, through the bulkplate, to a terminal block. The deployment device E-matches are connected to the terminal blocks on launch day, and continuity of the circuit is tested using a multimeter. The bulkplate assembly is shown below in Figure 71.

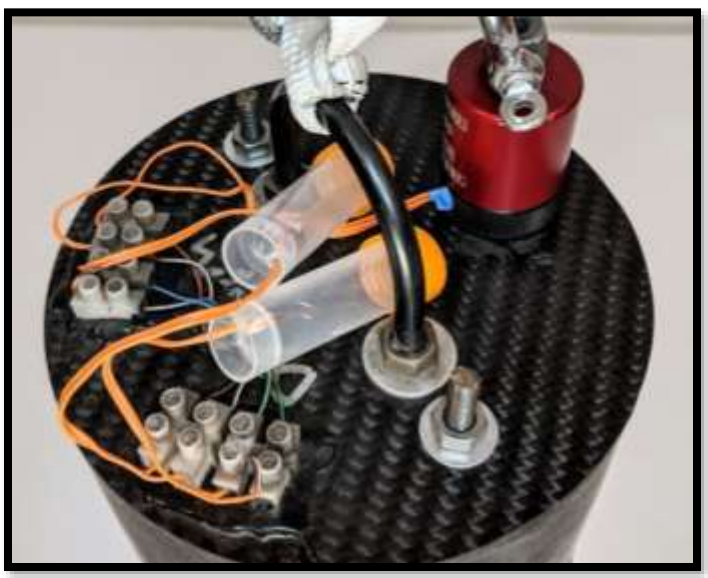


Figure 71: Bulkplate assembly showing terminal blocks and wiring to charge canisters.

4.1.3.8.1 Electrical Schematics

The electrical schematics are illustrated for each recovery event altimeter in the figures below. The Lone Coupler altimeters, which facilitate the separation of the Booster section from the Payload section and the separation of the Lone coupler from the Booster section, are shown below in Figure 72 and Figure 73.

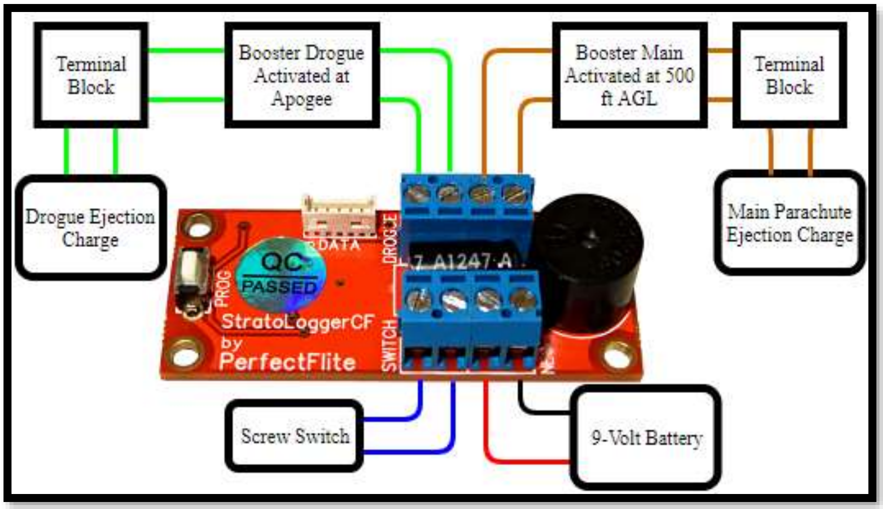


Figure 72: Electrical schematic of Lone Coupler primary altimeter.

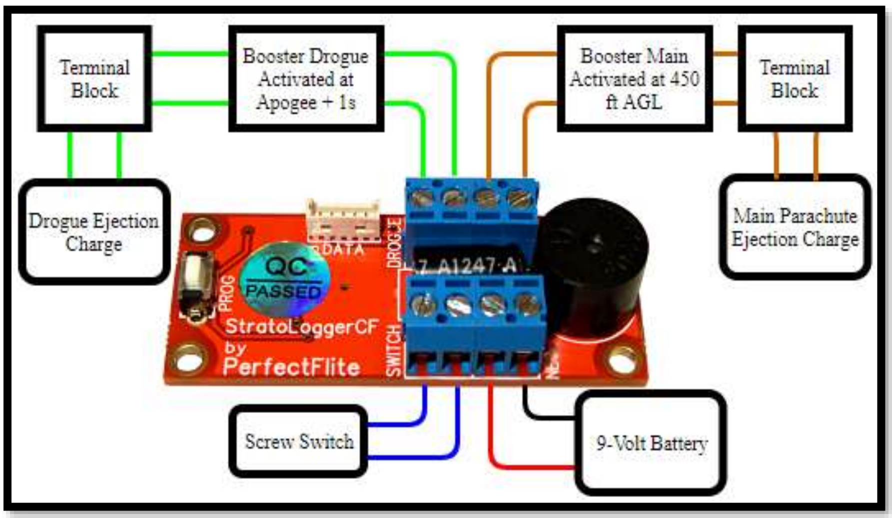


Figure 73: Electrical schematic of Lone Coupler secondary altimeter.

The Payload coupler altimeters, which facilitate the separation of the nose cone from the Payload section and the release of the ARRD, are shown below in Figure 74 and Figure 75.

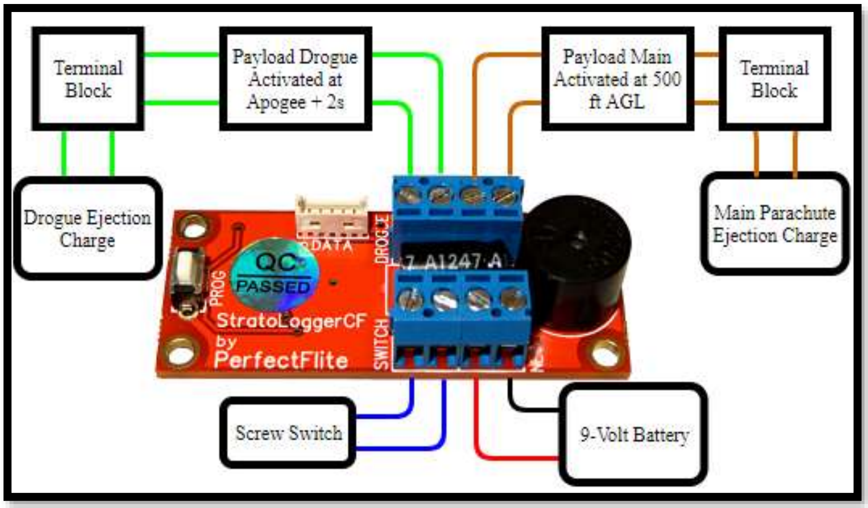


Figure 74: Electrical schematic of Payload Coupler primary altimeter.

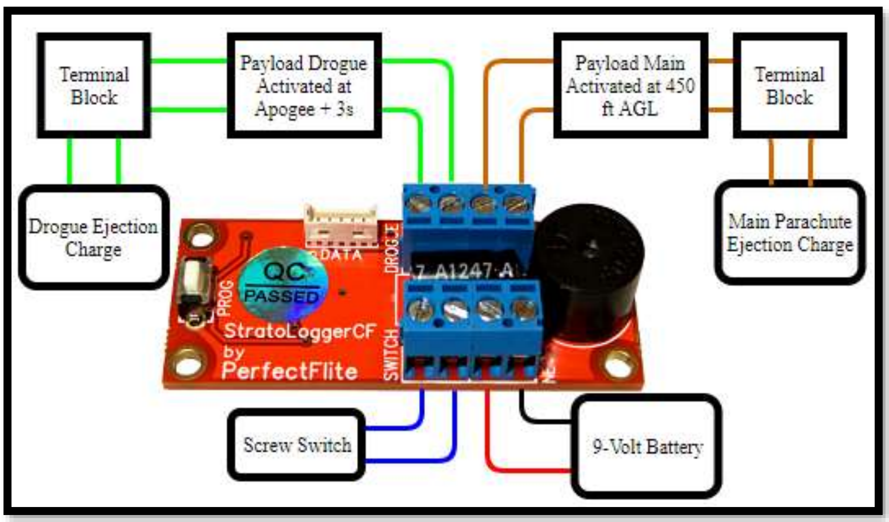


Figure 75: Electrical schematic of Payload Coupler secondary altimeter.

4.1.3.8.2 Ventilation Hole Sizing

To prevent the registration of pressure anomalies during flight ventilation holes have been drilled through the airframe into the avionics couplers. The diameter of the ventilation holes was calculated using the equation:

$$\boldsymbol{D_{vent} = D_i \sqrt{\frac{L \times A_{ref}}{N \times V_{ref}}}} \tag{2}$$

where D_i is the inner diameter of the coupler, L is the length of the coupler, A_{ref} is the reference area of the vent hole, N is the desired number of vent holes, and V_{ref} is the reference volume of the coupler. It is recommended that a one fourth of an inch ventilation hole be created for every 100 cubic inches of the avionics coupler. Therefore, 0.049 in^2 was used for A_{ref} and 100 in^3 was used for V_{ref}. The dimensions of each avionics coupler, and their respective calculated vent hole diameter are shown below in Table 17.

Avionics Coupler	Length (in.)	Interior Diameter (in.)	Calculated Vent Hole Diameter (in.)
Lone Coupler	5.75	5.85	0.310
Payload Recovery	5.875		0.314

Table 17: Ventilation hole sizes required for each avionics coupler.

4.1.3.8.3 GPS Tracking

Each independent section of the launch vehicle carries a GPS tracking device. The launch vehicle utilizes four different types of GPS tracking devices, outlined below in Table 18.

Independent Section	GPS Tracker
Booster	Skytraq S1216F8-GL
Lone Coupler	Trackimo TRKM010
Payload Bay	Eggfinder GPS Tracking System
Nose Cone	Entacore Electronics AIM Xtra 2.0

Table 18: GPS tracking devices used in each independent section.

4.1.3.8.3.1 *Skytraq S1216F8-GL*

The Skytraq S1216F8-GL, shown below in Figure 76, has been integrated into the VDS electronics coupler via surface mount on the printed circuit boards, and serves as the GPS unit for the booster section of the launch vehicle. This unit can track up to 12 satellite signals at any given position, and its –148dBm cold start sensitivity feature allows the unit to acquire, track, and fix onto any signal autonomously in weak signal environments. The positioning data from the Skytraq will be transmitted through the Xbee RG active telemetry system to the VDS ground station, allowing the team to monitor the position of this unit throughout the flight and upon recovery. The telemetry system operates on a frequency between 902MHz and 928MHz. At the location of the launch, the least noisy frequency within this range is determined and used for transmission of telemetry data.

Figure 76: Skytraq S1216F8-GL

4.1.3.8.3.2 *Trackimo TRKM010*

The Trackimo TRKM101 was chosen to track the lone coupler as it can be easily mounted on the exterior of the upper bulkplate facing the sky during decent. This bulkplate is generally exposed, during decent and landing, allowing the position signal to transmit around the carbon fiber coupler. The Trackimo uses GPS satellites and a worldwide cellular network to track the launch vehicle with an accuracy of up to 30 feet. The Trackimo TRKM010 operates on 850, 900, 1800, and 1900 MHz frequency, and the location of the device can be viewed via a mobile app as shown in Figure 77.

Figure 77: Trakimo TRKM010 tracking the coupler.

4.1.3.8.3.3 *Eggfinder GPS Tracking System:*

The Eggfinder GPS tracking system, shown below in Figure 78, is mounted inside the Payload recovery coupler of the launch vehicle. The Eggfinder has a mass of only 20 grams, has a range of 8000 feet from the tracking receiver, and operates at a frequency of 900MHz at 100mW. An antenna, connected to the Eggfinder, has been secured to the exterior of the launch vehicle through a ventilation hole in the airframe, reducing the risk of signal attenuation reduction from the carbon fiber airframe.

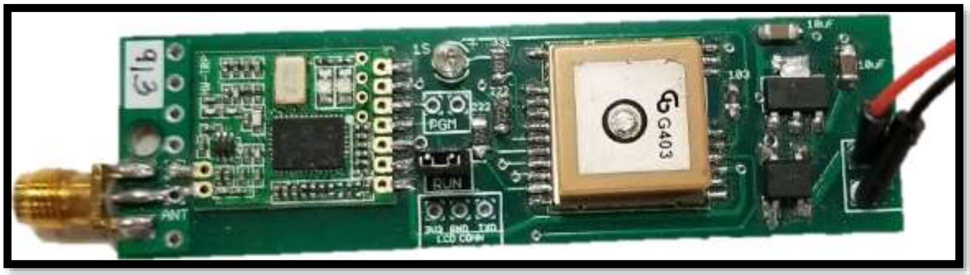


Figure 78: Eggfinder GPS tracking system.

4.1.3.8.3.4 *Entacore Electronics AIM XTRA 2.0*

The AIM XTRA, shown below in Figure 79, is an electronic device capable of GPS tracking, telemetry, and separation event triggering. The team is only utilizing the GPS tracking capability to track the nose cone section of the vehicle during recovery. The AIM XTRA can be operated in the 432-434MHz band without the need for a HAM radio license and makes use of the AIM BASE connected to a laptop computer on the ground. The AIM XTRA is secured on a custom 3D printed sled inside the nose cone, along with the official scoring altimeter.

Figure 79: AIM XTRA 2.0 GPS tracking device.

4.2 Recovery Subsystem

4.2.1 As-built materials and systems

The following section describes predicted dimensions and actual dimensions of each subset of the recovery system.

4.2.1.1 Attachment points and rigging components

The shroud lines used for all parachutes are 0.047 in. fire resistant bonded white nylon, commonly referred to as spectra lines. The centerlines of each main parachute are 0.118 in. woven nylon paracord. The shock cord chosen for the launch vehicle is a 9/16 in. tubular nylon cord which will be connected to the vehicle using 5/16 in. zinc plated steel quick-links. with a bowline hitch knot on each end of the cord. These values as well as their factors of safety are shown in Table 20 below.

The bowline hitch was chosen for its self-tightening characteristics. The drogue parachute shock cord and deployment bag tether for the payload section will be directly tied to the attachment point of the ARRD and will not utilize a quick-link. The shock cord configurations are shown below in Figure 80 and Figure 81 below.

Figure 80: Booster recovery bay assembly

Figure 81: Payload recovery bay

Each Individual length of shock cord is indicated by a different color. The lengths and attachment points of each shock cord is shown in Table 19.

Connection points	Length (in.)
Nose cone – Drogue (pink)	112
Drogue – ARRD (blue)	264
ARRD - Deployment bag (red)	12
Payload Main – Payload (green)	264
Drogue – Coupler (green)	108
Coupler - Deployment Bag (blue)	24
Booster Main – Booster (pink)	216

Table 19: Shock cord dimentions

Opening forces were calculated for the toroidal main parachutes to ensure the rigging materials would not break during deployment. Using the weights of both the booster segment and payload segment, opening force was found using

$$\boldsymbol{F_x = \frac{(C_D S)_p \rho V^2 C_x X_1}{2}} \tag{3}$$

Where F_x is the opening force of the main parachute, $(C_D S)_p$ is the drag coefficient proportional to the surface area of the parachute, ρ is the density of air at sea level, V is terminal velocity at opening, C_x is the opening force coefficient, and X_1 is the opening force reduction factor. C_x and X_1 are scaleable constants reliant on the design of the parachute. Using data acquired from subscale flight results, X_1 and a C_x can be obtained for a toroidal parachute. First the C_x is found using

$$\boldsymbol{C_x = \frac{F_x}{F_c}} \tag{4}$$

where F_x is the measured opening force of a subscale parachute and F_c is the measured steady state force of a subscale parachute. Next the equation is solved backwards to find X_1 which is now the only unknown. The force reduction factor and the opening force coefficient of a toroidal parachute design can be scaled. Applying data from a full-scale parachute design, predicted opening force values can be calculated. These values are also confirmed using

$$opening\ acceleration = \frac{drogue\ velocity\ -\ main\ velocity}{opening\ time}$$

where the velocities used are from drop tests and the opening time is found from video evidence of the February 17th launch. This removes the risk of having inaccurate opening force data from drop tests. These values are shown below in Table 20. The break strength rating and factors of safety of each component are shown below.

Component	Break Strength (lbs)	Factor of safety
9/16 in. tubular nylon shock cord	1500	6.7
Zinc plated steel quick link	660	2.9
Shroud line (x10)	3000	13.4

Table 20: Break strength and factor of safety of rigging components

4.2.1.2 Main parachutes

The two main parachutes are toroidal in design. Toroidal parachutes are modified 0.707 elliptical parachutes where the venthole is pulled lower into the canopy by a centerline to increase the drag coefficient without affecting weight or volume. These parachutes consist of 10 panels of ripstop nylon. Each panel is designed based on the diameter of the parachute and the number of panels. The diameter of each parachute is derived to meet the Kinetic Energy Requirements (KER) in SOW 2.3 outlined in section 6.1.1. Nominal diameter for a parachute can be found using

$$\boldsymbol{D_o = \sqrt{\frac{4m_v m_s g}{\pi E C_D \rho}}} \tag{5}$$

D_o is the nominal diameter, m_v is the mass of the vehicle, m_s is the mass of the subsection, g gravitational acceleration, E is the kinetic energy, C_D is the coefficient of drag and ρ is the air pressure at sea level. Each main parachute will have one tethered section, so this equation simplifies to

$$D_o = \sqrt{\frac{4m^2 g}{\pi E C_D \rho}} \tag{6}$$

The venthole diameter is a tenth of the outer diameter. The dimensions for the two main parachutes are shown in Table 21 below.

Component	Material	Predicted Outer Diameter	Actual Outer Diameter	Predicted Inner Diameter	Actual Inner Diameter
Booster Main Parachute	*Zero Porosity Ripstop Nylon*	99	104	9.9	10
Payload Main Parachute	*Zero Porosity Ripstop Nylon*	88	89	8.8	9

Table 21: Main parachute diameters

These parachutes feature an outer set and an inner set of shroud lines to both the outer canopy and the venthole respectively. The lengths for both sets of these shroud lines are twice the diameter of the circumference they are connected to. The Centerline was predicted to be approximately 81% of the shroud line length. This has been predicted by adjusting the length and measuring for maximum drag force. The manufactured dimensions are shown with the predicted dimensions below in Table 22.

Component	Material	Break Strength (lbs.)	Predicted Payload Length	Actual Payload Length	Predicted Booster Length	Actual Booster Length
Outer shroud lines	*Spectra Line*	300	176	167	198	211
Inner shroud lines	*Spectra Line*	300	35	32	40	36
Centerline	*Paracord*	320	136	135	153	175

Table 22: Parachute structural components

These dimensions are visualized in Figure 82: Payload main parachute and Figure 83.

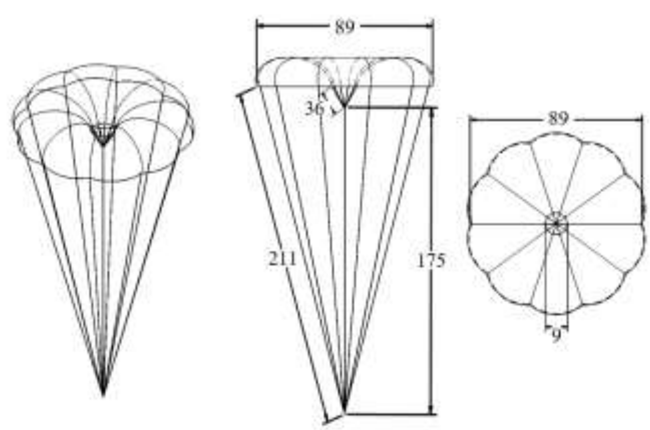


Figure 82: Payload main parachute design

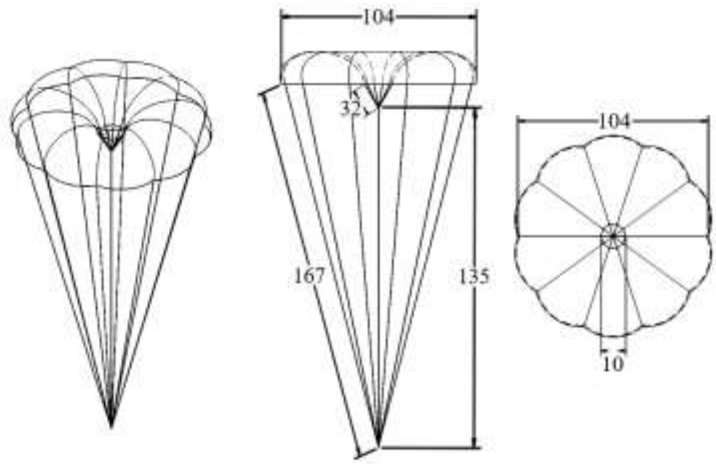


Figure 83: Booster main parachute design

Ten panels were chosen as a balance between number of shroud lines and amount of manufacturing time. A larger number of shroud lines means that the parachute can absorb more force without the possibility of a shroud line snapping. however, this also means that more panels must be sewn together, creating more room for manufacturing error. The main parachute for the booster section can be seen fully inflated on the ground in Figure 84.

Figure 84: Booster main parachute

4.2.1.3 Deployment bags

Each main parachute will be contained in a custom deployment bag made from fire retardant canvas that will hold the main parachutes but will not be tethered to them. The deployment bags will be pulled off by the drogue parachutes and will land separately with the nosecone or coupler that the drogues will carry.

Figure 85: Deployment bag line-stows

The deployment bags feature loops to stow the shroud lines of each parachute along the side of the bag to ensure an orderly deployment as shown in Figure 85. These line-stows are protected by a flap of canvas sprayed with fire retardant spray which is secured by a Velcro strip. The deployment of the line-stows is not affected by the flap. This is shown in Figure 86 below.

Figure 86: Line-stow protector

The deployment bags are also lined with low friction ripstop nylon, which is the same material as the parachutes. This low friction interface allows the main parachutes to deploy even in the case that the drogue parachutes become tangled and do not fully deploy. The effectiveness of the lining was tested by simply turning the bag upside down and watching the parachute deploy. This was repeated with no problems. This lining is shown in Figure 87.

Figure 87: Nylon lining

4.2.1.4 Drogue parachutes

The drogue parachutes have been changed from the design discussed in CDR. Upon manufacturing, each cruciform drogue parachute was tested for stability. Rotation was still observed after extensive precautions were taken to mitigate the asymmetry. After referencing the Parachute Recovery Systems Design Manual, By Theo W. Knacke with the Naval Weapons Center in China Lake, CA, the team concluded a redesign was necessary. The manual reads as follows:

> Cross parachutes have a tendency to rotate. Rotation can be diminished by connecting adjacent arm corners with a restricting line long enough to permit full canopy inflation but not long enough to permit over inflation.

Our previous design was calculated based on effective surface area. The design is shown below.

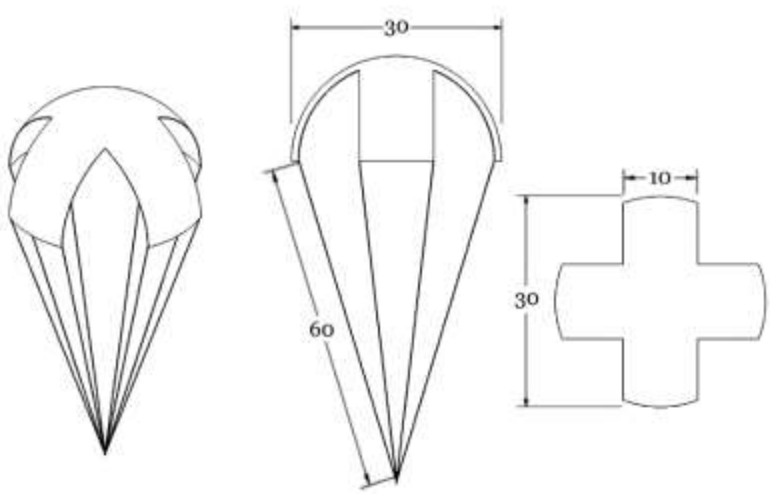


Figure 88: Previous cruciform design

The redesigned drogues are also cruciform, but the corners of the extending panels are sewn together creating an opening that is roughly square. This design is shown below in Figure 89.

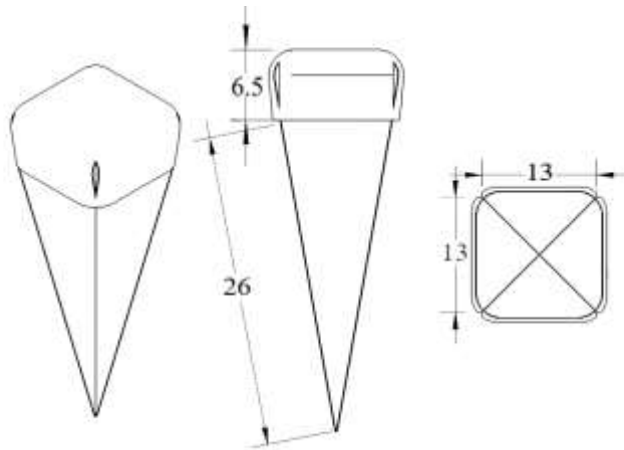


Figure 89: New cruciform design

The drogues form a rounded cuboid shape upon deployment and show little to no rotation. A fully inflated drogue can be seen in Figure 90.

Figure 90: New cruciform drogue

A coefficient of drag of 0.6 was confirmed for the new design using drop test data acquired from object tracking via video recordings. The altitude vs time graph of three trials is shown below in Figure 91.

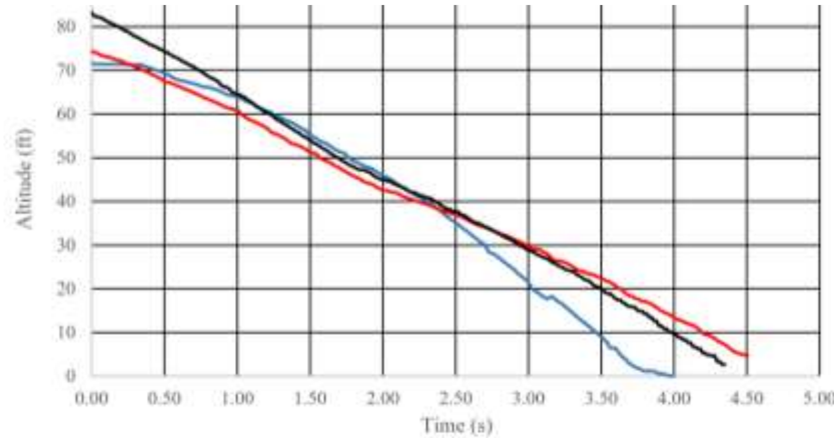


Figure 91: Drop test data

A surface area of ~500 in^2 was used for the previous design and upon confirming the same coefficient of drag, this surface area will be used again. The new design was flown on the first flight of the Zenith launch vehicle and performed exceptionally despite the anomalous flight. Due to the anomaly and varying wind speeds at higher altitudes, opening forces and drift were hard to discern and are representative of outlier behavior. The decent speed from this flight is comparable to drop tests data. The altitude vs time graph from the payload bay during this flight is shown below in Figure 92.

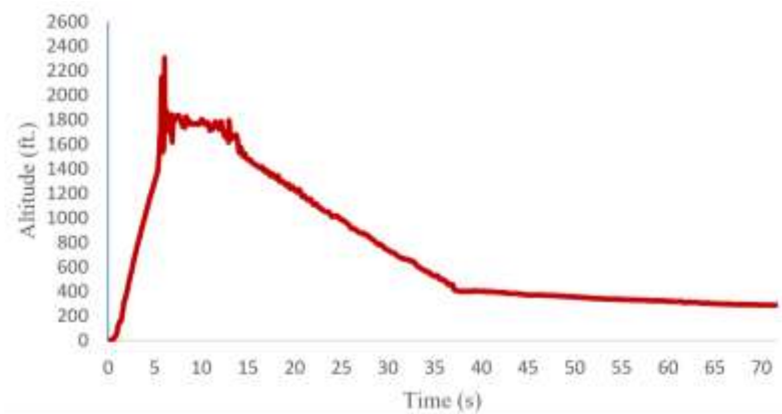


Figure 92: Altitude vs time graph from stratologger data

These drogue parachutes are dependent upon two criteria. The first of which is the Kinetic Energy Requirement (KER) outlined in SOW 3.3 section 6.1.4.1 where each drogue parachute will fulfill the role of main parachute for the coupler and nosecone after main deployment. The minimum diameter was calculated using

$$D_o = \sqrt{\frac{4m^2 g}{\pi E C_D \rho}} \tag{7}$$

where D_o is the length of a side of the parachute from line to line, m^2 is the mass of the coupler or nosecone, g is gravitational acceleration, E is the kinetic energy, C_D is the coefficient of drag and ρ is the air pressure at sea level.

The parachutes were sized to descend under a constant velocity such that the amount of drift in 20 MPH winds would remain within 2,500 ft. With the vertical velocity requirement of 102.7 ft/s during drogue decent found from calculations explained in the drift section, the surface area of the parachute can be found using this equation

$$So = \frac{2mg}{C_D V_e^2 \rho} \tag{8}$$

where V_e is terminal velocity, and S_o is the surface area of the drogue. The diameter can then be calculated using

$$D_o = \frac{\sqrt{S_o \times 3}}{3} \tag{9}$$

This produces a ceiling diameter. Applying both constraints, a diameter range is derived and shown in Table 23 below.

Parachute	Minimum Diameter (in.) (KER)	Maximum Diameter (in.) (Drift)
Payload	11.06	13.5
Booster	8.85	13.6

Table 23: Drogue parachute sizes

For simplicity and safety, a single size of 13 in. was chosen for both sections that would satisfy all requirements. These predicted dimensions along with the actual dimensions are shown below in Table 24.

Component	Material	Break Strength (lbs)	Predicted Length/Diameter	Actual Length/Diameter
Canopy	*Zero Porosity Ripstop Nylon*	n/a	13 in.	13 in.
Shroud Line	*Spectra Line*	300	26 in.	26 in.

Table 24: Drogue dimensions

Both drogue parachutes are identical in that their dimensions are arbitrarily different. Shroud lines for each drogue parachute will lead from each corner of the parachute to a central attachment point as shown in

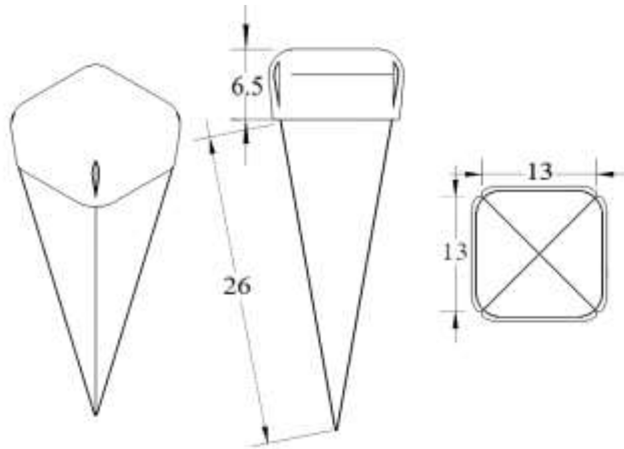


Figure 89 earlier in this section.

4.2.2 Kinetic energy

All main and drogue parachutes are designed to land their segments of the launch vehicle at or under 65 ft-lbs of force in a nominal landing. The kinetic energy at landing predictions of each independent section, as well as their terminal velocities at landing are shown below in Table 25. The data shown was collected velocity first, using drop tests, and kinetic energies were derived second using actual masses. All flight data was deemed as an outlier and drop tests were conducted to satisfy the need for data.

	Section Mass (lbs.)		**Ground Hit Velocity (ft/s)**		**KE (ft-lbs)**	
Section	**Predicted**	**Actual**	**Predicted**	**Actual**	**Predicted**	**Actual**
Nosecone	3.14	2.76	35.3	33.26	43.8	47.4
Payload	17.08	16.53	15.6	15.9	65	64.9
Coupler	1.98	2.20	28.0	28.4	17.5	26.6
Booster	19.29	18.96	14.7	14.85	65	64.9

Table 25: Predicted and actual kinetic energy and maximum velocities

4.2.3 Drift predictions

The team has manufactured custom parachutes to fit each niche of the recovery system. The drogues were manufactured to adhere to the maximum drift specifications dictated in SOW 3.9 of section 6.1.1. The maximum drift value is used to solve for the size of the drogue parachute since they are tailored to specific needs. Total drift is calculated by first finding the amount of drift seen while under the main parachute phase in 20 mph winds and subtracting it from the allotted 2500 ft. The main parachute size is dependent upon kinetic energy requirements and is a fixed number in this case. Its terminal velocity can be solved for using

$$V_e = \sqrt{\frac{2mg}{C_D S_0 \rho}} \tag{10}$$

Where V_e is terminal velocity, m is the mass of the segment, g is acceleration due to gravity, C_D is the drag coefficient, S_o is surface area, and ρ is the density of air at sea level.

Main deployment events occur at an altitude of 400 ft. at a predictable speed, time until landing is solved for using

$$\frac{400\,ft}{terminal\ velocity} = time \tag{11}$$

which is input to solve for the distance the main parachute will drift laterally using

$$Windspeed \times time = distance \tag{12}$$

The amount of distance left must be allotted to drogue decent phase. With this distance it is possible to solve for the minimum time at which the launch vehicle can safely descend without crossing these bounds. This equation is shown below.

$$\frac{2,500\,ft - main\ drift}{windspeed} = time \tag{13}$$

With the amount of time the vehicle can drift horizontally, speed at which it should fall vertically in that same time to cover the distance from apogee to main deployment height can be found. The booster segment, which will have the largest drift, will have 57 seconds to fall from apogee to main deployment height before it crosses the bounds.

$$\frac{5,280\ -\ deployment\ height}{time} = vertical\ velocity \tag{14}$$

The vertical velocity found for the booster segment was 102.7 ft/s or 60 mph. The surface area of each drogue can then be solved for and simplified into a whole number for manufacturing simplicity, for example 13.09 in. becomes 13 in. The drift is then recalculated using the rounded number. The inputs for this calculation is shown in Table 26.

Section	Section Mass (lbs.)	Main Size (in.)	Terminal Velocity (ft/s) Drogue / Main		decent duration (s) Drogue / Main	
Nosecone	2.76	11		33.13		15.09
Payload	16.53	88	107.53	15.9	44.08	31.45
Coupler	2.2	11		38.8		12.89
Booster	18.96	99	98.01	14.85	48.77	33.68

Table 26: Important data for drift calculation

The calculated drift values from these data are shown below in Table 27.

Wind Speed (MPH)	Wind Speed (Ft/s)	Booster Drift (Ft.)	Payload Drift (Ft.)	Coupler Drift (Ft.)	Nosecone Drift (Ft.)
5	7.3	615	562	505	480
10	14.7	1230	1123	1011	961
15	22.0	1845	1685	1516	1441
20	29.3	2460	2247	2022	1922

Table 27: Drift calculations at different wind speeds

All drift values are within the dictated boundaries. Figure 93 shows the booster's drift values overlaid on the competition field.

Figure 93: Drift overlaid onto the launch field

Again, due to the anomaly and varying wind speeds at higher altitudes, drift was hard to discern and is representative of outlier behavior. The data acquired from this launch was deemed inconclusive. However, drop tests were performed to satisfy the want for data and confirm decent speeds that were predicted. These speeds were deemed appropriately collected and representative of accurate data due to their similarity to predictions. These speeds were used to calculate the drift values shown above.

4.2.4 Structural Analysis of Parachutes

During the anomaly flight on March 3rd, 2018, the booster main parachute deployed at 500 ft MSL and "zippered" the booster recovery section of the launch vehicle. After reaching the strongest part of the structure (The motor centering rings) it snapped the spectra shroud lines midway along their length. This represents an important result for safety as it implies a weakest link in the recovery subsystem. The shroud lines, as referenced above, can withstand a maximum of 3000 ft/lbs without breaking (300 lbs. each). Their failure is a clear indicator that the seams, ripstop nylon panels, quick links and centerline all have break points at or above 3000 ft/lbs. This result produces a factor of safety of approximately 1.9 for the parachute seams.

4.3 Mission Performance Predictions

4.3.1 Mission Success Criteria

For our mission to be considered a success, the launch vehicle must meet the following criteria:

1. The launch vehicle shall ascend upon motor ignition, exiting the launch rail at a velocity greater than 75 ft/s.
2. The launch vehicle's motor shall burnout without incident, and the Variable Drag System (VDS) shall then become active.
3. The launch vehicle shall reach an apogee altitude of 5,280ft +/- 23ft AGL.
4. All recovery events shall occur at their programmed altitudes.
5. All sections of the launch vehicle shall have a stable descent.
6. All sections of the launch vehicle shall land safely under kinetic energy requirements and be fully reusable.

4.3.2 Applicable Equations

While software exists that can accurately simulate the flight of the launch vehicle, hand calculations were performed to verify the simulations accuracy. To assess the performance of the rocket in flight, three main values are calculated: peak altitude, center of gravity, and center of pressure of the rocket. Calculating peak altitude requires a specific sequence of equations. First, average mass of the rocket before burnout is calculated using

$$\boldsymbol{m_a = m_r + m_e - \frac{m_p}{2}} \tag{15}$$

in which m_r is the mass of the rocket, m_e is the mass of the motor, and m_p is the propellant mass. Then the rocket's aerodynamic drag coefficient (kg/m) is calculated using

$$\boldsymbol{k = \frac{1}{2}\rho C_D A} \tag{16}$$

where ρ is air density (1.22kg/m^3), C_D is the drag coefficient, and A is the rocket's cross-sectional area (m^2). Burnout velocity coefficient (m/s) is calculated using

$$\boldsymbol{q_1 = \sqrt{\frac{T - m_a g}{k}}} \tag{17}$$

where T is the motor thrust and g is the gravitational constant (9.81 m/s^2). The rocket's burnout velocity delay coefficient (1/s) is calculated using

$$\boldsymbol{x_1 = \frac{2kq_1}{m_a}} \tag{18}$$

The burnout velocity (m/s) is calculated using

$$\boldsymbol{v_1 = q_1 \frac{1 - e^{-x_1 t}}{1 + e^{-x_1 t}}} \tag{19}$$

where t is the motor burnout time (s). The rocket's altitude at motor burnout can then be computed using

$$\boldsymbol{y_1 = \frac{-m_a}{2k} \ln\left(\frac{T - m_a g - k v_1^2}{T - m_a g}\right)} \tag{20}$$

After the altitude at burnout is calculated, the rocket's coasting distance must then be calculated. Comparable to burnout altitude, rocket mass must be calculated first. The coasting mass is calculated using

$$\boldsymbol{m_c = m_r + m_e - m_p} \tag{21}$$

Using coasting mass, the coasting velocity coefficient is calculated using

$$\boldsymbol{q_c = \sqrt{\frac{T - m_c g}{k}}} \tag{22}$$

Also using coasting mass, the coasting velocity delay coefficient was calculated using

$$x_c = \frac{2kq_c}{m_c} \tag{23}$$

The rocket's coasting velocity is then found using

$$v_c = q_c \frac{1 - e^{-x_c t}}{1 + e^{-x_c t}} \tag{24}$$

The coasting distance is found using

$$y_c = \frac{m_c}{2k} \ln\left(\frac{m_c g + k {v_c}^2}{T - m_c g}\right) \tag{25}$$

The peak altitude of the rocket can then be found using

$$PA = y_1 + y_c \tag{26}$$

The rocket's center of gravity location is calculated using

$$\boldsymbol{cg = \frac{d_n w_n + d_r w_r + d_b w_b + d_e w_e + d_f w_f}{W}} \tag{27}$$

where W is the total weight of the launch vehicle and d is the distance between the denoted section's center of gravity (nose, body, rocket, body, engine, and fins, respectively) and the aft end. The vehicle's center of pressure measured from the nose tip is computed using

$$\boldsymbol{X = \frac{(C_N)_N X_N + (C_N)_F X_F}{(C_N)_N + (C_N)_F}} \tag{28}$$

where C_{NN} is the nose cone center of pressure coefficient (2 for conical nose cones). X_N is calculated using

$$\boldsymbol{X_N = \frac{2}{3} L_N} \tag{29}$$

where L_N is the nose cone's length. Variable C_{NF} of equation 14 is defined by the fin center of pressure coefficient calculated using

$$\boldsymbol{(C_N)_F = \left[1 + \frac{R}{S+R}\right] \left[\frac{4N\left(\frac{S}{d}\right)^2}{1 + \sqrt{1 + \left(\frac{2L_f}{C_R + C_T}\right)^2}}\right]} \tag{30}$$

where R is the cross-sectional radius of the vehicle body at the aft end, S is the fin semispan, N is the number of fins, L_F is the length of the fin mid-chord line, and C_T is the fin tip chord length. X_F is calculated using

$$\boldsymbol{X_F = X_B + \frac{X_R(C_R + 2C_T)}{3(C_R + C_T)} + \frac{1}{6}\left[(C_R + C_T) - \frac{(C_R C_T)}{(C_R + C_T)}\right]} \tag{31}$$

where X_B is the distance from the nose tip to the leading edge of the fin root chord, X_R is the distance between the fin root leading edge and the fin tip leading edge measured parallel to the vehicle body. Equations 14 through 17 are also known as the Barrowman Equations (The Theoretical Prediction of the Center of Pressure, 1966).

Note that Equation 14 makes use of a simplified form because the vehicle makes no transition in the body diameter, thus the transitional terms have been omitted. These equations are used to verify the OpenRocket simulation conducted of the full-scale launch vehicle.

4.3.3 OpenRocket Flight Simulations

4.3.3.1 OpenRocket Model

To simulate the flight of the vehicle as accurately as possible, the as built vehicle was modeled in the OpenRocket simulation software. The OpenRocket model of the as built full scale launch vehicle is shown in Figure 94.

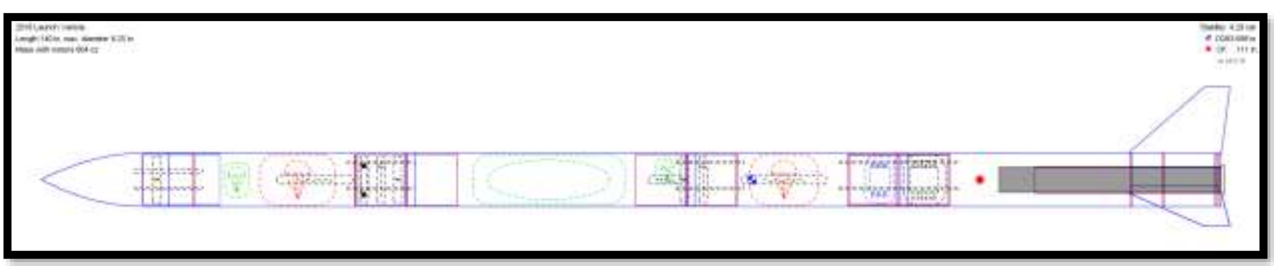


Figure 94: OpenRocket model of the as built launch vehicle.

4.3.3.2 Motor Thrust Simulation

The OpenRocket software includes hundreds of rocket motors' thrust curves used for conducting simulations. In the OpenRocket software's data sheets, it lists that the Aerotech L2200's thrust curve was acquired from the manufacturer, Aerotech Consumer Aerospace. The simulated motor thrust curve used in all simulations is shown in Figure 95.

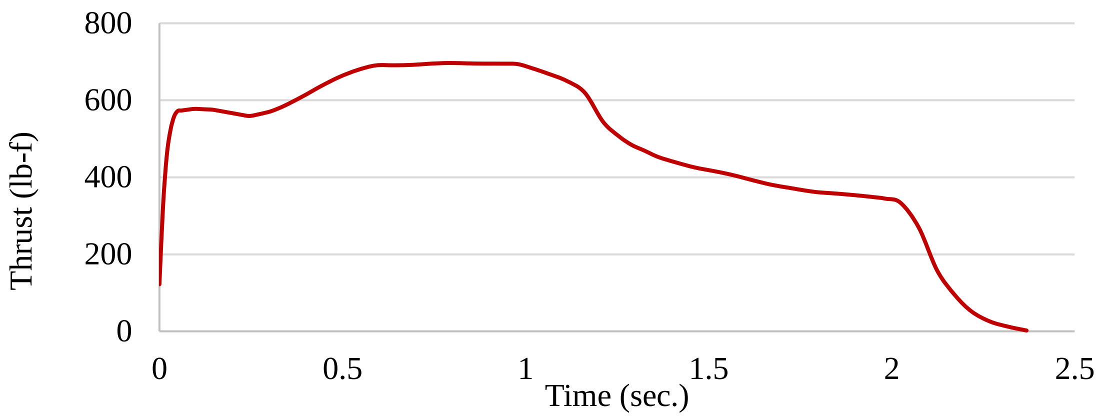


Figure 95: L2200 motor thrust curve used in OpenRocket simulations.

The maximum expected thrust produced by the motor is approximately 700lbs. To account for the possibility of a centering ring failure, each centering ring was designed to withstand a minimum load of 350 lbs., while maintaining a minimum factor of safety greater than 2.0. Finite Element Analysis (FEA) was performed on each centering ring using ANSYS to verify that they could support the loads generated during motor burn. The results of the FEA were further discussed in 4.1.3.5.1 and showed that the centering ring design would withstand the forces experienced during motor burn.

4.3.3.3 Component Masses

To accurately model the vehicle's center of gravity, each component's mass was measured using a high precision digital scale and entered into the OpenRocket model. The component masses for each independent section are shown below in Table 28 though Table 32.

Nose Cone Section			
Component	**Mass (lbs.)**	**Quantity**	**Total Mass**
9-Volt battery	0.05	1	0.05
Altimeter Sled	0.05	1	0.05
Nose Cone	1.1	1	1.1
Nose cone all thread	0.03	2	0.06
Nose cone coupler	1	1	1
Nose cone recovery U-bolt	0.065	1	0.065
Outer bulkplate	0.055	1	0.055
Stratologger	0.03	1	0.03
Inner bulkplates	0.05	1	0.05

AIM XTRA + sled	0.185	1	0.185
AIM XTRA battery	0.15	1	0.15
Total Mass (lbs.)			2.80

Table 28: Nose cone section component masses.

Payload Section			
Component	**Mass (lbs.)**	**Quantity**	**Total Mass**
Payload bay airframe	2.7	1	2.7
Payload recovery bay airframe	2.15	1	2.15
Payload recovery coupler all thread	0.1	2	0.2
Payload recovery coupler U-bolt	0.1	1	0.1
Outer bulkplates	0.1	2	0.2
Inner bulkplates	0.6	2	1.2
Payload coupler Nuts	0.008	2	0.016
Payload Drogue	0.2	1	0.2
Stratologger	0.03	2	0.06
Payload recovery coupler	1.15	1	1.15
ARRD	0.37	1	0.37
Altimeter Sled	0.11	1	0.11
GPS Receiver, Sled, Battery	0.183	1	0.1825
Payload Main	1.6	1	1.6
ROCS	3.467	1	3.967
RLM	1	1	1
DTS	0.139	1	0.139
RBS	0.988	1	0.988
RDS	1.136	1	1.636
OAS	0.063	1	0.063
SAS	0.498	1	0.498
SIS	0.044	1	0.044
CES	0.204	1	0.204
Total Mass (lbs.)			18.78

Table 29: Payload section component masses.

Lone Coupler			
Component	**Mass (lbs.)**	**Quantity**	**Total Mass**
Payload coupler	1.5	1	1.5
Payload coupler all thread	0.02	2	0.04
Payload coupler plate	0.04	1	0.04
Payload coupler Nuts	0.01	16	0.128
Payload coupler U-bolt	0.1	1	0.1
GPS Receiver, Sled, Battery	0.18	1	0.1825
Altimeter Sled	0.11	1	0.11
Stratologger	0.03	2	0.06

Total Mass (lbs.)	2.16

Table 30: Coupler section component masses.

Booster Section			
Component	**Mass (lbs.)**	**Quantity**	**Total Mass**
Booster airframe	2.6	1	2.6
Booster Recovery Equipment	1.7	1	1.7
Booster recovery bay airframe	1.8	1	1.8
Centering Ring	0.3	3	0.9
Epoxy	0.5	1	0.5
Fin	0.95	3	2.85
Fin Retainer	0.13	1	0.13
Inner bulkplates	0.05	2	0.1
Motor Retainer	0.1	1	0.1
Outer bulkplates	0.06	2	0.11
Aerotech L2200	10.6	1	10.6
Batteries	0.23	2	0.45
VDS blade	0.09	3	0.27
VDS bottom AL plate	0.11	1	0.1073
VDS coupler	1.15	1	1.15
VDS coupler all thread	0.05	3	0.15
VDS custom spacers	0	3	0.0105
VDS Delrin plate	0.17	2	0.34
VDS electronics	0.2	2	0.4
VDS limit switch	0	2	0.008
VDS middle wooden plate	0.05	1	0.05
VDS motor	0.76	1	0.7605
VDS Motor Shim	0.02	1	0.0185
VDS sled	0.3	1	0.3
VDS sled lid	0.05	1	0.05
VDS top AL plate	0.1	1	0.1
Shoulder Bolt large	0.02	3	0.06
Shoulder Bolt small	0.02	3	0.045
Telemetry electronics	0.2	1	0.2
Camera	0.5	1	0.5
Nuts	0.01	18	0.18
Total Mass (lbs.)			26.54

Table 31: Booster section component masses.

The launch vehicle's overall wet mass is shown in Table 32.

Total Vehicle	
Section	**Mass (lbs.)**
Nose Cone	2.8

Lone Coupler	2.2
Payload Section	17.8
Booster Section	26.5
Total Vehicle Mass (lbs.)	**49.3**

Table 32: Total launch vehicle mass.

4.3.3.4 Simulation Results

Flight simulations have been conducted using the OpenRocket software to predict the flight of the as built launch vehicle with an inactive VDS. All simulations, unless stated otherwise, were conducted with a wind speed of 10mph, under international standard atmospheric conditions, and launching from a 12 ft. rail in Toney, AL, at an elevation of 251 meters above sea level. Simulated apogee altitudes achieved by the as built launch vehicle in varying wind speeds are shown below in Table 33.

Wind Speed (mph)	Apogee Altitude (ft.)
0	5,392
5	5,385
10	5,363
15	5,336
20	5,298

Table 33: Simulated apogee altitudes of the as built at varying wind speeds

The plots in Figure 96 through Figure 99 show various simulation results indicating proper vehicle design and motor hardware.

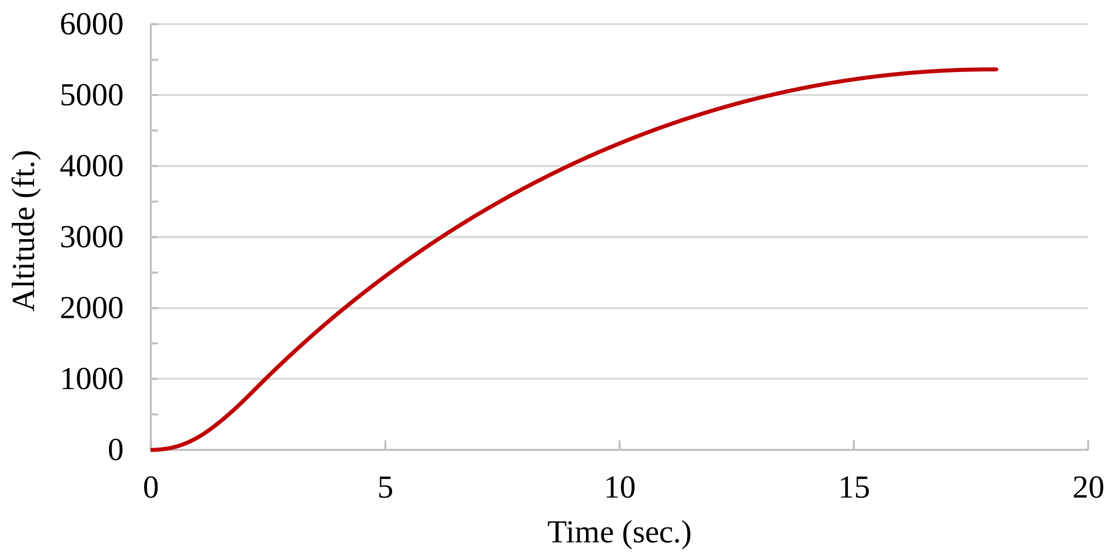


Figure 96: Altitude versus time plot of the as built vehicle during flight.

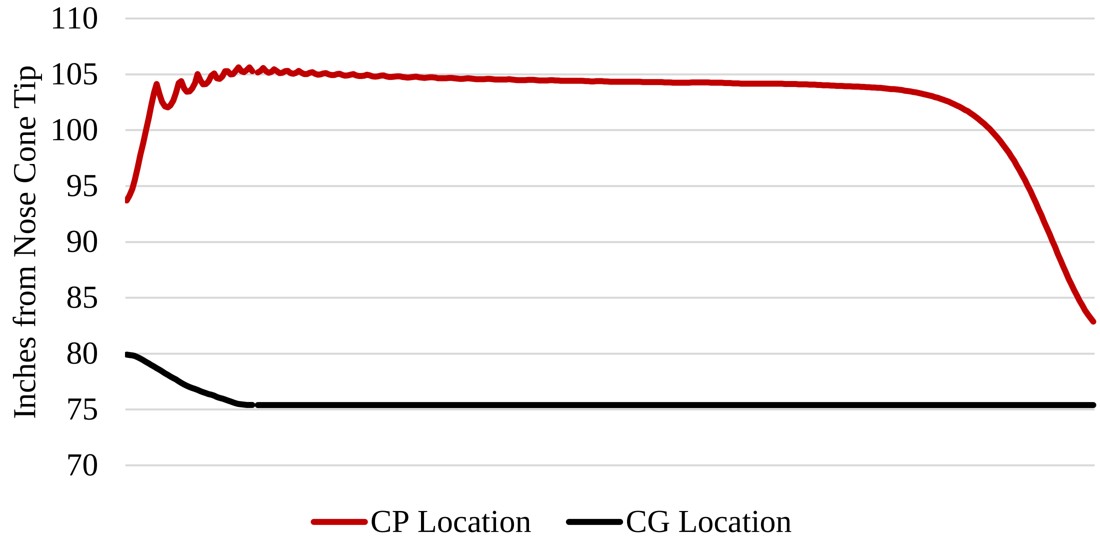


Figure 97: CP and CG location of the as built launch vehicle over time.

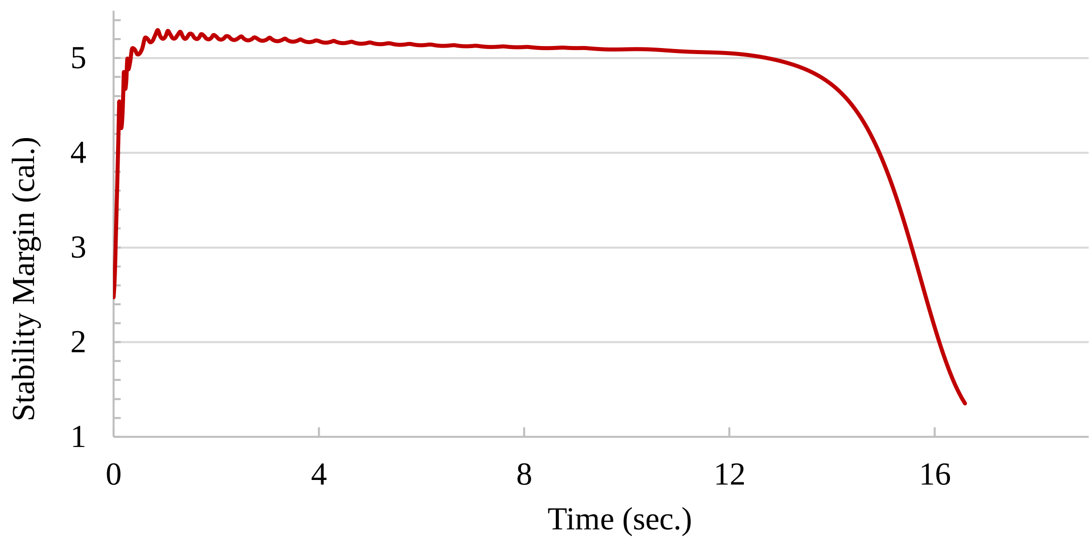


Figure 98: Stabiliy margin of the as built launch vehicle over time.

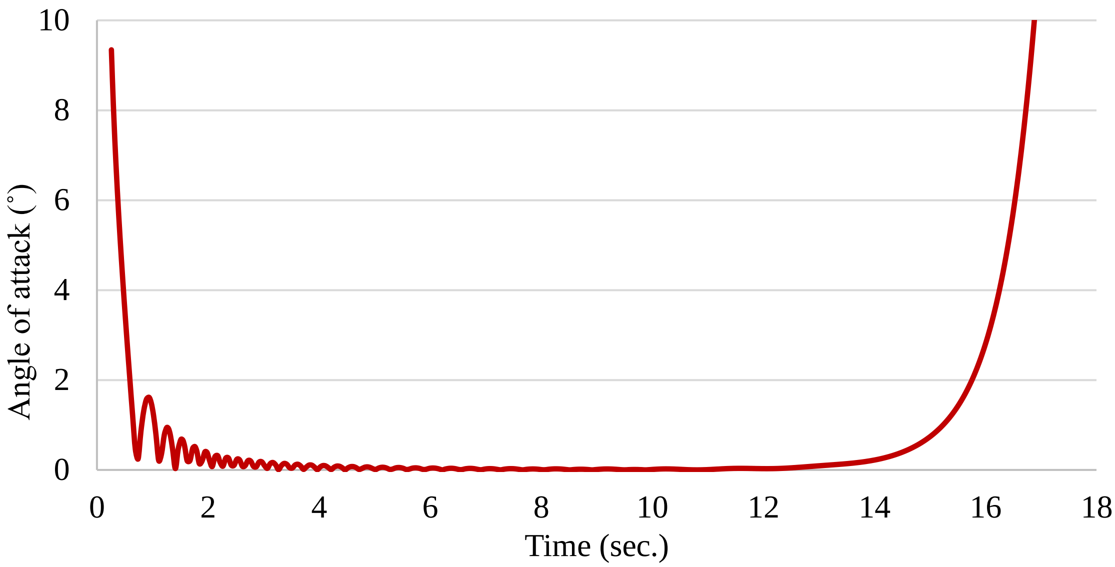


Figure 99: Angle of attack versus time.

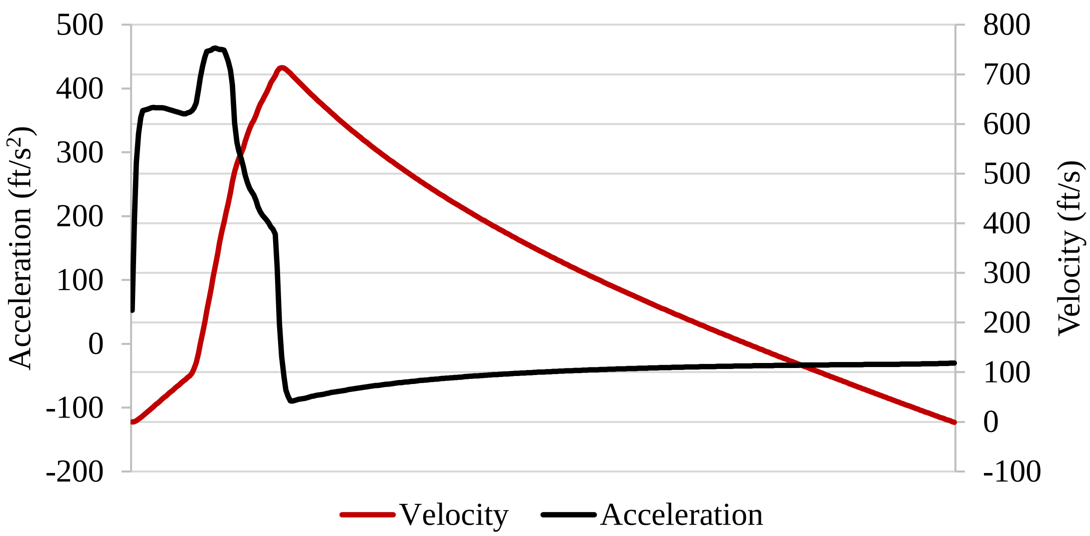


Figure 100: Predicted velocity and acceleration of the as built vehicle during flight.

1.2.1.1. *Flight Characteristics*

Using a combination of the equations discussed in 4.3.2 and the OpenRocket software, several flight related characteristics of the launch vehicle were calculated. Critical flight characteristics of the as built vehicle are shown in Table 34.

Exit Rail Velocity from a 144-inch rail (ft./s)	91.6
Center of Gravity Location at Rail Exit (in. from nose cone tip)	83.0

Center of Pressure Location at Rail Exit (in. from nose cone tip)	98.5
Stability Margin at Rail Exit (cal.)	2.48
Maximum Acceleration (ft./s^2)	428
Maximum Velocity (ft./s)	664
Maximum Thrust to Weight Ratio	13.9
Predicted apogee in 10mph wind (ft.)	5,363
Time to Apogee (sec.)	18

Table 34: Flight characteriscs of the as built launch vehicle.

4.3.3.5 VDS Simulation

To simulate the VDS actuation protocol for the 2017-2018 Launch Vehicle, a rocket simulated environment was built within Matlab Simulink. The goal of this simulation was to observe the effects of the VDS algorithm utilized to reach a desired apogee of 5,280 [ft].

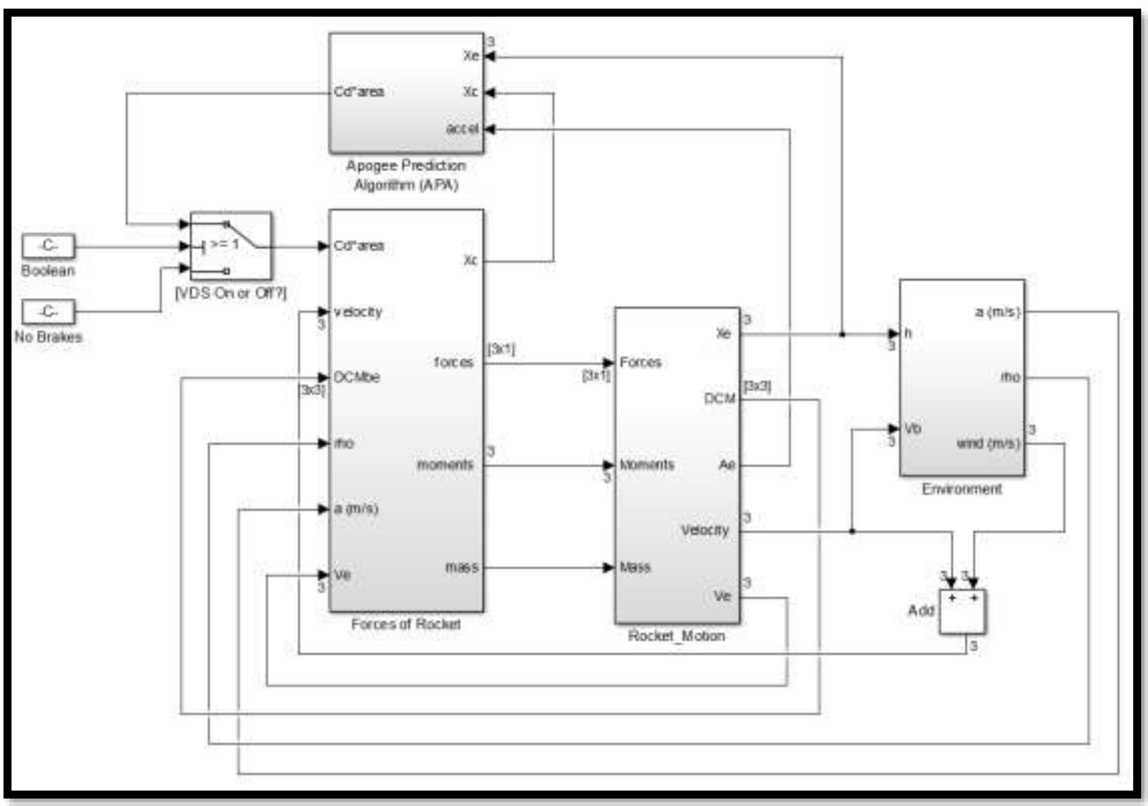


Figure 101: VDS simulation blocks.

The simulated environment was designed by utilizing the OpenRocket equation processes and Matlab Simulink block systems. The VDS flight simulation was constructed from the following steps:

1. Compute the effect of motor thrust and gravity.
2. Initialize the rocket in a known position and orientation at time t = 0.
3. Compute the aerodynamic forces and moments affecting the rocket.
4. Compute the current airspeed, angle of attack, lateral wind direction and other flight parameters.
5. Compute the local wind velocity and other atmospheric conditions.
6. Compute the moments of inertia of the rocket and from these the linear and rotational characteristics of the rocket.
7. Compute the predicted apogee of the rocket and actuate the blades of the rocket if the predicted apogee is higher than 5,280 [ft.].
8. Reiterate processes 1-6 and update the current time $t \rightarrow t_{-1} + \Delta t$

The VDS simulation contained the following parameters of the launch vehicle:

Simulation Parameters	
Dry Mass	19.78 [kg]
Wet Mass	22.30 [kg]
Coefficient of Drag (No Brakes)	0.59
Coefficient of Drag (With Brakes)	0.63
Diameter	0.159 [m]
Reference Area (No Brakes)	0.0195 [m^2]
Reference Area (With Brakes)	0.0260 [m^2]
Dry Center of Gravity (measured from nosecone)	1.9125 [m]
Wet Center of Gravity (measured from nosecone)	2.0426 [m]
Longitudinal Moment of Inertia (about CG, dry)	12.71 [$kg*m^2$]
Longitudinal Moment of Inertia (about CG, wet)	14.72 [$kg*m^2$]
Average Wind Speed	10.0 [mph]

Figure 102: VDS simulation parameters.

Additionally, a thrust curve of the Aerotech L2200 motor was imported into the simulation.

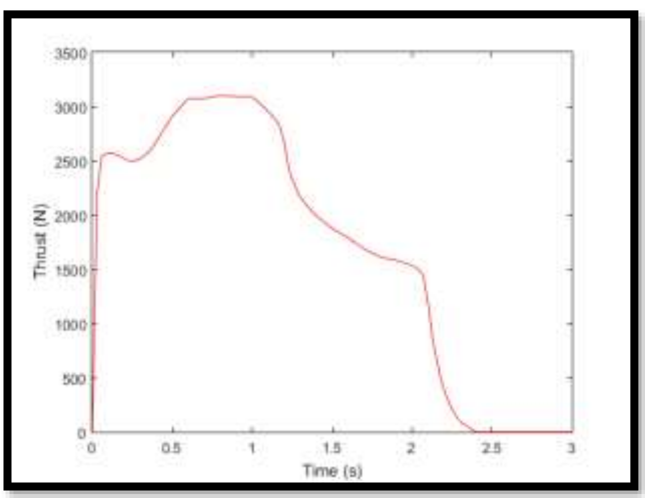


Figure 103: Aerotech L2200 simulated motor thrust cuve.

The plots in Figure 104 display the comparison of launch results of the OpenRocket and the non-actuating VDS Simulations.

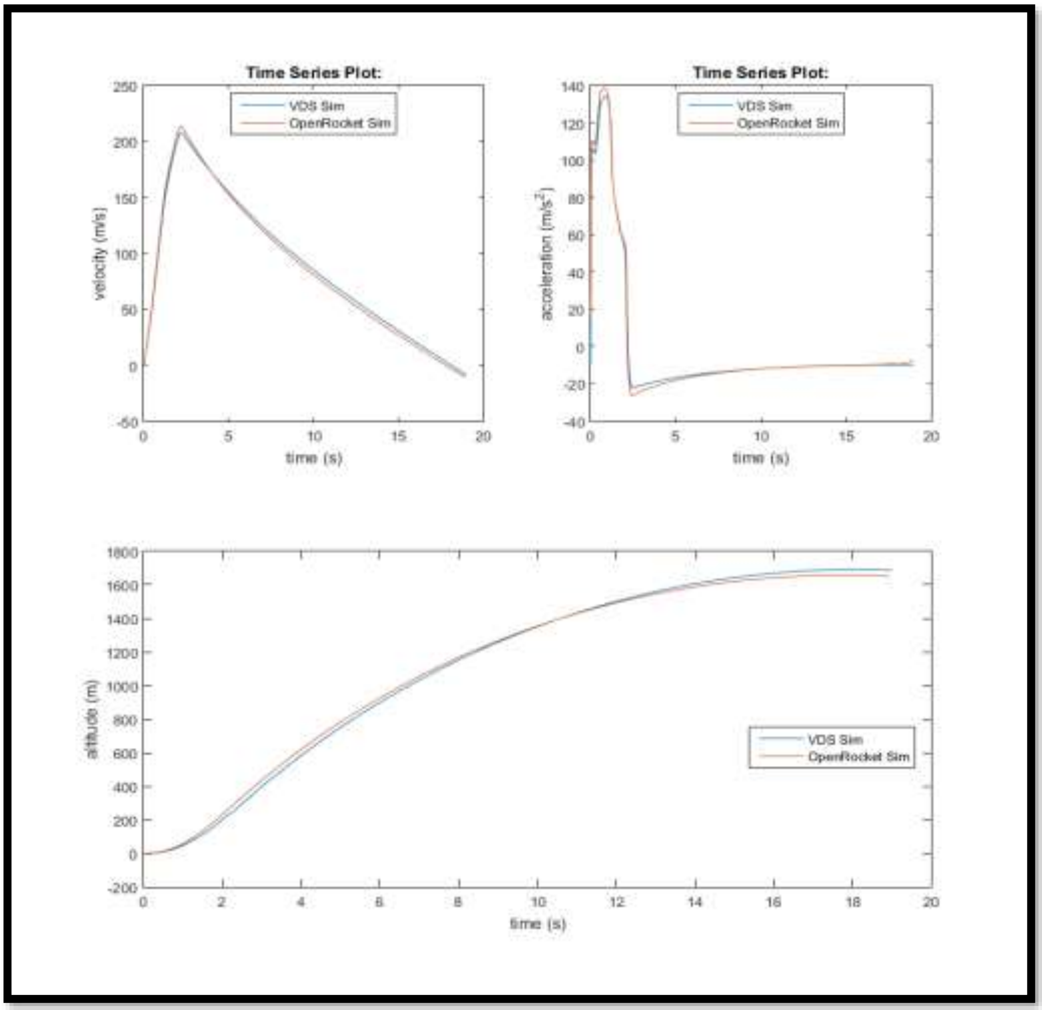


Figure 104: Flight simulation results of OpenRocket and Simulink models.

To reach the altitude of 5,280 [ft], the simulation used the following equation to determine the coast altitude:

$$X_c = \frac{\mathrm{m}}{\rho \mathrm{C_d A}} \ln\left(\frac{mg + {}^{1}/_{2}\, \rho C_d A V_e^2}{mg}\right)$$

where m is the rocket mass, ρ is the air density, $\mathrm{C_d}$ is the coefficient of drag, A is the reference area, g is gravity, and V_e is the velocity relative to Earth. The predicted apogee was found by summing the coast distance and current altitude.

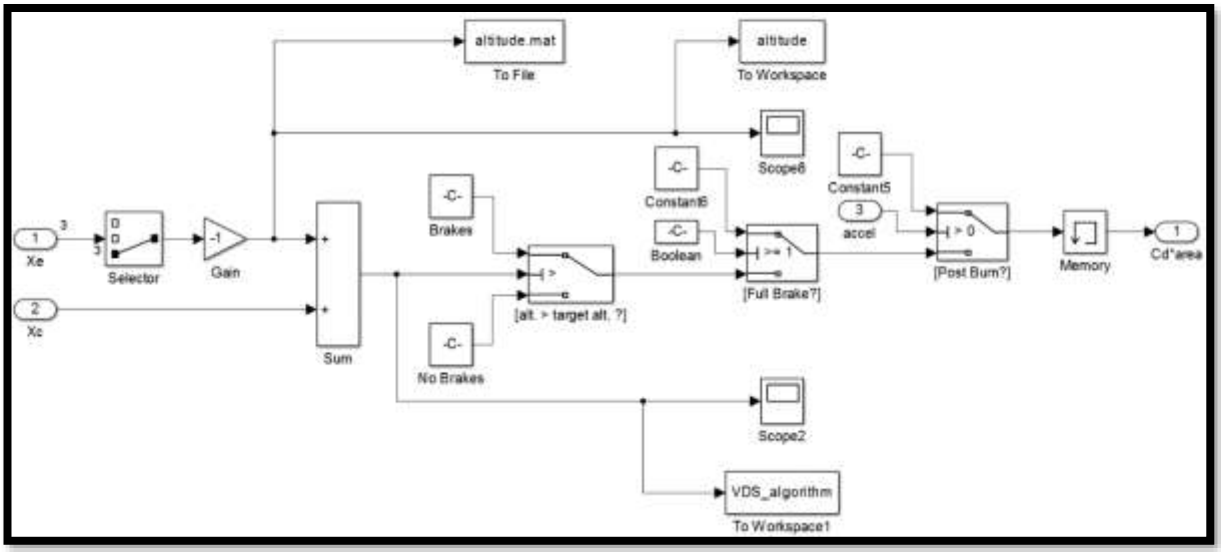


Figure 105: VDS actuation algorithm.

The predicted apogee was fed through the following series of nested statements to determine whether actuation was to be performed. Through these statements, the VDS responds accordingly to the user prompted situation.

1. Is the predicted apogee greater than the targeted altitude?
2. Is the VDS in full brake mode?
3. Has the motor burn phase ended?
4. Is the VDS in actuation mode?

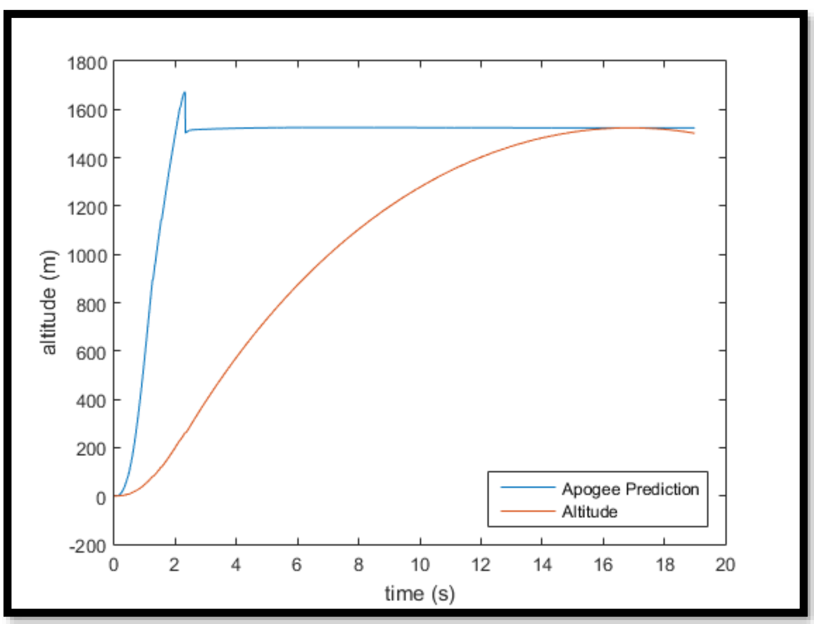


Figure 106: VDS apogee prediction and the flight altitude with full brake actuation.

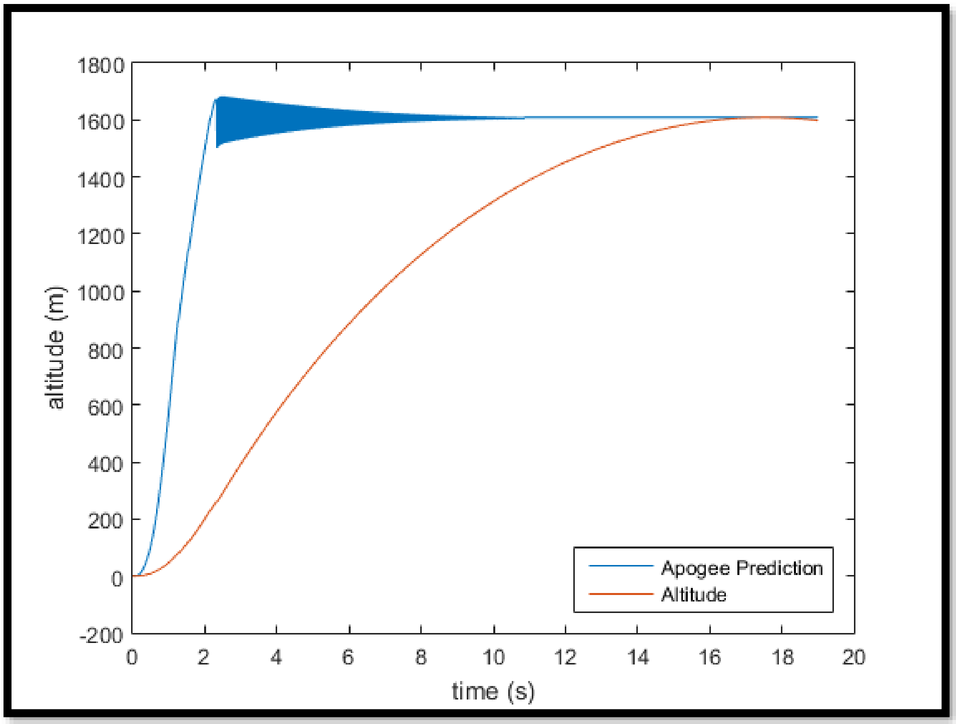


Figure 107: VDS apogee prediction, and flight altuitude with active VDS actuation.

OpenRocket Simulation Apogee Altitude [ft]	VDS Simulation (No Actuation) Apogee Altitude [ft]	VDS Simulation (Full Brakes) Apogee Altitude [ft]	VDS Simulation (Actuation) Apogee Altitude [ft]
5,437	5,549	4,977	5,276.6

Figure 108: Flight simulation apogee results.

OpenRocket produced an apogee of 5,437 [ft] with 10 mph wind conditions. The VDS simulation without brakes produced an apogee of 5,549 [ft] with 10 mph wind conditions, a resultant error of 112 [ft.] or 2.06% from OpenRocket's predicted apogee. The simulated VDS full brakes produced an apogee of 4,977 [ft], verifying that the blades increase the coefficient of drag and area enough to slow the vehicle to 5,280 [ft]. The simulated VDS actuation produced an apogee of 5,276 [ft], an error of 3.4 [ft] or 0.06% of the desired apogee, verifying the apogee prediction algorithm used to actuate the VDS blades.

4.3.4 Center of Pressure Analysis

The center of pressure of the launch vehicle discussed in section *1.2.1.1* is the launch vehicle's center of pressure at rail exit. SolidWorks Flow Simulation was used to verify the accuracy of the center of pressure location determined using OpenRocket. The center of pressure at launch rail exit must be known to ensure that the vehicle begins its ascent with an adequate stability margin. The CFD simulation was configured under the parameters presented in Table 35.

Parameter	Value
Airflow Velocity in Axial (Z) Direction (ft/s)	95

Airflow Velocity in Radial (Y) Direction (ft/s)	14.67
Angle of Attack (degrees)	0
Static Pressure (lbf/ft^2)	2116.217
Fluid Temperature (°F)	68.09

Table 35: SolidWorks Flow Simulations CFD Parameters for Center of Pressure Analysis.

The location of the center of pressure was measured from the tip of the launch vehicle's nose cone. A local coordinate system was established in the CFD simulation at the aft end of the launch vehicle. The coordinate system is shown in Figure 109.

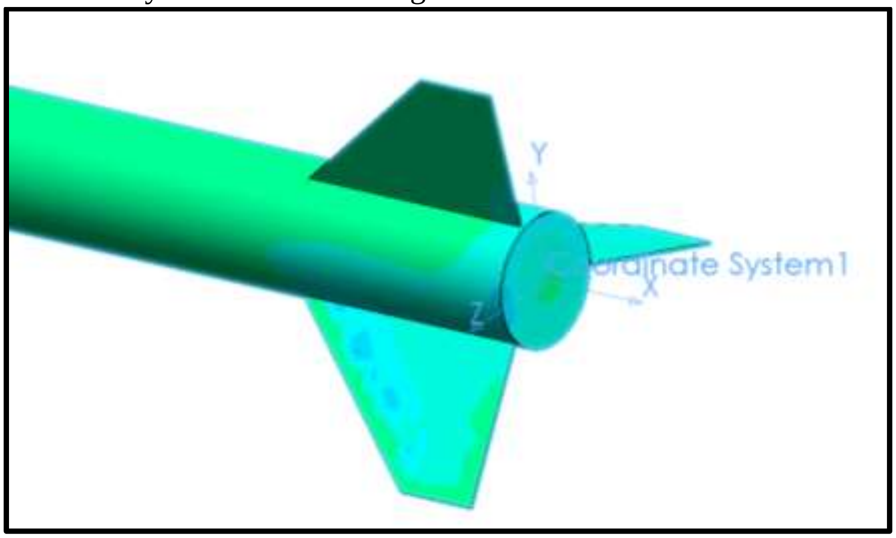


Figure 109: CFD simulation local coordinate system.

A global goal was established to determine the force in the Z direction of the local coordinate system, and the torque in the Y direction of the local coordinate system. The center of pressure was determined by dividing the torque in the Y direction by the force in the Z direction. The surface pressure plot resulting from the CFD simulation are shown below in Figure 110.

Figure 110: CFD simulation surface pressure plot.

The simulation converged to a solution after 90 iterations. The results of the simulation are compared to the center of pressure determined using OpenRocket in Table 36.

Center of Pressure Location at Rail Exit Measured from Nose Cone Tip		
CFD Simulation CP (in.)	OpenRocket Simulation CP (in.)	Percent Difference (%)

89.28	92.26	3.28

Table 36: CFD simulation and OpenRocket Center of Pressure Analysis Results Comparison.

The center of pressure obtained using OpenRocket simulation software resulted in a higher stability margin higher than the value obtained using SolidWorks Flow Simulation for CFD. The results obtained using SolidWorks Flow Simulation were less consistent than those obtained using OpenRocket, and therefore were only used to verify the value obtained using OpenRocket.

4.4 Full Scale Flight Tests

4.4.1 Launch Day Conditions

The first full-scale test flight was conducted in Talladega, Alabama. Simulations of the flight trajectory for the full-scale vehicle were created using the meteorological data gathered before the launch. The launch day conditions on February 17th were gathered by an AcuRite 01604 weather station that collected windspeed, temperature, air pressure, and air density. The launch day conditions of the March 3rd launch were recorded by a La Crosse Technology EA-3010U Anemometer. This data is presented in **Error! Reference source not found.**.

Property	February 17th in Talladega, Al	March 3rd in Elsburry, Mo
Average Wind Speed (mph)	10	13
Wind Speed at Launch (mph)	9	9
Wind Direction	North East	South East
Temperature (F°)	72	60
Pressure at Ground Level (inHg)	29.9	30.2

Table 37: Launch day conditions for the full-scale launch vehicle.

4.4.2 February 17th Flight

For the first test launch, neither VDS nor the payload were launched in their final configurations. The VDS drag blades were inactive and were stowed within the airframe to allow for the collecting of vehicle acceleration data without additional VDS drag. Payload launched without its rover, however the ROCS system was integrated to test its performance. A dummy rover body and a steel bar were used to simulate the mass of the rover.

4.4.2.1 Flight Analysis

For the February 17th full-scale launch, very little launch vehicle data could be collected due to the Aerotech L2200 motor suffering a CATO. Recovery and analysis of surviving parts concluded that the forward motor enclosure ruptured and the motor began to expel hot gases from both ends. This resulted in a low apogee of 1,835ft. AGL and critical damage to booster section components. An altitude vs time plot from the StratologgerCF is shown below in Figure 111.

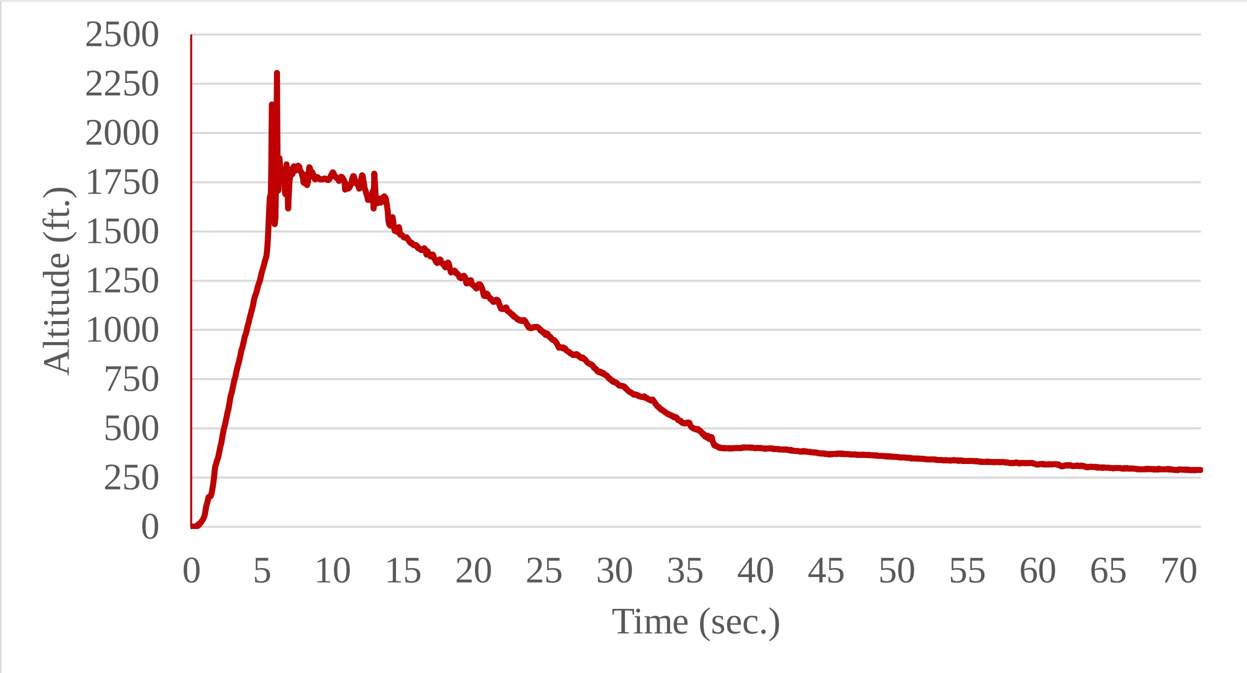


Figure 111: February 17th altitude vs. time.

At two seconds after ignition, flames could be observed exiting the three VDS slots. Because of the design of the booster section, the flames also swept downward, past the centering rings and fin mounting points. Near apogee, flames were seen violently sputtering from the VDS blade slots and the end of the booster. A photo of the launch vehicle shortly after ignition is shown below in Figure 112.

Figure 112: Launch vehicle during CATO.

At apogee, a plume of black smoke is observed before the launch vehicle violently flips. The vehicle unexpectedly separates at apogee and booster main parachute deploys. The heat from the motor burning within the booster sections likely melted the epoxy retaining the motor mount tube. This, along with the resulting opening forces freed the motor and fin assembly from the booster as shown in Figure 113. Soon afterwards, drogue parachutes deployed and recovery of all sections aside from booster performed as planned.

Figure 113: Launch vehicle separating at apogee.

At about 800ft. AGL, the still burning booster section burns through its own shock cord. It then falls without p arachute until landing next to a field. A photo of the booster descending without parachute is shown below in Figure 114.

Figure 114: Booster section in freefall after the shock chord burned.

All other sections were recovered successfully and without damage. The booster section fire fused the epoxy of rocket sections together and the fall destroyed the lower half of the section. The fins and motor assembly which had ejected at 1,835ft. AGL had significant damage as the carbon fiber motor casing and the mounting points of the carbon fiber fins were irreparably delaminated by the motor's fire.

4.4.3 March 3rd Flight

A full-scale test flight was performed on March 3rd to verify the performance and competition-readiness of vehicle, recovery, VDS, and payload subsystems because of the CATO two weeks prior. This test launch was the second of the test campaign.

For the launch, VDS was to deploy its blades after burnout and retract them at apogee to verify the overall operation of the VDS and to gather data. Payload was launched with all systems operational and was planned to perform in competition conditions.

4.4.3.1 Flight Analysis

Upon ignition of the motor, the launch vehicle exited the launch rail stably and ascended to apogee without incident. Photos showing the launch vehicle ascending are shown below in Figure 115 and Figure 116.

Figure 115: Launch vehicle exiting the rail stably.

Figure 116: Launch vehicle ascending after motor burnout.

The vehicle experienced minimal spinning, and no fin flutter, thus demonstrating accurate manufacturing methods and adequate material selection for the fin design. Upon reaching apogee, the launch vehicle failed to separate and entered a ballistic state as shown in Figure 117.

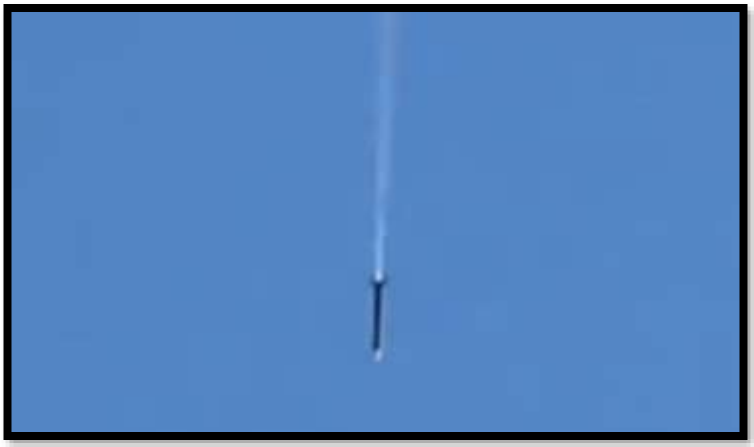


Figure 117: Launch vehicle in a ballistic state.

At approximately 500ft. AGL, the booster main separation charge ignited and the vehicle separated into two sections at approximately 435 ft/s. The separation, showing the booster main parachute, booster, and payload section, is shown below in Figure 118.

Figure 118: Launch vehicle separting at 500ft. AGL.

Due to the extremely high velocity at main parachute deployment, the shock chord zippered through the airframe and the parachute shroud lines failed. This resulted in the launch vehicle impacting the ground at over 400ft/s. The launch vehicle experienced enough damage to be considered a total loss, with only the fins, and motor hardware surviving. Photos showing the damage are shown below in Figure 119 and Figure 120.

Figure 119: Damage to the payload bay. **Figure 120: Damage to the booster section.**

4.4.3.2 Failure Analysis

Upon the failure to separate, the team attempted to determine the issue that caused the vehicle not to separate at apogee. After looking in the payload recovery bay, one of the ejection charges successfully ignited while the redundant one failed to. As shown in Figure 121, the charge that failed to ignite had become disconnected from the terminal block.

Figure 121: Unignited redundant ejection charge.

Despite this, the first charge that did ignite should have been sufficient to eject the nose cone from the recovery bay and deploy the drogue. After conducting ejection tests the night prior to launching, it was evident that the charge size was adequate to eject the nose cone and payload bay, as shown in Figure 122 and Figure 123.

Figure 122: Successful nose cone separation test.

Figure 123: Successful payload bay separation test.

However, on two occasions after the vehicle had landed, it was heard by team members, and recorded on video, that ejection charges were igniting on the ground. The video file's audio was analyzed, and the ejection charge can be seen on the audio waveform 34 seconds after landing, as shown below in Figure 124.

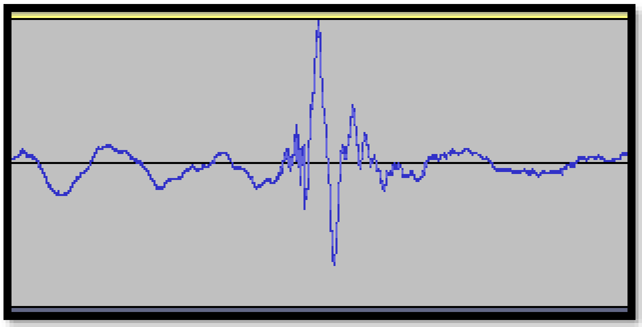


Figure 124: Waveform spike of ejection charge detonating 34 seconds after landing.

A second charge ignition can be heard on the video audio but does not significantly show up on the audio waveform. This demonstrates that the likely cause of the separation failure was faulty StratoLogger altimeters, as the ejection charges did not ignite at apogee but rather after landing. To prevent this in future test flights, only new, unused StratoLoggers will be used, and each with be pressure tested prior to flight.

4.4.3.3 Flight Data Analysis

All data collecting devices besides the Stratologger altimeters were damaged to the point that no data was able to be collected. The three cameras on board the launch vehicle, one of which was to record the VDS blades actuating, were damaged and no video was able to be recovered. Due to all data being destroyed, and no photos that clearly demonstrate that the VDS blades actuated during the flight, we cannot determine if the blades actuated or not. The Stratologger data was able to be recovered and is compared to an OpenRocket simulation below in Table 38.

OpenRocket Simulated Apogee (ft.)	5,421
Stratologger Recorded Apogee (ft.)	5,114

Table 38: Stratologger data compated to OpenRocket simulation apogee.

The Stratologger data shows an apogee altitude of 5,114 ft. This apogee altitude is lower than the simulated altitude, but not by the expected amount if the VDS blades were to be actuated for the flight. It is also unknown as to what the surface finish of the vehicle is, which can drastically affect the apogee of the vehicle. The Stratologger data versus time plot is shown below in Figure 125.

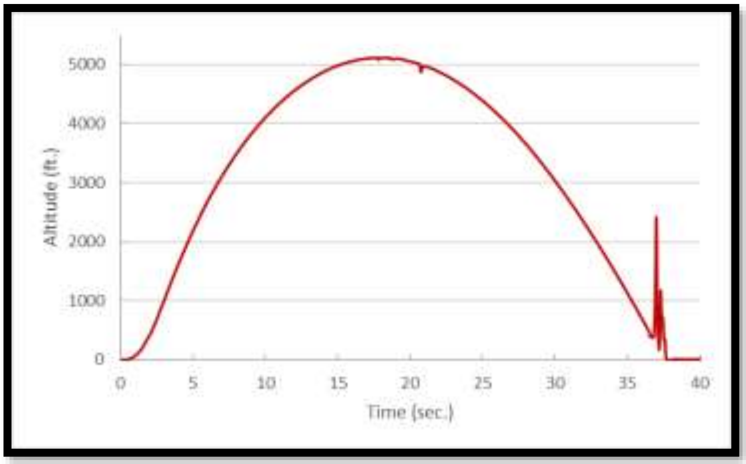


Figure 125: Stratologger Altitude Vs. Time Graph

4.4.3.4 Coefficient of Drag Estimation

When the launch vehicle entered a ballistic state during its descent, it reached a terminal velocity of approximately 488 ft/s based on first derivative approximations from altitude vs. time data found with the Stratologger. Using this value and then back calculating and solving for the total coefficient of drag of the launch vehicle, taking account of skin shear stress induced frictional drag cross sectional drag:

$$\mathbf{C_D = .815} \tag{32}$$

Frictional drag can be calculated by assuming turbulent (High Reynolds number) air flow over the launch vehicle body, which allows us to use Prandti's One-Seventh-Power law:

$$\mathbf{C_f = \frac{.027}{Re_x{}^{1/7}}} \tag{33}$$

Using the total surface area of the three fins plus the launch vehicle tube and nosecone, skin friction force can be calculated using the following:

$$\mathbf{F_s = \int C_f \frac{\rho v^2}{2} dA} \tag{34}$$

Using Newton's second law under free-fall conditions ($\Sigma F = 0$) and balancing the three forces; cross sectional drag, frictional drag and gravitational force, it becomes a trivial matter to calculate the total coefficient of drag for the launch vehicle. (Stated above in **(32)**

5 Payload Design

5.1 Overview

The deployable rover challenge was selected for this year's experimental payload. An orientation correction system utilizing custom made bearings will ensure proper orientation of the rover at landing. The rover will be remotely deployed after landing by a team member after RSO permission to proceed has been granted. The rover will be made to resemble a military tank with a tread style drive system capable of driving the rover a minimum of five feet from the launch vehicle. A custom designed foldable solar array will be autonomously deployed to conclude the payload's primary mission. The final design of the payload in its fully stowed, flight ready configuration and fully deployed, mission complete configuration is shown below in Figure 126.

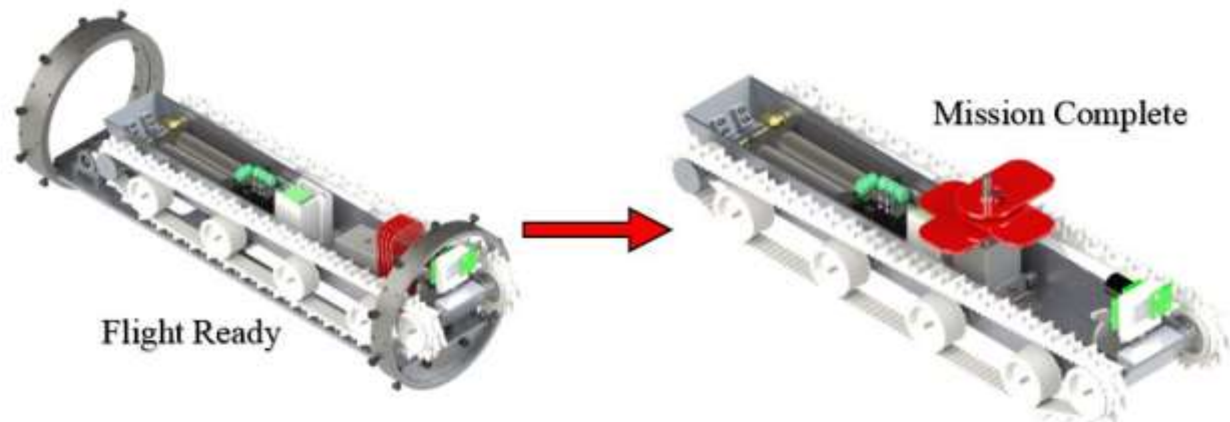


Figure 126: Final Payload design stowed and deployed.

5.1.1 System Overview

The payload has been divided into nine subsystems for division of labor to ensure that the payload be able to successfully achieve all requirements set forth in the NASA Statement of Work and all team derived requirements. These subsystems are listed and briefly described below in Table 39.

Payload Subsystem	Subsystem Overview
Rover Orientation Correction Systems (ROCS)	The ROCS will be responsible for ensuring upright orientation upon landing prior to deployment of the rover.
Rover Locking Mechanism (RLM)	The RLM will be responsible for retaining the rover in the launch vehicle for the entirety of the flight and releasing the rover at the time of deployment.
Deployment Trigger System (DTS)	The DTS will be responsible for sending the deployment signal to the rover upon receiving approval to proceed from the RSO.
Rover Body Structure (RBS)	The RBS will be responsible for providing structural support for the rover and assist in retaining the rover in the launch vehicle during flight.

Rover Drive System (RDS)	The RDS will be responsible for advancing the rover five feet away from the launch vehicle.
Obstacle Avoidance System (OAS)	The OAS will be responsible for the recognition of objects in front of the rover that may hinder forward motion.
Solar Array System (SAS)	The SAS will be responsible for supporting and deploying the foldable solar panels.
Surface Imaging System (SIS)	The SIS will be responsible for collecting image data of the rover and ground area surrounding the payload after deployment of the SAS.
Control Electronics System (CES)	The CES will be responsible for the control scheme that will govern operation of all electronic components of the payload.

Table 39: Payload subsystems.

5.1.2 Dimensional Overview

The Rover Orientation Correction System, Rover Locking Mechanism, and Deployment Trigger System will remain fixed in the launch vehicle airframe after deployment of the rover and as such, dimensions of the ROCS and RLM will be discussed separate from the other subsystems which will be referred to as the rover for simplicity. The final dimensions and weights of the payload are listed below in Table 40.

ROCS/RLM	
Dimension	**Value**
Diameter	6.000 in.
Length	17.9 x 6.000 in.
Weight	4.495 lbs.
Rover	
Dimension	**Value**
Stowed Length x Width	16.82 x 4.73 x 3.73 in.
Deployed Length x Width	16.82 x 4.73 x 4.05 in.
Weight	3.20 lbs.
Payload	
Total Weight	7.695 lbs.

Table 40: Final dimensions and weights.

5.1.3 Mission Overview

The mission of the payload is outlined below in Table 41.

Mission Step	**Mission Step Description**
1	The payload will be integrated into the launch vehicle ready for flight.
2	The launch vehicle will carry the payload to the intended apogee and begin recovery events.

3	Upon landing, the ROCS will allow the rover to rotate independently from the airframe allowing it to settle with the rover upright inside the airframe.
4	A unique deployment signal will be sent to the rover after gaining RSO permission to proceed.
5	The rover will perform an orientation check using two high precision gyroscopes.
6	The RLM will release the rover allowing it to begin advancing forward and exit the airframe.
7	The rover will begin to autonomously drive forward to reach a linear distance of at least five feet from the launch vehicle.
8	While driving, the OAS will detect insurmountable objects in the direct path of the rover and indicate to the CES that the rover should be turned to avoid the obstacle.
9	After reaching at least five feet from the launch vehicle, the rover will stop moving and deploy the SAS concluding the payload's primary mission.
10	The rover will use the energy harvested by the solar array to trigger the SIS to begin taking pictures of the rover and its surroundings.
11	Pictures will continue to be taken until the payload is retrieved and powered down.

Table 41: Payload mission overview.

5.2 Rover Orientation Correction System (ROCS)

5.2.1 Subsystem Overview

The Rover Orientation Correction System (ROCS) is responsible for ensuring that the rover is upright prior to deployment regardless of the recovery orientation of the payload bay of the launch vehicle. The ROCS has been broken into three main subassemblies that provide a means of integration with the airframe of the launch vehicle and supporting the rover during flight. The three subassemblies and their function are described below in Table 42.

ROCS Subassembly	Subassembly Function
Aft-End Thrust Bearing (AETB)	To absorb critical forces (without yielding) applied during motor burn, airframe separation, airframe landing, allow free rotation of the payload along its central axis, and support AFT end of BSS
Fwd-End Support Bearing (FESB)	To support FWD end of BSS and allow free rotation of the payload along its central axis
Bridging Sled System (BSS)	To support payload for entirety of vehicle flight, to bridge AETB and FESB, and to prevent rover translation along radial axis of airframe

Table 42: ROCS subassemblies and function.

The fully manufactured ROCS and model is shown in Figure 127.

Figure 127: Fully manufactured ROCS and model

5.2.2 AFT End Thrust Bearing (AETB)

The primary purpose of the AETB is to support and allow free rotation of the payload, while remaining structurally sound under applied loads experienced during vehicle flight. An exploded view of the fully manufactured AETB is displayed in Figure 128 and a model section view in Figure 129.

Figure 128: Fully manufactured AETB

Figure 129: Section view of AETB.

5.2.2.1 AFT End Thrust Bearing: Manufacturing process and as built drawings of non-purchased components

5.2.2.1.1 Outer Ring

Oversized 6 in. round stock was placed into vertical milling center and roughed to a depth of .01 in. past groove face and +.01 in. from nominal ID using a ⅝ square endmill. The groove was then machined to nominal dimensions using a .065 key cutter. After the groove was machined, all final machining to nominal dimensions at associated depth was performed. The process was repeated until all internal grooves were machined. At raceway depth, an ⅛ ball endmill was used to machine the ball bearing raceway. Once all outer ring features were machined, the outer ring was placed into a manual lathe and parted off from excess stock. The outer ring was then placed onto a CNC horizontal grinder and ground to nominal thickness. Following the grinding process and demagnetization, the outer ring was bolted onto radial drilling fixture and placed into the milling center where the airframe 10-24 fastening holes and ⅛ retention dowel holes were drilled and tapped/reamed respectively. To complete the manufacturing process, the outer ring was demagnetized, deburred, and polished.

An as built drawing of the AETB outer ring is displayed in Figure 130.

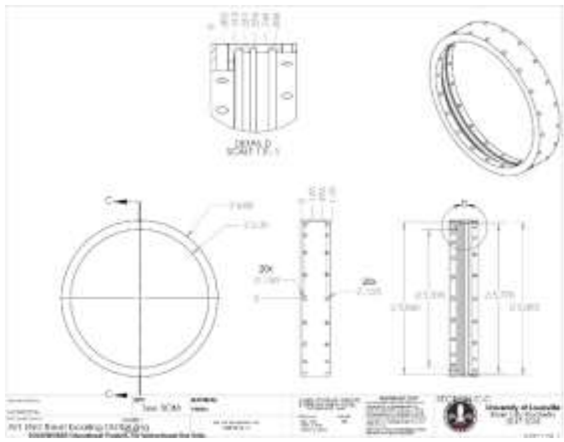


Figure 130: AETB outer ring as built drawing

5.2.2.1.2 Primary Inner Ring

Oversized 6 in. round stock was placed into vertical milling center and machined to nominal dimensions using a ½ square endmill. Next the raceway was machined using an ⅛ ball endmill. The 10-24 fastening holes and 3/16 alignment holes for the crescent mounting bracket were then drilled and tapped/reamed respectively into the primary inner ring raceway face. Once all primary inner ring features were machined, the primary inner ring was place into a horizontal band saw and sawed off from excess stock. The primary inner ring was then placed onto a CNC horizontal grinder and ground to nominal thickness. To complete the manufacturing process, the primary inner ring was demagnetized, deburred, and polished.

5.2.2.1.3 Secondary Inner Ring

Oversized 6 in. round stock was placed into vertical milling center and machined to nominal dimensions using a ½ square endmill. Next the raceway was machined using an ⅛ ball endmill. Once all secondary inner ring features were machined, the secondary inner ring was placed into a manual lathe and parted off from excess stock. The secondary inner ring was then placed onto a CNC horizontal grinder and ground to nominal thickness. Following the grinding process and demagnetization, the secondary inner ring was bolted onto radial drilling fixture and placed into the milling center where the ⅛ retention dowel holes were drilled and reamed. To complete the manufacturing process, the secondary inner ring was demagnetized, deburred, and polished.

An as built drawing of the AETB secondary inner ring is displayed in Figure 131.

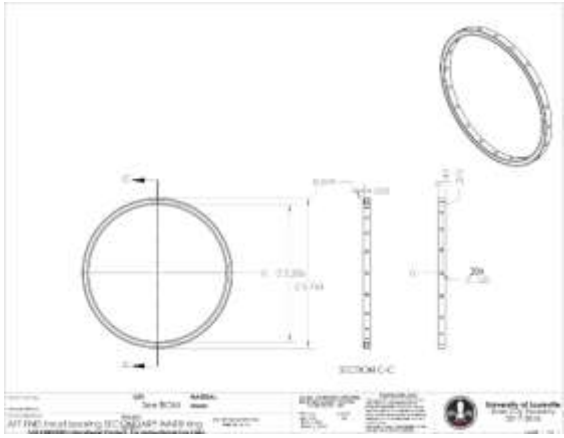


Figure 131: AETB secondary inner ring as built drawing

5.2.2.1.4 Ball Bearing Retention Ring

The ball bearing retention ring was printed using a 3D printer.

An as built drawing of the ball bearing retention ring is displayed in Figure 132.

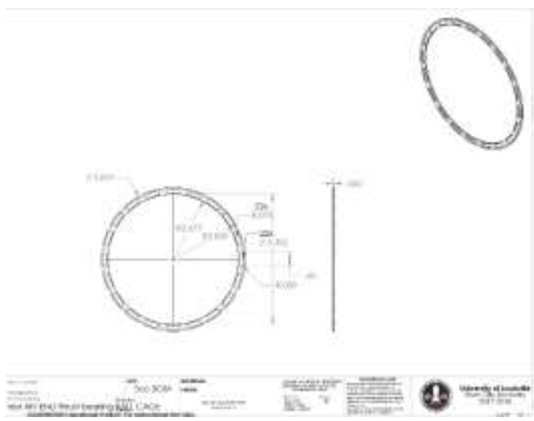


Figure 132: AETB ball bearing retention ring as built drawing

5.2.3 FWD End Support Bearing (FESB)

The primary purpose of the FESB is to assist the AETB by supporting and allowing free rotation of the payload while providing clearance for the rover to exit the launch vehicle.

An exploded view and section view, shown in Figure 133 and Figure 134 respectively, of the FESB are shown below to display the individual components and method in which the parts will be integrated with one another.

Figure 133: Exploded view of fully manufactured FESB.

Figure 134: FESB section view.

5.2.3.1 FWD End Support Bearing: Manufacturing process

5.2.3.1.1 Outer Ring

Oversized 6 in. round stock was placed into vertical milling center and roughed to a depth of .01 in. past groove face and +.01 in. from nominal ID using a ⅝ square endmill. The groove was then machined to nominal dimensions using a .065 key cutter. After the groove was machined, all final machining to nominal dimensions at associated depth was performed. The process was repeated until all internal grooves were machined. Once all outer ring features were machined, the outer ring was placed into a manual lathe and parted off from excess stock. The outer ring was then placed onto a CNC horizontal grinder and ground to nominal thickness. Following the grinding process and demagnetization, the outer ring was bolted onto radial drilling fixture and placed into the milling center where the airframe 10-24 fastening holes and ⅛ retention dowel holes were drilled and tapped/reamed respectively. To complete the manufacturing process, the outer ring was demagnetized, deburred, and polished.

An as built drawing of the FESB outer ring is displayed in Figure 135.

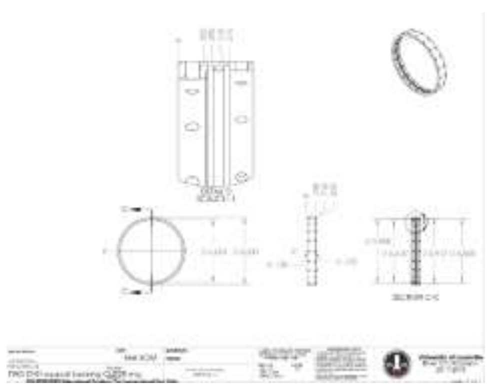


Figure 135: FESB outer ring as built drawing

5.2.3.1.2 Primary Inner Ring

Oversized 6 in. round stock was placed into vertical milling center and machined to nominal dimensions using a ½ square endmill. The 10-24 fastening holes and 3/16 alignment holes for the crescent mounting bracket were then drilled and tapped/reamed respectively into the primary inner ring face. Once all primary inner ring features were machined, the primary inner ring was place into a horizontal band saw and sawed off from excess stock. The primary inner ring was then placed onto a CNC horizontal grinder and ground to nominal thickness. To complete the manufacturing process, the primary inner ring was demagnetized, deburred, and polished.

An as built drawing of the FESB primary inner ring is displayed in Figure 136.

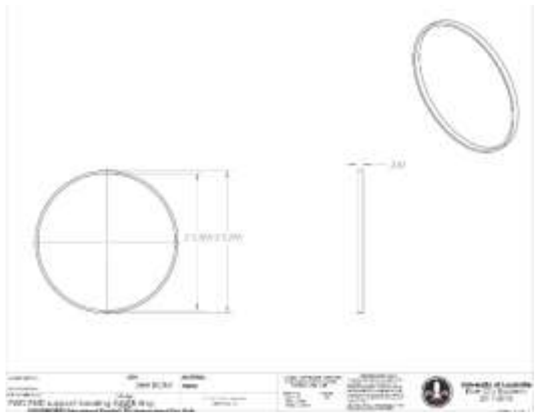


Figure 136: FESB primary inner ring as built drawing.

5.2.3.1.3 Secondary Inner Ring

Oversized 6 in. round stock was placed into vertical milling center and machined to nominal dimensions using a ½ square endmill. Once all secondary inner ring features were machined, the secondary inner ring was placed into a manual lathe and parted off from excess stock to nominal thickness. Following the parting process, the secondary inner ring was bolted onto radial drilling fixture and placed into the milling center where the ⅛ retention dowel holes were drilled and reamed. To complete the manufacturing process, the secondary inner ring was deburred and polished.

An as built drawing of the FESB secondary inner ring is displayed in Figure 137.

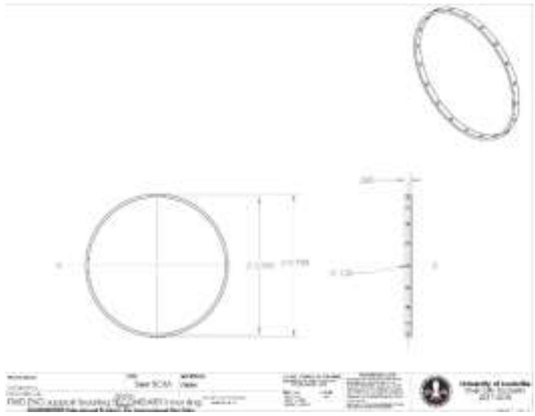


Figure 137: FESB secondary inner ring as built drawing.

5.2.4 Bridging Sled System (BSS)

The primary purpose of the Bridging Sled System (BSS) is to provide a stable surface for the rover to mount to. The BSS also mechanically prevents the rover from translating perpendicular to the central axis of the payload bay. A bill of materials for the Bridging Sled is shown below in Figure 138.

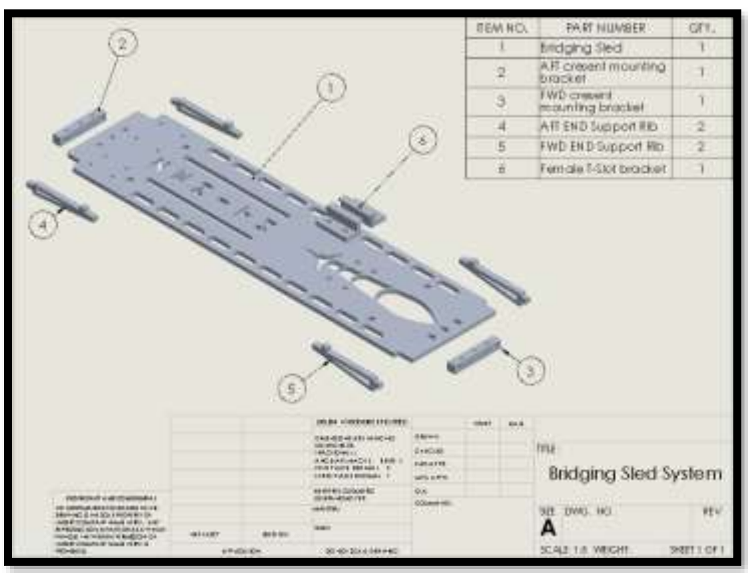


Figure 138: BSS bill of materials.

An exploded view of the model and fully manufactured BSS are shown in Figure 139 and Figure 140 respectively to display the individual components and the method in which the parts will be integrated with one another.

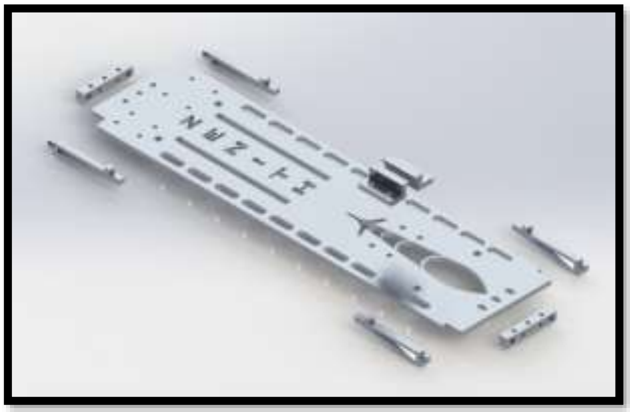


Figure 139: Exploded view of BSS model.

Figure 140: Exploded view of fully manufactured BSS.

5.2.4.1 Bridging Sled System: Manufacturing process

5.2.4.1.1 Bridging Sled

Bridging sled was cut on a water jet

An as built drawing of the bridging sled is displayed in figurex.

5.2.4.1.2 FWD and AFT End Support Rib

The FWD and AFT end support ribs were cut on a water jet

An as built drawing of the FWD and AFT end support rib is displayed in Figure 141.

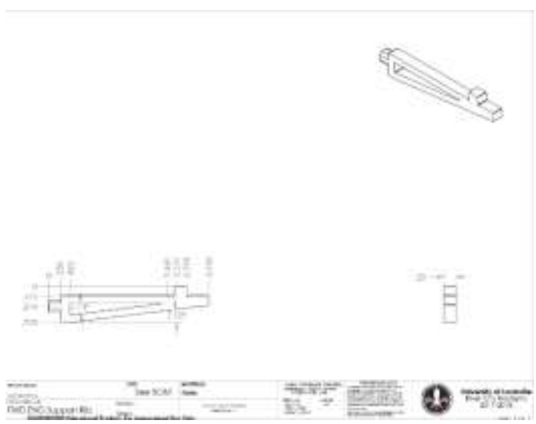


Figure 141: FWD and AFT end support rib as built drawing.

5.2.4.1.3 FWD and AFT end crescent mounting plate

Sawed aluminum billet was placed into vertical machining center and squared with a ⅜ square endmill. The 10-24 fastening holes and 3/16 alignment holes used to mount to the primary inner ring were drill and tapped/reamed respectively into the top machined face. The mounting plate was then rotated 90 degrees and drilled and tapped for 10-24 SHCS that would be used to fasten the mounting plate to the bridging sled.

An as built drawing of the FWD and AFT end crescent mounting plate is displayed in figurex.

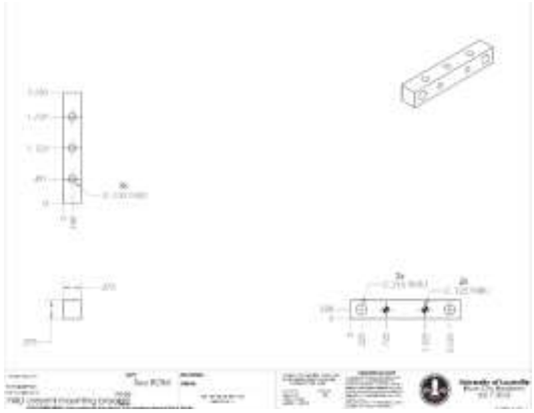


Figure 142: FWD and AFT end crescent mounting plate as built drawing.

5.2.4.1.4 Support Ribs

The BSS will provide structural support for the rover and provide a rigid surface for the rover's tracks to transfer power to. During vehicle flight, the payload bay will be subjected to forces from multiple directions. While the AETB is designed to absorb the majority of the forces propagating through the central axis of the payload bay, the BSS and RLM is also impacted by the same forces.

To reduce static deflection and deflection caused by forces perpendicular to the central axis of the payload bay, FWD and AFT end support ribs will be used. The support ribs are situated directly under the point of contact between the rover and bridging sled and extend inward towards the center of the bridging sled. In doing so, the distance between the center of gravity of the rover and its nearest "rigid" support is minimized. By reducing the distance between the center of gravity of the rover and its nearest rigid support, single point bending is reduced. A fully manufactured fwd end support rib is shown below in Figure 143.

Figure 143: FWD End Support Rib

5.2.4.1.5 T-Slot

The female T-slot brackets situated on the bridging sled will work in conjunction with the male T-slot nut fastened to the chassis of the rover. When the male T-slot nut and female T-slot are engaged, translation of the rover in the radial axis direction will be minimized. A front view of the final design of the male T-slot nut engaged with the female T-slot is shown below in Figure 144. Figure 145 displays the actual female-male T engagement.

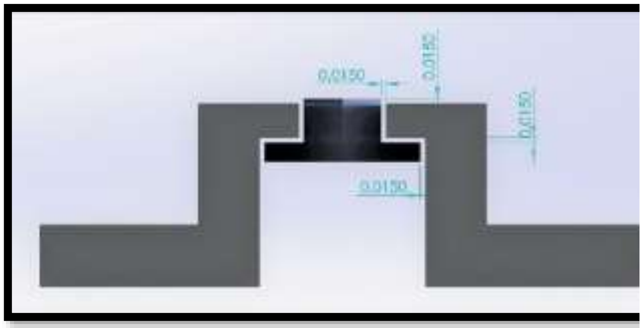


Figure 144: Male T- slot nut and Female T-slot engagement.

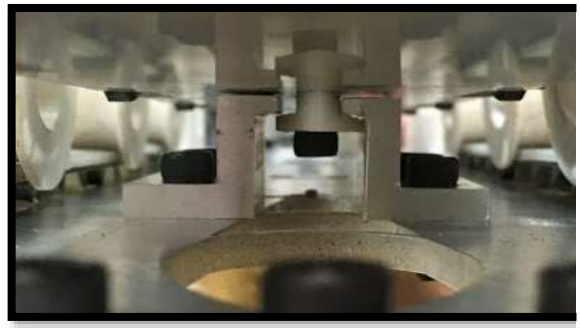


Figure 145: Actual female-male T engagement.

The T-slot assembly will aid the RLM by providing a point of contact close to the payloads forward end, where the translation and rotation of the payload along the radial axis is restricted. The T-slot assembly's 0.015 in. clearance will allow the rover to translate along the central axis of the payload once the RLM is disengaged.

5.2.4.1.6 Crescent Mounting Bracket

The FWD and AFT end Crescent Mounting Brackets will connect the BSS to the AETB and FESB's Primary Inner Ring. Three 10-24 SHCS will be used to mount the BSS onto the mounting bracket from the top and two 10-24 SHCS aligned by two 0.1250 in. Grade 8 Alloy Steel dowel pins will be used to fasten the bracket to the primary inner rings. Each 10-24 socket head cap has a rated yield strength of 2,835 lbs., single shear strength of 3,060 lbs, and a tensile strength of 3,150 lbs. Figure 146 below illustrates the mounting method.

Figure 146: Crescent mounting bracket (dark blue) fully fastened and pinned to FESB and BSS

5.2.5 Requirement Verifications

All ROCS requirement verifications have been conducted in accordance with the methods discussed in section 8.2.3.

5.2.5.1 ROCS-1 Verification

FEA analysis was performed on the ROCS and its subassemblies. The ROCS as a whole and its subassemblies met the minimum required yielding criteria factor of safety of 2.

5.2.5.2 ROCS-2 Verification

A single team member was capable of integrating and removing the ROCS within 5 minutes over a series of three trials. The times achieved for integration were logged in the following Table 43.

ROCS Only	ROCS + Screws
1:00	2:40
1:05	4:15
0:28	2:08

Table 43: ROCS integration times.

The screws being used to secure the ROCS to the airframe had been cut to shorten them leaving unclean ends of the screws. This led to slower integration times and were replaced with screws of the proper length. The inside of the payload bay will also now be cleaned with acetone prior to integrating the ROCS to ease the integration process. The difference made by changing the screws and cleaning the bay thoroughly is exemplified by the reduced integration time of trial 3. These results verify the requirement.

5.2.5.3 ROCS-3 Verification

See ROCS Roll Test.

5.2.5.4 ROCS-4 Verification

See Flight Loads Testing Series.

5.3 Rover Locking Mechanism (RLM)

The primary purpose of the Rover Locking Mechanism (RLM) is to mitigate the translational movement of the rover along the central axis of the payload bay and to absorb critical forces applied, while remaining structurally sound. A bill of materials for the RLM is shown below in Figure 147.

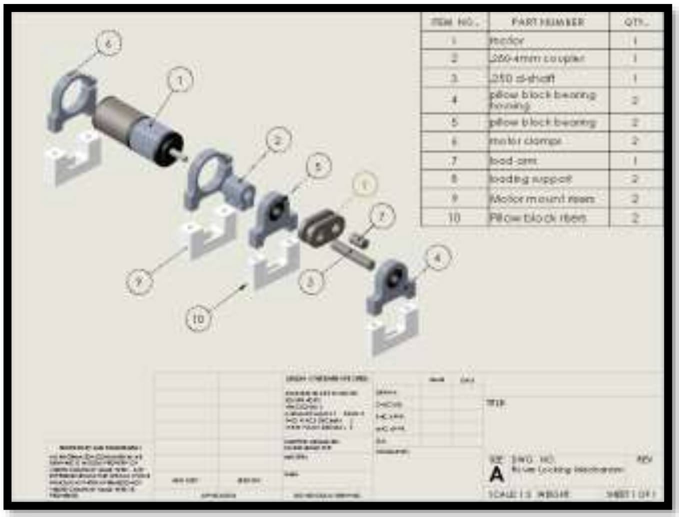


Figure 147: RLM Bill of Materials.

The full RLM model is displayed in Figure 148 and the fully manufactured RLM in Figure 149.

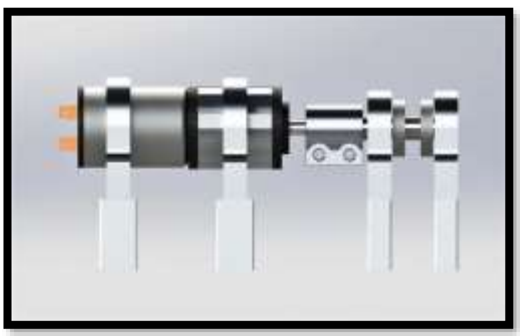


Figure 148: RLM solidworks model.

Figure 149: Actual RLM assembly.

5.3.1 Rover Locking Mechanism: Analysis, Manufacturing

5.3.1.1 Rover Latch Design

During verification RLM-3 the rover latch pinched the RLM's loading arm when attempting to release. Excessive latch length which interfered with the path of the loading arm was the root cause of the pinching. The latch's redesign was shorter, accounting for the circular path taken by the loading arm. The redesign also included repositioning the rover latch from the bottom of the rover body to the top. During verification RDS-1 it was noticed that the previous latch design drug the ground when the rover was put at steep angles. These characteristics drove the change of the rover latch location.

Stress analysis was performed on the redesigned rover latch to satisfy verification RLM-1. The latch was fixed at the outer face surrounding the bolt holes to simulate the clamping force from the head of two 8-32 SHCS. An applied force of 70lbf was applied normal to the face where the latch interfaces with the loading arm. Simulation results determined a max stress of 19.2ksi and

FOS of 2.1. Figure 150 shows the boundary conditions and stress plot for the redesigned rover latch.

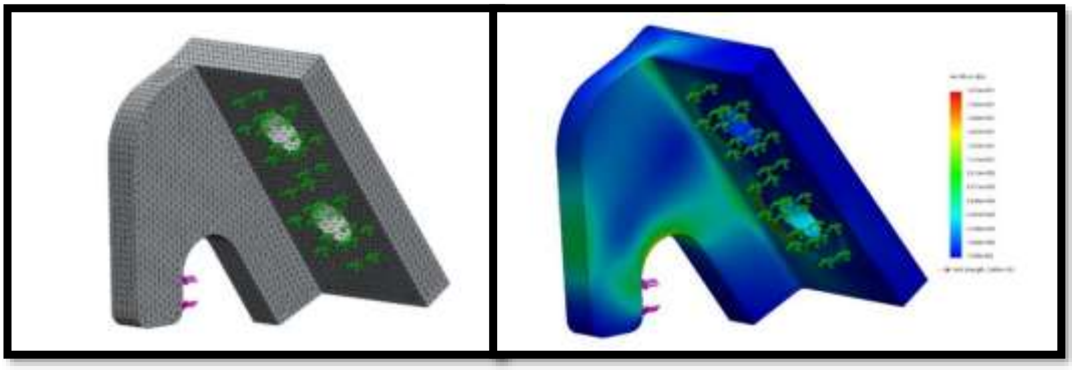


Figure 150. Rover latch boundary conditions and stress plot.

The rover latch is fastened to rear end of the rover body by two 8-32 x 0.25in SHCS. The rover latch was CNC machined out of 6061-T6 aluminum. Figure 151 below displays a machined rover latch in the new location.

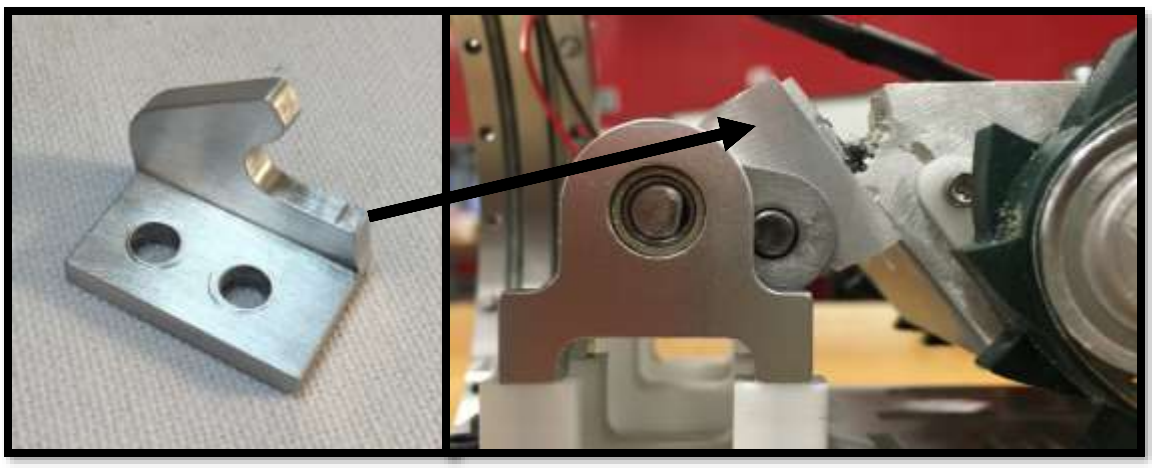


Figure 151. Redesigned rover latch in new position.

5.3.1.2 Manufacturing process

5.3.1.2.1 Loading Bracket

⅛ feed holes were drilled into a piece of flat ground stock and then clamped to the bed of the wire EDM. The wire was fed through the feed holes and proceeded to cut out the loading bracket features. Once fully wired, the loading brackets were demagnetized, deburred, and polished.

An as built drawing of the loading bracket is displayed in Figure 152.

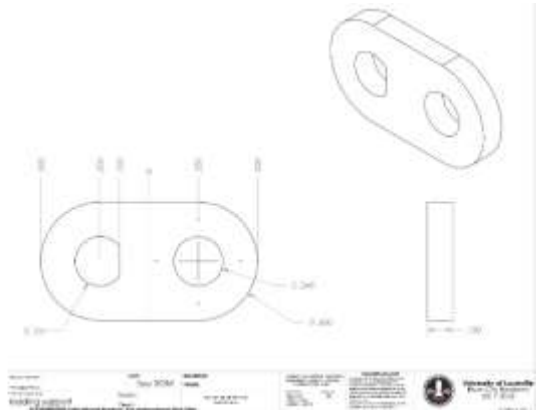


Figure 152: Loading bracket as built drawing.

5.3.1.2.2 Motor Mount and Pillow Block Riser

The ball motor mount riser was printed using a 3D printer.

An as built drawing of the motor mount and pillow block riser is displayed in Figure 153.

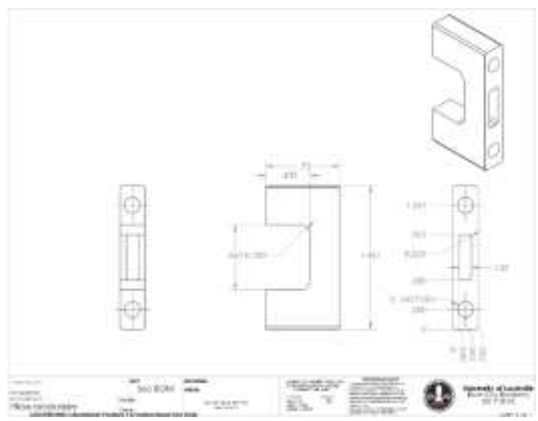


Figure 153: Motor mount and pillow block riser as built drawing.

5.3.2 Requirement Verifications

Requirement verifications were conducted according to the methods discussed in section 8.2.3 to confirm operation of the RLM as it is during flight of the launch vehicle.

5.3.2.1 RLM-1 Verification

This verification has been successfully completed by analysis shown in CDR section 5.1.10.

5.3.2.2 RLM-2 Verification

The rover was integrated into the ROCS and locked by engaging the RLM. The rover was then spun inside the airframe and held in flight orientation with the RLM above the rover while 3 bystanders watched the rover. The rover was successfully retained in the airframe section throughout all testing successfully verifying the requirement.

5.3.2.3 RLM-3 Verification

The RLM's mechanical components were verified by fastening the rover latch and male t-slot to the rover. The rover was inserted through the front of the ROCS, engaging the male and female t-slots. Loosening the loading arm coupler allowed the loading arm to swing to a horizontal position and engage the rover latch. Once in position, the loading arm coupler was tightened to keep the loading arm in place. Before releasing the rover, the rover was given several tugs to simulate the latch and arm interface after experiencing the flight loads. 11.1V was applied to the loading arm motor which rotated the loading arm down to disengage the rove latch. Five successful releases satisfied the verification.

5.3.2.4 RLM-4 Verification

See Flight Loads Testing Series.

5.4 Deployment Trigger System (DTS)

The Deployment Trigger System consists of two transceiver modules that will be used to deploy the rover upon gaining permission from the RSO to continue with the payload mission. Reception of the deployment signal will begin autonomous operation of the rover.

5.4.1 DTS Range

The maximum range to which the system has been successfully tested by the team is 3,268 linear feet between the transmitter module and receiver. This test was conducted with the antenna adhered to the exterior of a carbon fiber airframe section placed on the ground to most accurately simulate mission conditions. This distance was determined by plotting the distance between two GPS coordinates on Google Earth and measuring the distance between the points. This data is shown below in Figure 154.

Figure 154: DTS maximum range test.

5.4.2 Receiver Module

The DTS receiver is an HC-12 transceiver module. This device is powered by the Control Electronics System and communicates via Rx and Tx lines. An antenna adapter is connected to the receiver module to interface the module with the mud-flap antenna through the airframe.

5.4.2.1 Mounting

The HC-12 module is secured inside the payload recovery bay coupler using a 3D printed sled pressed on to two pieces of all-thread. The sled holds the HC-12 module with the connector pins accessible for ease of wiring. The sled is manufactured out of PLA plastic by a Makerbot Replicator+. An SMA type connection is positioned on the open, top side of the sled which allows for the antenna connection cable to connect the module.

5.4.2.2 Slip Ring Flange

The slip ring flange is installed in the bulk plate of the payload recovery bay coupler using three bolts with the rotational end open to the payload bay. This allows for the HC-12 module and antenna to be connect to the rover CES on the opposite side of the bulk plate. Once the rover has landed the flange rotates with the ROCS mitigating the possibility of wires detaching prematurely due to rotation. The slip ring flange is shown below along with the payload bay side of the flange after mounting in Figure 155.

Figure 155: Slip ring flange (left) and mounted to bulkplate (right).

5.4.3 Pull-apart Mechanism

The magnetic connectors used for the pull apart connection allow for the rover to disconnect from the receiver module and antenna. Once the rover has landed and received the signal to deploy, the rover begins to exit the payload bay. Upon stretching the wires to their maximum length, the magnetic connectors separate without impeding the forward motion of the rover. This has been ground tested to confirm both signal fidelity through the magnetic connectors and the ability of the rover to disconnect the wires. The connectors are shown below in Figure 156.

Figure 156: Magnetic connectors.

5.4.4 Receiving Antenna

The receiver antenna is adhered to the exterior of the payload recovery bay airframe using adhesive tape. The antenna has been wrapped around the curvature of the airframe to provide signal reception regardless of landing orientation of the bay. The antenna adhered to the airframe is shown below in Figure 157.

Figure 157: Receiver antenna adhered to airframe.

5.4.5 DTS Transmitter Station

The DTS Transmitter Station is comprised of a Yagi high gain antenna connected to the transmitting HC-12 module. A Yagi is being used to directionalize the deployment signal and increase range. The transmitter module is connected to a designated Arduino Uno microcontroller that has the sole purpose of transmitting the desired deployment packet for the rover at 433.4 MHz. The module and Yagi are connected using an F type coaxial cable. While the transmission station is active the deployment RF signal is transmitted at a rate of 1 Hz. The Yagi antenna being used for the transmitter is shown below in Figure 158.

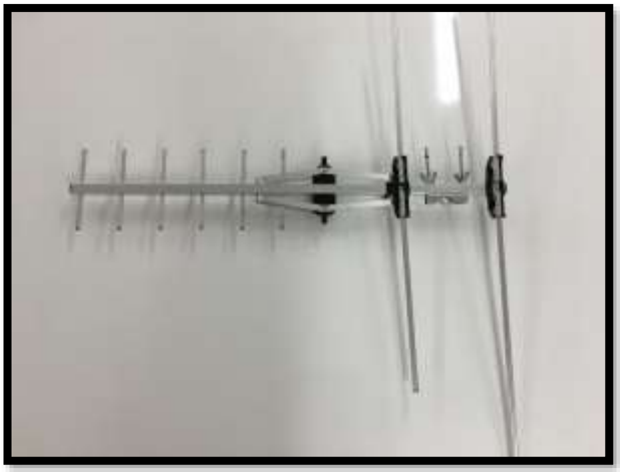


Figure 158: DTS Yagi antenna.

5.4.6 Requirement Verifications

Requirement verifications have been conducted in accordance with the methods outlined in section 8.2.3 to confirm functionality of the system as is being used during flight.

5.4.6.1 DTS-1 Verification

Two HC-12 Modules were each connected to their own antenna and Feather M0 Bluefruit LE microcontroller. Connection between the modules was then verified by sending a signal from a transmitter module and displaying the signal on the receiver module serial monitor. The software and hardware on each module mirrored each other. Each program used the default frequency of 433.4 MHz and a power level of 100 mW for sending and receiving RF communications. Connection was successfully established and a packet of data was sent back and forth from each module 10 times.

5.4.6.2 DTS-2 Verification

The slip ring flange was successfully tested by installing it in the bulkplate of the payload recovery bay coupler. A transmitter was configured to continuously relay data to the receiver module to view any breaks in communication. Connection from the transmission station was maintained throughout the demonstration and data integrity was never compromised by the rotating of the flange.

5.4.6.3 DTS-3 Verification

When the rover drives forward the DTS module is disconnected from the rover. This is done using magnetic connectors that are placed on the rover. These magnetic connectors disconnect from the rover pulling away. The magnetic connectors pull apart without causing the rover with minimal force and doesn't hinder the rover's ability to exit the payload bay. During this verification the module maintained its position on the opposite side of the couple and the rover is able to disconnect and leave the module behind with the antenna. This allows the rover to not be hindered by the receiving antenna and module.

5.4.6.4 *DTS-4 Verification*

See DTS 50 Foot Radius Test._DTS_50_Foot

5.4.6.5 *DTS-5 Verification*

The system has been successfully tested using a string of text being sent by the transmitter as the unique deployment signal. The receiver module passes the packet received to the Control Electronics System controller for comparison to a preset string matching the string that is sent by the transmitter. The indicator LED changes state after comparison of the two strings confirms their equality. Any incorrect data does not pass the comparison test on the CES controller and the received packet is then cleared to allow for a new packet to be received. This successfully verifies the requirement.

5.4.6.6 *DTS-6 Verification*

See Full Flight Performance Testing Series._DTS-6

5.5 Rover Body Structure (RBS)

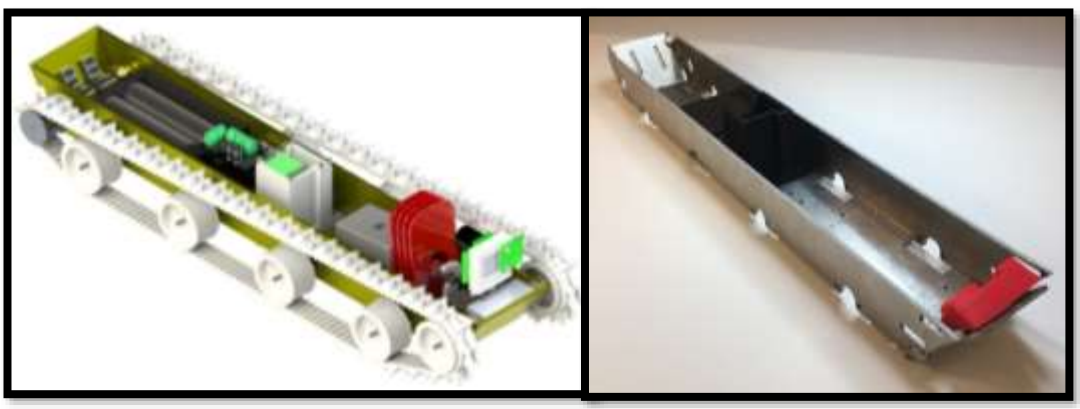


Figure 159: RBS highlighted in yellow and assembled RBS.

The RBS will be responsible for providing support for all the components in the rover. It will also serve as the electronics bay of the rover. The RBS includes the aluminum rover body, battery mount, drive electronics platform, and camera mount.

5.5.1 Aluminum Rover Body

The rover body is sloped 55 degrees from the horizontal in the front to deflect objects downwards, improving the rover's ability to traverse obstacles. The rear end is also at a 55 degree angle to provide extra ground clearance when climbing. Cutouts have been added to the flat pattern CDR to allow the bearings to be mounted on the inside of the rover body wall. The manufactured aluminum rover body is shown below in Figure 160Figure 160.

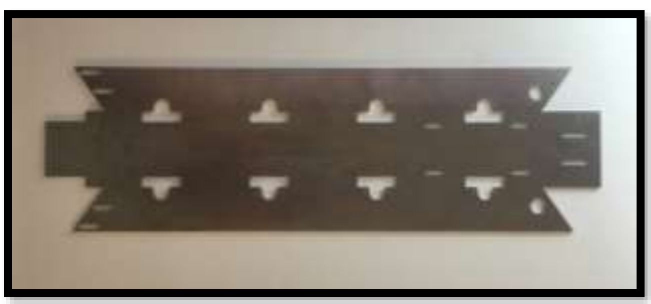
Figure 160: Manufactured rover body.

5.5.1.1 Justification of Material

5052-H32 aluminum was selected for its high ductility. Ductility was a critical parameter considering the rover body bending process. Ductile aluminum allows for small bend radii to be achieved without cracking.

5.5.1.2 Manufacturing

The rover body will be constructed of a single sheet of 1/10in. thick 5052-H32 aluminum. The bodies flat pattern was cut with a water jet. The flat pattern of the rover body is shown below in Figure 161.



.

Figure 161: Rover body flat pattern.

Using a finger brake, each side of the rover was bent to 90 degrees. The front and rear ends of the rover were bent to 55 degrees. Squares cutouts in the flat pattern served as alignment features for the bend location of each wall. Side was tig welded at the corners to increase the bodies strength. **Figure 161** below shows the rover body being bent in a metal brake, and a welded corner.

Figure 162: Rover body bending and welded seam.

5.5.2 CES Platform

The CES platform serves as the mount for the Control Electronics System (CES). The CES is based on a custom designed PCB printed by Advanced Circuits. The sled elevates the CES electronics just above the bearings inside the rover body. Four 4-40 SHCS thread into the bottom of the platform while four M2 screws attach the circuit board onto the top of the sled.

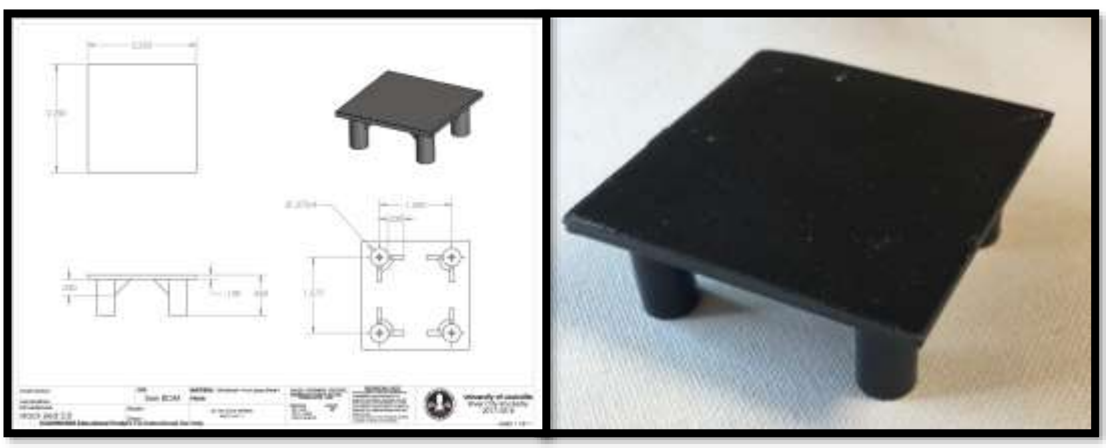


Figure 163: CES Platform drawing and actual printed platform.

5.5.3 Motor and Controller Battery Mount

The battery mount is responsible for housing both the motor battery and the controller battery. The battery mount was manufactured out of PLA using a Maker Select v2 3D printer. The battery mount is threaded to the rover body by four 0.5in. 4-40 screws that thread into the bottom of the rover. Each leg on the sled ribsThe printed battery mount and drawing can be viewed in

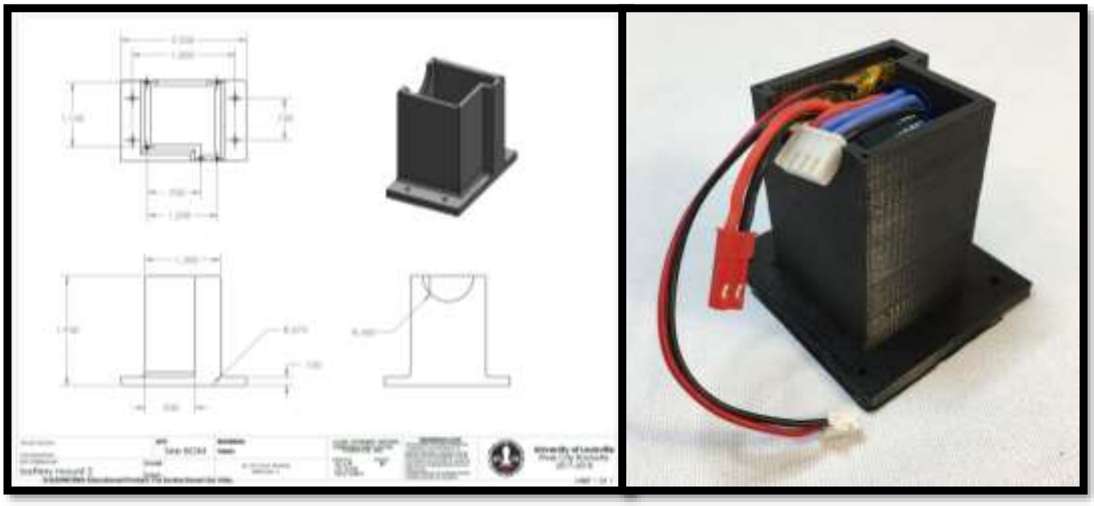


Figure 164.

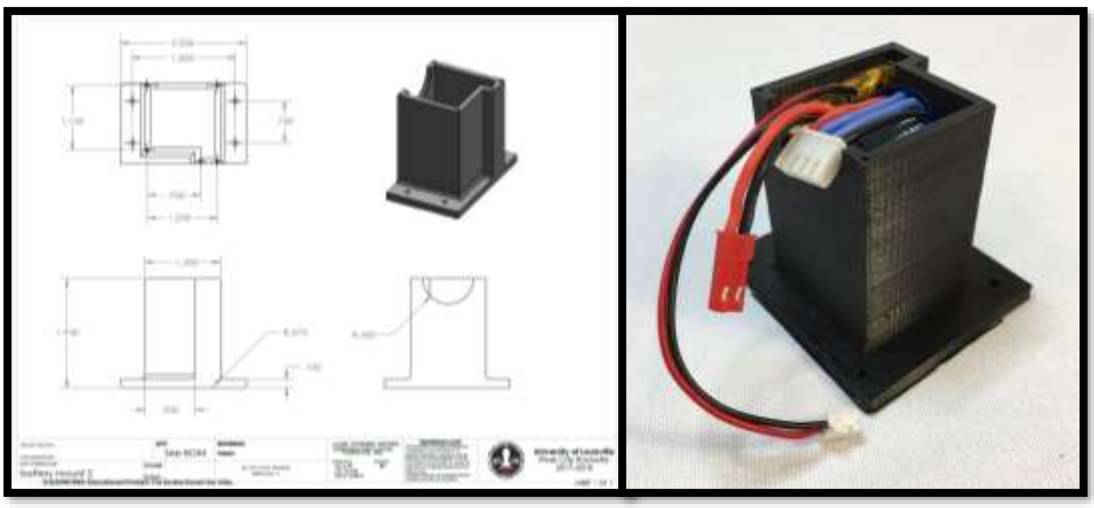


Figure 164: Battery mount drawing and printed battery mount.

The overall dimensions of the battery mount are shown below in Table 44.

Length (in.)	Height (in.)	Width (in.)
1.350	1.950	1.450

Table 44: Battery Mount Dimensions

5.5.4 Requirement Verifications

5.5.4.1 RBS-1 Verification

This verification was completed by driving the rover over the heads of three bridging sled fasteners which sit 0.225in. above the ground. This height exceeds the required height of 0.125in. This test was also verified by sitting the assembled rover onto a flat surface and measuring the distance between the lowest point of the rover body and the ground. The ground clearance of the rover was determined to be 0.375in. Figure 165 shows the rover fulfilling RBS-1 verification.

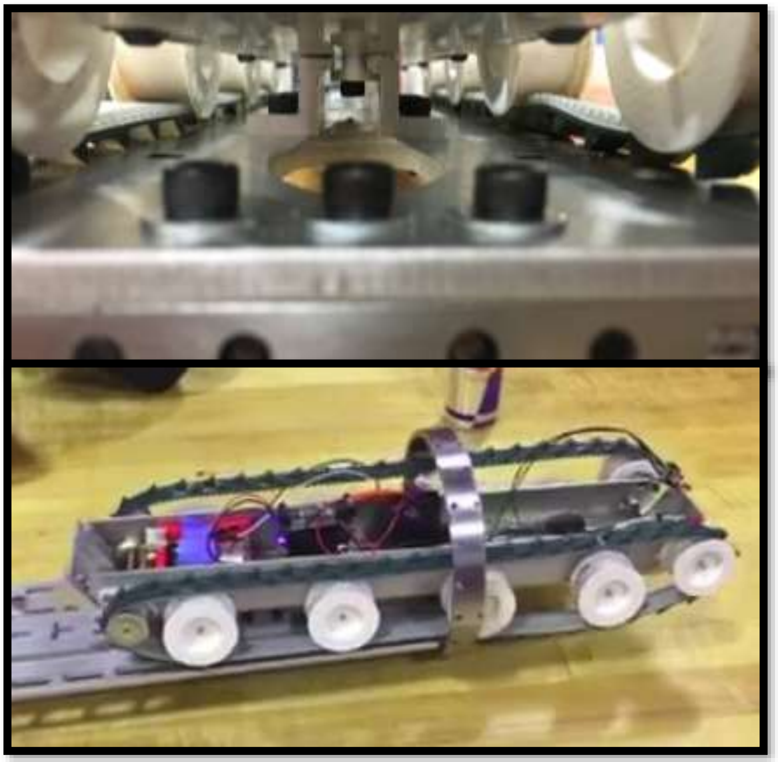


Figure 165: RBS ground clearance verification test.

5.5.4.2 RBS-2 Verification

The battery mount, CES electronics, lidar mount, and body structure were assembled into their final configuration, the RBS was flipped ups. Each mount fully restrained all electrical components contained in the RBS. This test fulfilled RBS-2 verification.

5.5.4.3 RBS-3 Verification

In the first two test flights the RBS was not subjected to nominal flight loads. As a result, this verification has not been satisfied. RBS-3 has been postponed and rescheduled for completion during the next test flight on 3/17/2018.

5.6 Rover Drive System (RDS)

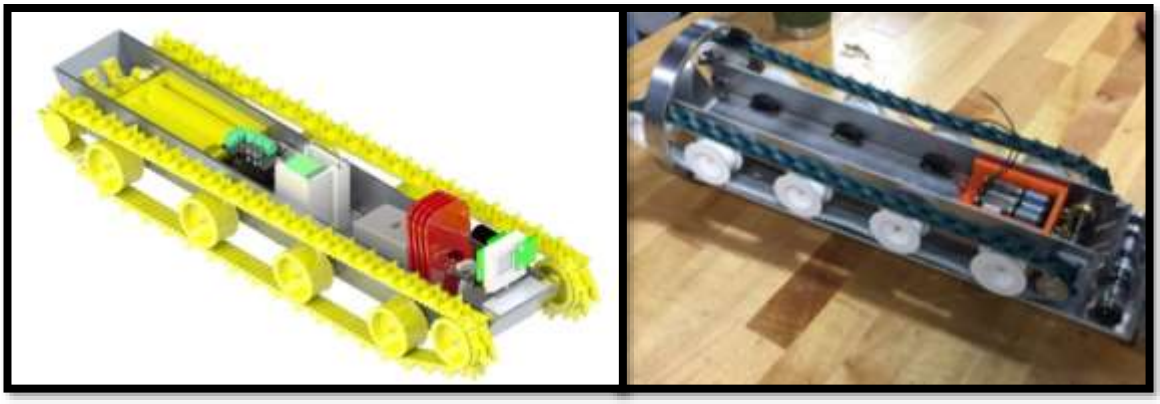


Figure 166: Highlighted rover drive system and manufactured rover drive system.

The primary purpose of the RDS is to translate the rover at least five feet from the launch vehicle on any terrain and traverse obstacles in the rover's path. The rover drive system consists of two smaller sub-assemblies, the motor assembly, and the belt drive system.

5.6.1 Belt Drive System

The belt drive system utilizes passive pulleys and polyurethane belts to drive the rover. The belt drive system contains the belt, passive wheels, bearings, and shafts.

5.6.1.1 Belt Tread Design

The belts that will drive the rover will be T5 timing belts. Table 45 shows the overall specifications of the timing belt.

Specification	Value
Pitch	0.197in
Width	0.63in
Material	Polyurethane
Coefficient of Friction (on dry concrete)	1.0

Table 45: Timing Belt Specifications.

Timing belts minimize the possibility of slippage between the belt and drive pulleys. Large treads on the outside of the belt were chosen to improve traction on all terrains and provide additional ground clearance. Polyurethane was chosen for its high coefficient of friction and durability. The timing belt drawing is shown next to the actual belt below in Figure 167.

Figure 167: Belt drawing and actual belt.

5.6.1.2 Pulley Configuration

Passive pulleys support the T5 timing belt along each side of the rover. The front pulley is located 0.84in. higher than the bottom 4 passive pulleys. This design allows the belt to contact obstacle before the rover body, mitigating the risk of bottoming out on an object while driving. This design feature was especially displayed its effectiveness in RDS-2. The rear pulley will be the driving pulley. The length of the timing belt in this configuration is 33.46in. An illustration of the pully configuration is shown in Figure 168.

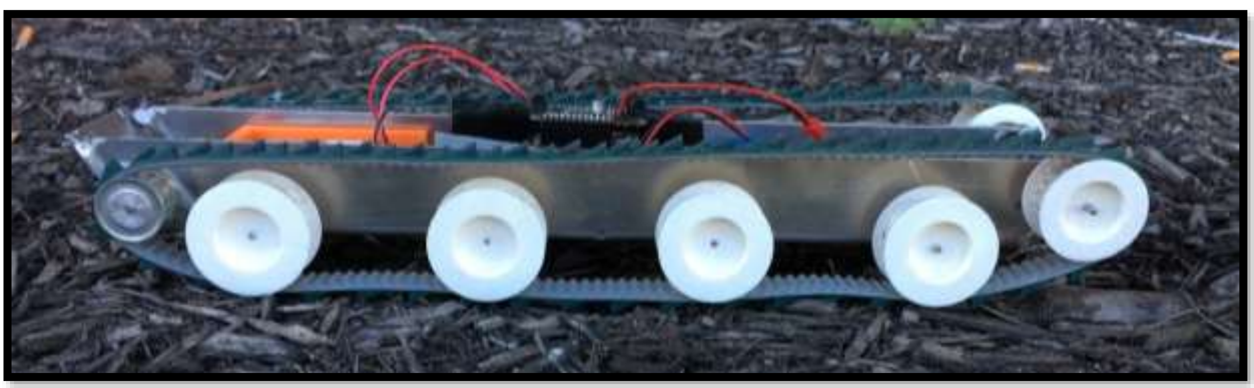


Figure 168: Pulley configuration.

5.6.1.3 Drive Pulley Design

The drive pulleys will be responsible for driving the timing belt. The drive pulleys have a 0.197in. pitch to match the timing belts. Each drive pulley is machined aluminum and will be fastened to the 4mm drive shaft with an 8-32 set screw. The drive pulley can be seen in its assembled configurations below in Figure 169.

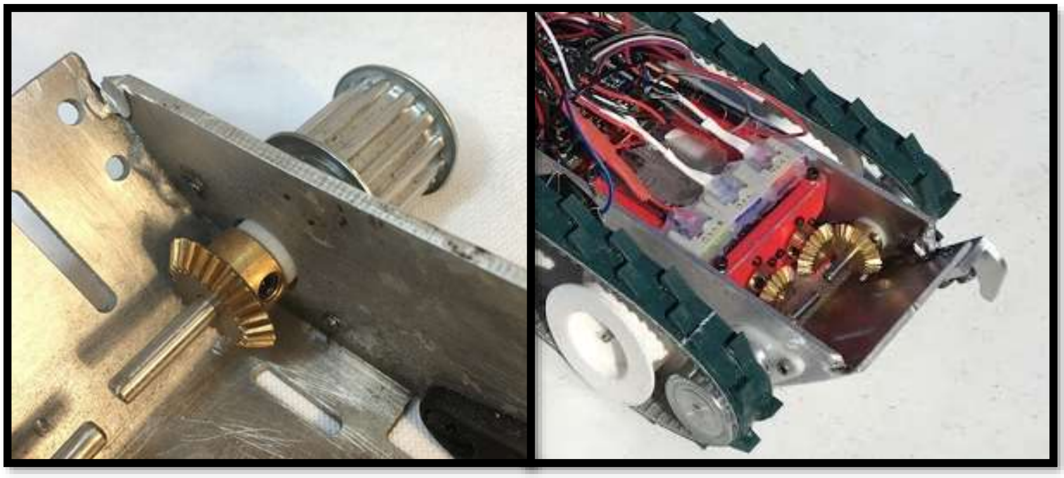


Figure 169: Drive pulley design.

5.6.1.4 Drive shaft spacer

The drive shaft spacer keeps the drive shaft aligned perpendicular to the motor assembly's bevel gears. The design presented in CDR depended on two 3D printed PLA plastic washers to align the shaft. The new design functions as a single part, reducing the number of parts to be manufactured. A material change from 3D printed PLA to CNC milled delrin was made to lower the coefficient of friction, lower tolerances, and increase toughness. Figure 171 displays a machined drive shaft spacer and drive shaft spacer drawing.

Figure 170: Drive shaft spacer drawing and machined drive shaft spacer.

5.6.1.5 Passive Pulley Design Material Justification

Eight total passive pulleys mounted along the sides of the rover body are responsible for aligning the timing belts during operation. Walls 0.180in. high on each side of the passive wheels prevent the timing belt from slipping off the wheels while driving. Each pulley was 3D printed out of ABS plastic. ABS plastic provides a 30% weight reduction from machined delrin. 3D printing also requires less time to produce than machining. A drawing of the passive pulley and a printed pulley can be seen below in Figure 170.

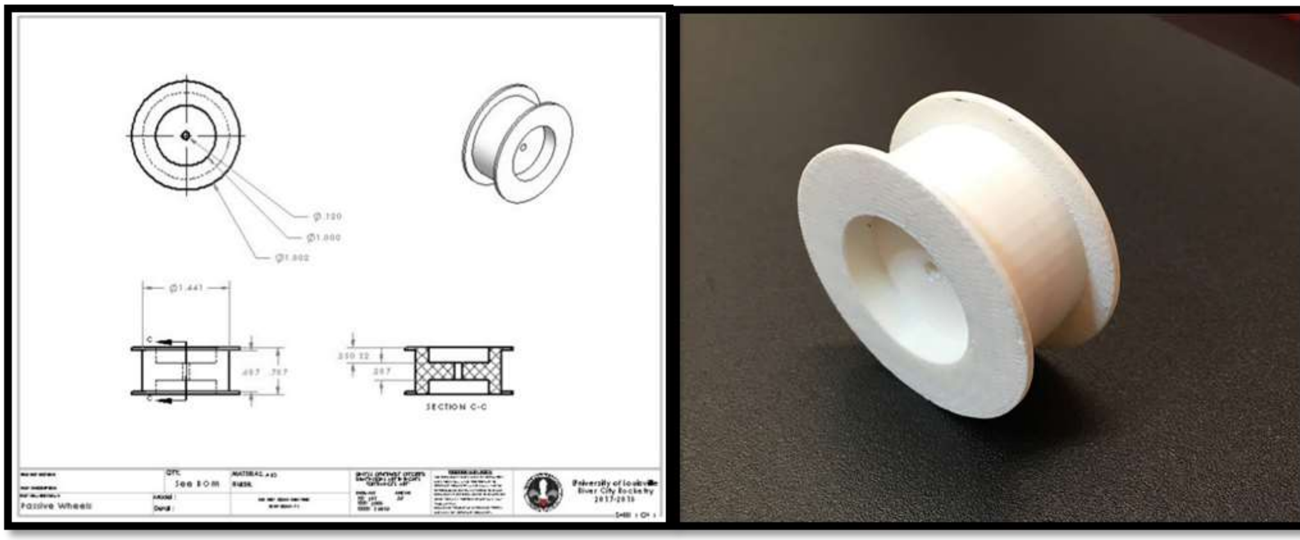


Figure 171: Passive pulley drawing and actual printed wheel.

5.6.1.6 Pulley Bearings

Stainless steel two-bolt flange-mounted ball bearings are attached to the inside of the rover body. These bearings are responsible for attaching the passive pulleys. Two 8-32 x 0.25in. flat head screws thread into the rover body and fasten the bearings to the wall. Each bearing takes a 1in. long by 0.125in. diameter 1080 steel shaft. The shafts press fit into the passive wheels and bearings. The bearings have a dynamic radial load capacity of 125 lbs. Figure 172 below shows the bearing assembled to the rover body.

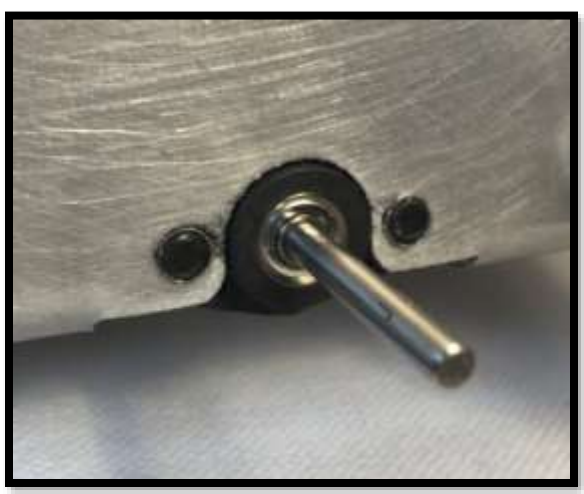


Figure 172: Pulley Bearing.

5.6.2 Motor Mount

The motor mount is responsible for retaining the motors during flight and while driving the rover. The motor mount was manufactured using PLA plastic from a MakerBot Replicator+ 3D printer and is fastened to the bottom of the RBS using four 0.5in. 4-40 SHCS located in the four corners of the part. Each cap screw is fastened through slots in the rover, allowing the motor mount to adjust to the drive shaft bevel gears. Each motor is secured to the mount using four M2 bolts secured to the motors back wall utilizing the motors four front tapped mounting holes. A motor mount drawing along with an as-built image with the motors installed are shown below in Figure 173.

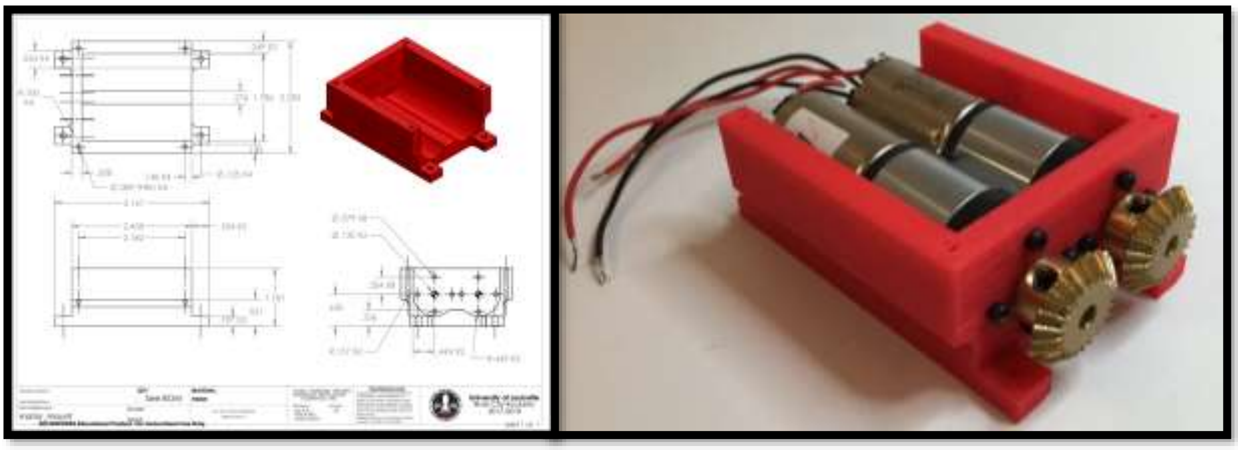


Figure 173: Motor mount drawing and actual motor mount.

The overall dimensions of the mount are shown below in Table 46.

Length (in.)	Height (in.)	Width (in.)
2.283	1.181	2.812

Table 46: Motor Mount Dimensions.

5.6.3 Rover Drive System Bracket

The RDS brackets will be responsible for supporting both drive pulley axels. These brackets will be laser cut out of delrin, rather than aluminum. ensure minimal wear and high rigidity. The brackets will be mounted to the rear of the rover body via two 4-40 bolts. A detailed drawing of the bracket design is shown below in Figure 174

Figure 174: Drive shaft spacer drawing and manufactured drive shaft spacer.

5.6.4 Tipping Analysis

The Control Electronics System will use the angle at which the rover will tip on the roll axis to determine if the rover is in a safe orientation to deploy. The following equations were used to find the tipping angle.

$$\tan\theta = (Y/X) \tag{35}$$

where θ is the angle between the ground and the line connecting the center of gravity (CG) to the point of tipping, Y is the distance from the ground to the CG, and X is the horizontal distance from the point of tipping to the CG. The maximum angle before tipping (α) is defined by

$$\alpha = 90 - \theta \tag{36}$$

Solidworks was used to determine the CG. An illustration of the variables is shown in Figure 175.

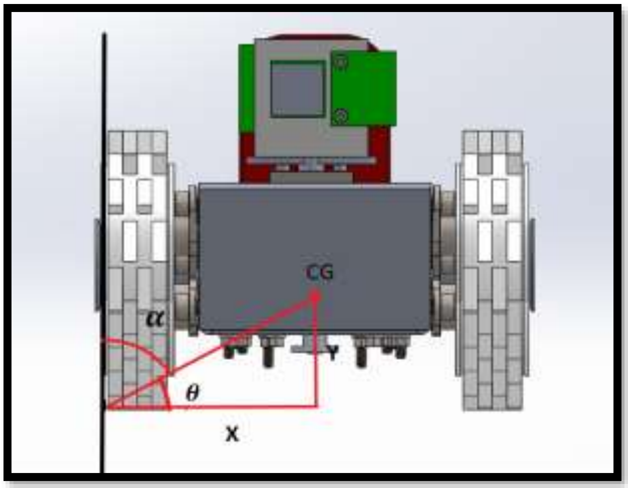


Figure 175: Tipping Analysis.

The result of this analysis is that an angle of 59.7° is the maximum angle of roll before the rover will tip.

5.6.5 Requirement Verifications

The Rover Drive System has been tested by assembling the system through multiple iterations of minor changes and driving the rover in accordance with the verification methods outlined in section *8.2.3*. The results of the RDS team derived requirement verifications are described below.

5.6.5.1 RDS-1 Verification

A steel block was placed in the Rover Body Structure as a simulated mass along with the electronics needed to drive the main drive motors of the RDS bringing the rover weight to 5.925 lbs. This exceeds the expected weight of the rover. Despite this weight, the torque of the main motors allowed the system to translate and turn in all directions. This result verifies the requirement is complete.

5.6.5.2 RDS-2 Verification

The RDS demonstrated the ability to surmount a vertical step height of one inch five times successfully verifying the requirement. The rover before and after surmounting the step is shown below in Figure 176.

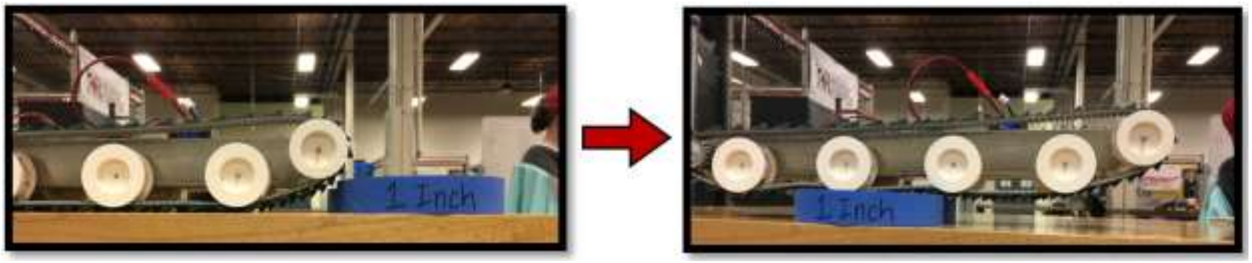


Figure 176: Step height before and after.

The maximum step height successfully surmounted by the system is 3.25 in. and is shown below before, during, and after clearing the step in Figure 177.

Figure 177: 3.25 inch vertical step.

This step height was achieved by driving the rover over a railroad rail with grass and dirt on either side of the rail.

5.6.5.3 RDS-3 Verification

See RDS Sloped Driving Test._RDS_Sloped_Driving

5.6.5.4 RDS-4 Verification

To account for all terrains that the rover may experience during the mission, the RDS was constructed and driven on six different terrains that are intended to simulate possible terrains of the launch field. The system was driven on these six terrains for two minutes each performing forward, backward, left turn, and right turn maneuvers in wet and dry conditions while being controlled using Bluetooth from a team member’s cellphone. The rover can be seen on the six terrains in dry conditions below in Figure 178.

Figure 178: Multiterrain driving - dry.

The system was capable of driving on all terrains performing all maneuvers without the treads slipping at any time. The average drive time to reach a distance of five feet from the starting point was approximately 30 seconds on all six terrains and the climbing ability of the system was not significantly affected by the terrain.

The system is shown on the same six terrains in wet conditions below in Figure 179.

Figure 179: Multiterrain driving – wet.

Again, the rover was capable of performing all maneuvers on all terrains, the average drive time to reach a distance of five feet from the starting point was approximately 30 seconds, and climbing was minimally affected on all six terrains.

Based on these results, the requirement has been considered successfully verified.

5.7 Obstacle Avoidance System (OAS)

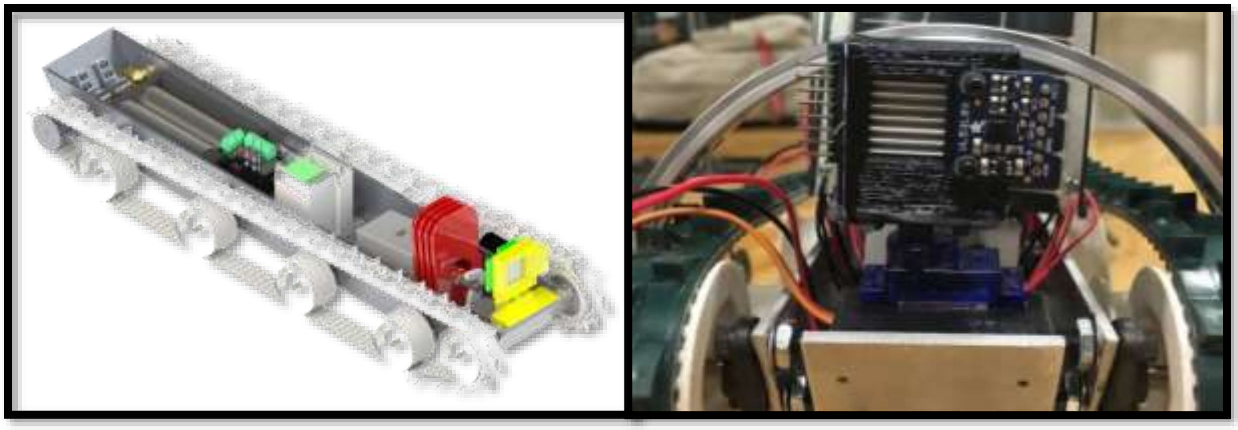


Figure 180: OAS highlighted in yellow and assembled onto rover body.

The OAS will be responsible for detecting objects in the rover's path. This will be achieved by using a Lidar sensor on the front of the rover, sweeping the sensor from left to right giving it a field of view, and analyzing the data to determine if an obstacle taller than the rover is in the immediate path of the rover. If the data concludes that an obstacle is present, the Control Electronics System control scheme will determine a course of action as described in section *8.1.2.7.6*. This section will outline the final hardware configuration and functional confirmations for the system.

5.7.1 Hardware Configuration

The SG92R servo motor is secured to the front of the rover inside of a 3D printed mount by two M2 bolts. The mount is made of PLA plastic printed from a Maker Select v2 3D printer and will connect to the rover's body by two 4-40 bolts. This mount is designed to mount the servo vertically to the front of the rover, which is slanted at 55 degrees. A detailed drawing of the servo motor's mount along with the fully manufactured mount are shown below in Figure 181.

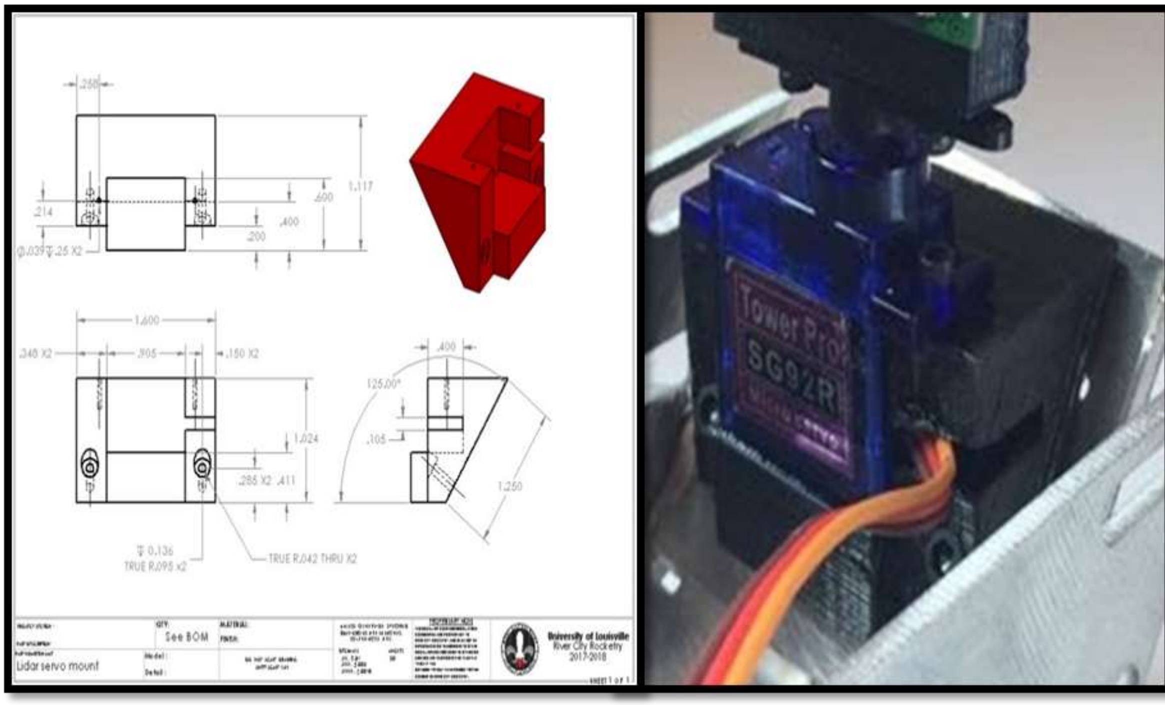


Figure 181: Servo Mount Design

The overall dimensions of the Lidar sensor mount are shown below in Table 47.

	Length (in.)	Height (in.)	Depth (in.)
Servo motor mount	1.600	1.024	1.117
Lidar/camera mount	1.225	1.265	.350

Table 47: Servo and Lidar Mount Dimensions

The Lidar distance sensor is mounted to a 3D printed mount manufactured by a MakerBot Replicator+ out of PLA plastic. Two M2 bolts tapped into the mount will hold the sensor. The mount is also connected by two M2 bolts to the top of the servo motor, allowing the Lidar sensor to rotate. The camera described in 5.9.1 will also be secured to the same mount by two 3-32 bolts tapped into the mount. A drawing of the sensor's mount along with an as-manufactured photo are shown below in Figure 182.

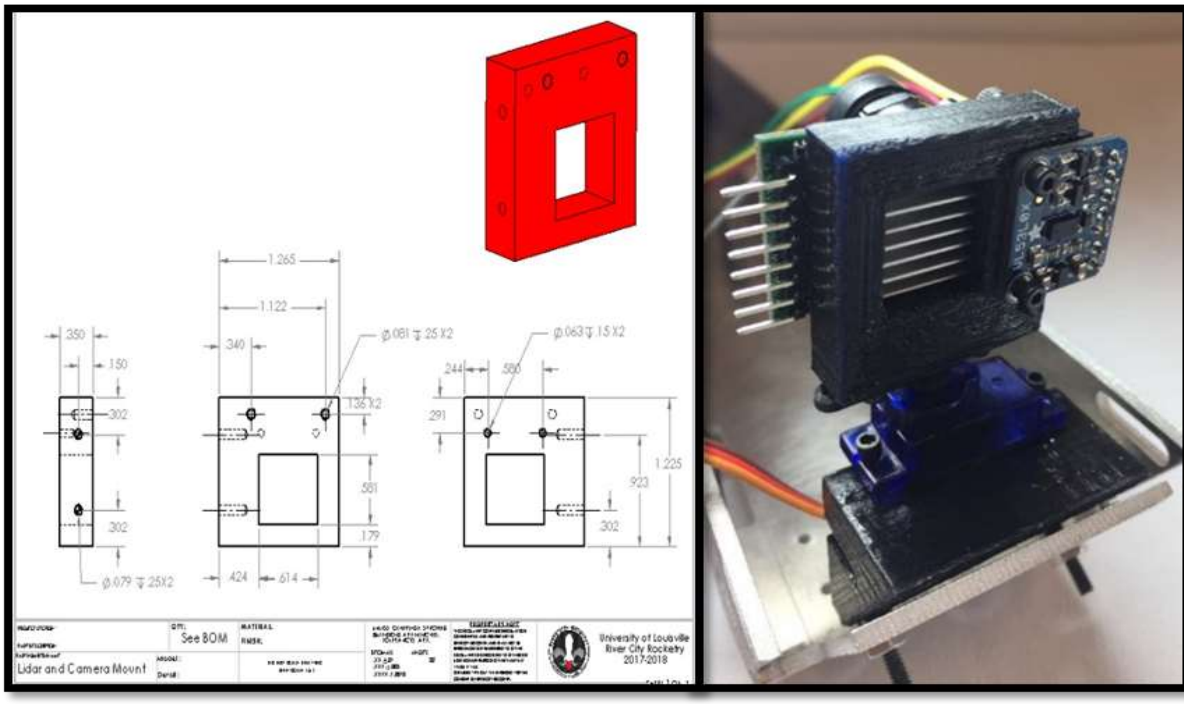


Figure 182: Lidar Sensor Mount

The overall dimensions of the two mounts are shown below in Table 48.

	Length (in.)	Height (in.)	Depth (in.)
Servo motor mount	1.600	1.024	1.117
Lidar/camera mount	1.225	1.265	.350

Table 48: 3D printed mount dimensions.

5.7.2 OAS Algorithm

The Obstacle Avoidance System program uses a VL53L0X sensor to detect any objects in front of the rover. The program will continuously measure straight ahead until an object is within 10 inches of the sensor. If an object is detected, the SG92R servo will pan from 0 to 180 degrees. The Lidar sensor simultaneously takes 180 measurements (one at each degree) and stores them individually in an array. The program selects the first viable element and tests it with the Gaussian Filter. The filter and its process are explained in greater detail below. The testing process repeats until the filter algorithm has gathered and compared all the sums. Once all sums have been compared, the program then prints the degree value of the largest sum which indicates the path of least obstruction for the rover.

5.7.2.1 Gaussian Filter

The Gaussian Filter allows the program to provide priority to data elements based on their position in the array. The filter algorithm works by multiplying a set of nine data elements with their respective filter values. The set of data elements removes the last element and adds a new one using an index loop. Ex: 0 – 8: selected element [4], 1 – 9: selected element [5], 2 – 10: selected element [6]. The products of the set are then added together to create a sum. This sum is representative of the selected element. The provided data shows the effect of the filter as it gives more weight to the middle values. This allows the program to select the maximum sum value with greater precision. Sample data acquired by the lidar sensor during a sweep is shown below in Table 49, Figure 183, and Figure 184.

	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6	Value 7	Value 8	Value 9
Elements	250	400	750	800	800	690	740	770	530
Filter	.000229	.005977	.060598	0.251732	.382928	.251732	.060598	.005977	.000229
Product	.05725	2.3908	48.4784	188.799	306.3424	151.0392	44.84252	4.60229	.316781

Table 49: Gaussian Filter Values.

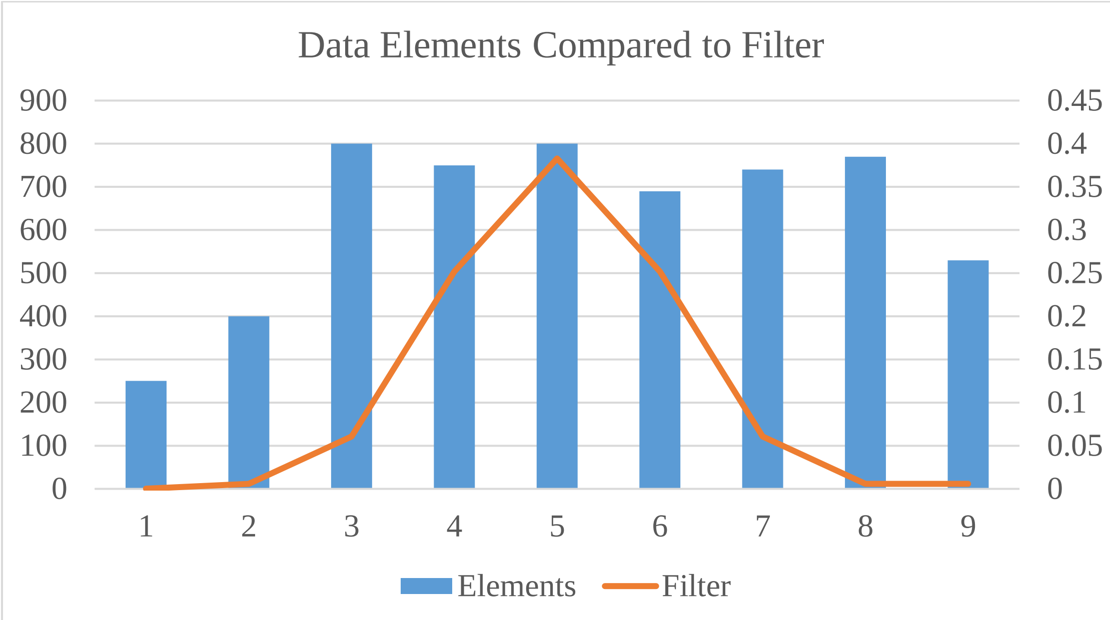


Figure 183: Lidar data elements compared to filtered data values.

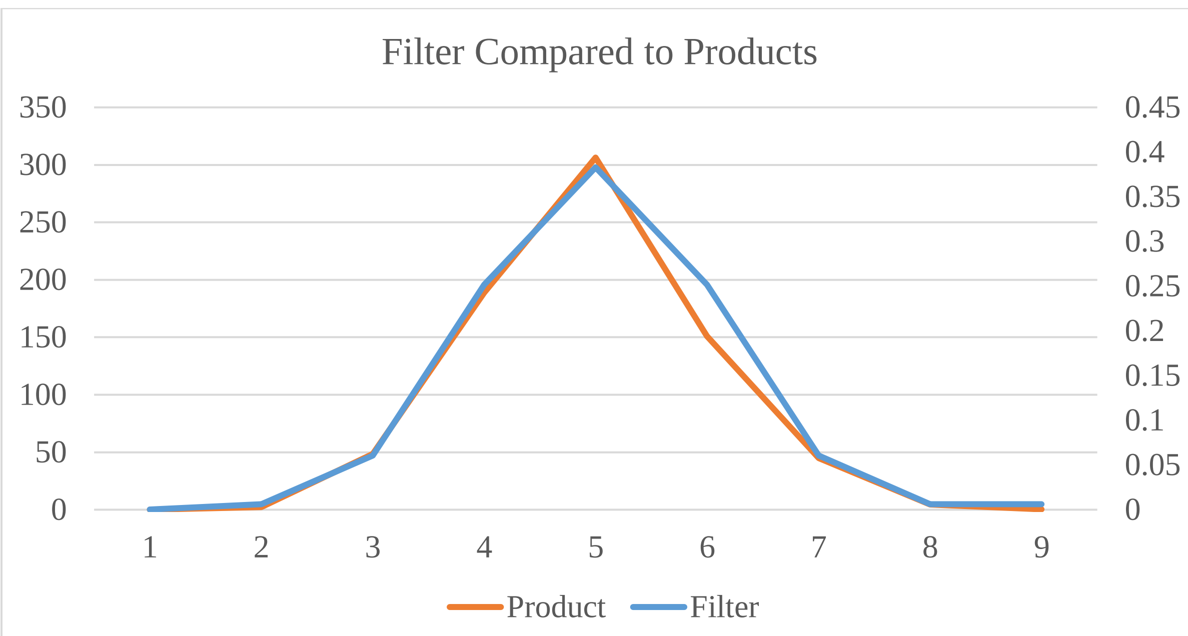


Figure 184: Filtered data compared to products of values and elements.

5.7.3 Requirement Verifications

The VL53L0X lidar sensor and controls of the OAS system have been tested extensively to confirm functionality of the system in accordance with the verification methods outlined in section 8.2.3. Results of the team derived requirement verifications are described below.

5.7.3.1 [OAS-1](#) Verification

The VL53L0X sensor was chosen for its documented range of approximately 2 to 47 in. The sensor has been tested at all distances within the range of 5 to 45 in. successfully. The sensor was able to successfully detect an object in front of the sensor everywhere within the range verifying the requirement.OAS1

5.7.3.2 OAS-2 Verification

See OAS Accuracy Test.

5.7.3.3 OAS-3 Verification

The field of view of the sensor has been increased to at least 156° successfully achieving object recognition at both limits of this field of view. This test was verified by viewing the Arduino Serial Plotter data after sweeping the sensor across the field of view taking range measurements at each degree of the sweep. The plotter data over multiple sweeps is shown below in Figure 185.

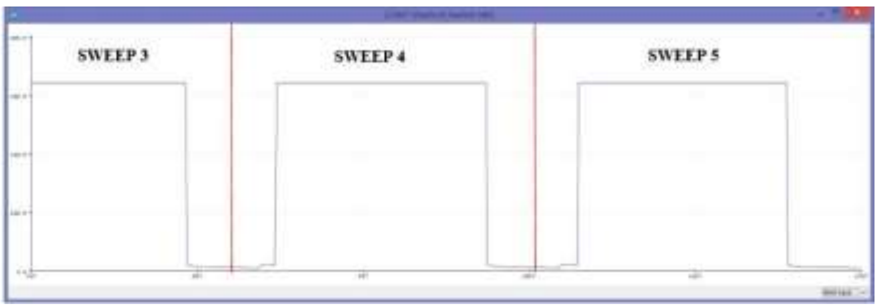


Figure 185: Arduino Serial Plotter data.

The low troughs in the data indicate lower values collected by the sensor indicating that an object is present in front of and in short range of the sensor. The high plateaus in the data indicate a period during which the sensor did not detect an object in the immediate path of the sensor. The measurement data in millimeters at three regions (the beginning, middle, and end of the field of view) is shown in

below to further represent the detection of objects at both ends of the field of view.

```
dataPoint[15] = 194          dataPoint[100] = 800          dataPoint[163] = 313
dataPoint[16] = 228          dataPoint[101] = 800          dataPoint[164] = 316
dataPoint[17] = 211   • • •  dataPoint[102] = 800   • • •  dataPoint[165] = 318
dataPoint[18] = 210          dataPoint[103] = 800          dataPoint[166] = 308
dataPoint[19] = 210          dataPoint[104] = 800          dataPoint[167] = 305
```

Figure 186: OAS-3 range data.

5.8 Solar Array System (SAS)

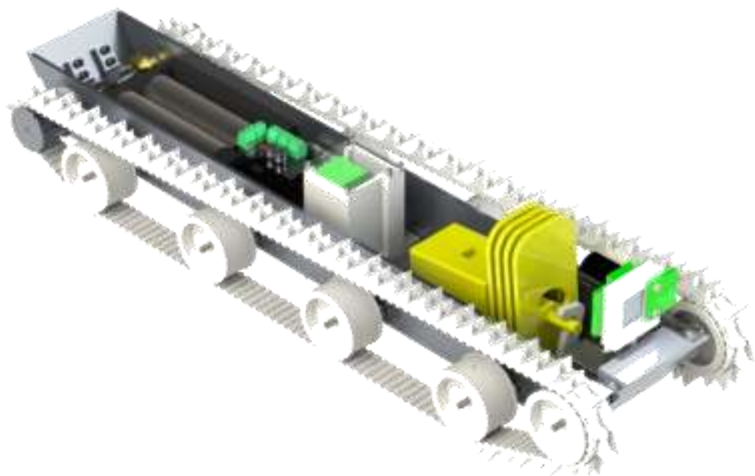


Figure 187: SAS Highlighted in Yellow.

The Solar Array System will be responsible for satisfying requirement 4.5.4 of the SOW. This system consists of four thin film solar panels mounted to support arms that are actuated by means of a tower assembly including a deployment motor, locking motor, and spring hinge. The operation and completed design of this system is discussed in this section. Statement_of_Work

5.8.1 Solar Panels

The solar cell panels will be responsible for harvesting solar energy and using the power generated as an input to the Control Electronics System. Thicker, rigid solar panels were not considered for this design of the SAS to save space, weight, and allow flexibility of the panels. The efficiency of the panels is also considered low priority as the panels will not be used to power any systems directly. For these reasons, the PowerFilm Solar MPT3.6-150 solar panels were chosen for their ultra-thin profile of 0.00787 in., large solar cell surface area of 17.11 in.^{2}, low weight of 0.0068 lbs., and high flexibility while maintaining a wattage of 360 mW. The MPT3.6-150 solar panels are shown below in Figure 188.

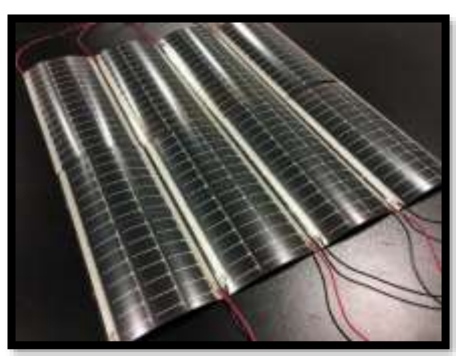


Figure 188: PowerFilm Solar MPT3.6-150 solar panels.

5.8.2 Deployment Motor

The deployment motor is responsible for actuating the solar array from the stored flight position to the fully actuated position. The 32 RPM, 0.65 ft-lb Micro Metal Gearmotor motor is powered by the 11.1V LiPo battery and it is controlled by the Control Electronics System as described in section 5.8.4. The motor is shown in Figure 189.

Figure 189: Pololu 1000:1 Micro Metal Gearmotor.

The motor is fixed inside the tower assembly housing which is described in 5.8.3.1. The deployment motor's 0.354 in. long, 0.118 in. diameter D shaft drives the solar panel support arms to deploy the solar array. The deployment motor is shown inside the tower assembly housing below in Figure 190.

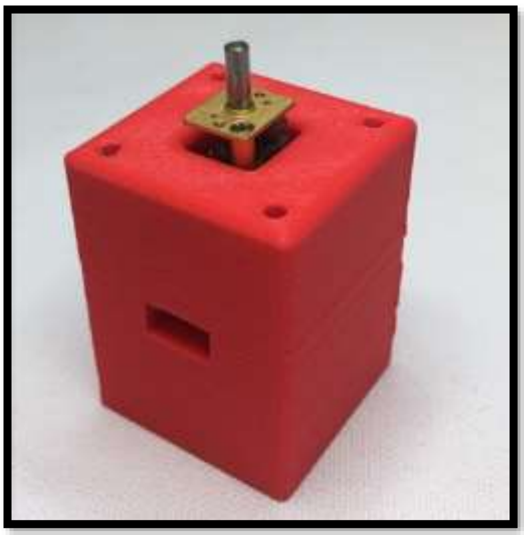


Figure 190: Deployment motor inside tower base.

5.8.2.1 Shaft Extension

The 0.354 in. long D shaft of the deployment motor was extended to drive the uppermost panel support arm, that is described in 0. The 0.118 in. diameter motor shaft has been coupled to the 0.236 in. diameter D shaft of the deployment motor with a set screw shaft coupler, shown below in Figure 191. The 0.236 in D shaft motor was cut to an overall length of 1.537 in., 1.157 in. of which extend past the shaft coupler. The shaft extension allows for the snap ring above the top panel to retain the panels. The extension also allows for the tower to be locked in its flight configuration, as discussed in Section 5.8.3.3.

Figure 191: Set screw shaft coupler.

Acrylic washers are used as spacers between each of the panel support arms and have been pressed onto the coupler. The washers prevent accidental contact between the support arms and sandwich the arms together to keep them aligned horizontally during flight. There is a washer fit on the shaft coupler below each panel support arm and one additional spacer below the bottom fixed panel support arm. The spacers were laser cut from 0.0815 in. thick cast acrylic with an inner diameter of 0.411 in. and an outer diameter of 0.570 in. The spacers are press fit onto 0.420" for precision that allowed the needed press fit. The as built assembly drawing is shown in Figure 192 and the constructed assembly is shown in Figure 193.

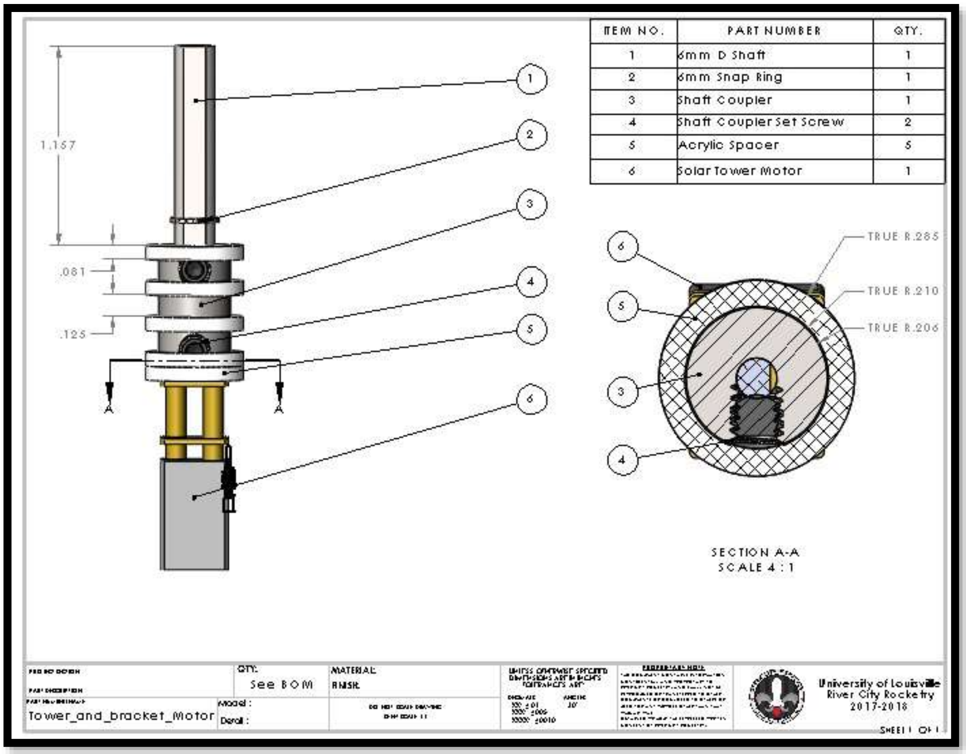


Figure 192: Deployment motor assembly drawing.

Figure 193: Deployment motor shaft extension and spacers.

5.8.3 Tower Assembly

The tower assembly rotates about a hinge from the stowed flight position and deploys the solar array after the rover reaches its final destination. Array deployment requires the panels to be above the walls of the rover and clear of any other system for proper deployment and this has been ensured by Payload SAS-4. The actuating design allows the solar panels to be larger as they are deployed after the Rover exits the vehicle, without the limitation of the airframe diameter. The assembly is shown in Figure 194.

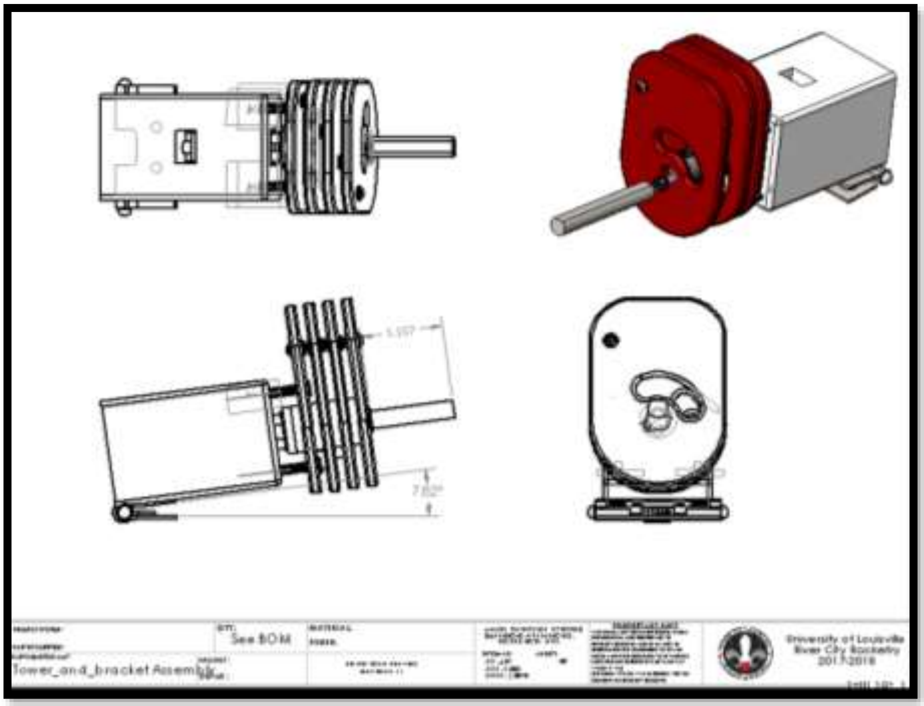


Figure 194: Tower assembly as built drawing.

5.8.3.1 Tower Base

The tower base is the deployment motor housing as well as the solar array mount. The deployment motor fits into the slot in the top of the tower base and the motor power wires exit through an aft-facing hole. There is a 0.236 in. tall cylindrical standoff in the inside of the tower base that the deployment motor bottom sits on to prevent damage to the motor wires. A chamfer was added to the deployment motor hole to allow for easy installation.

The solar panel support arms also mount to the tower base through 4 0.750 in. long 4-40 socket head cap screws. The screws pass through the 4 holes in the bottom support arm and thread 0.400 in. into the tower base.

The tower base was 3D printed out of PLA with 85% infill on a printer with a heated build plate. The as built drawing of the tower is shown in Figure 195 and

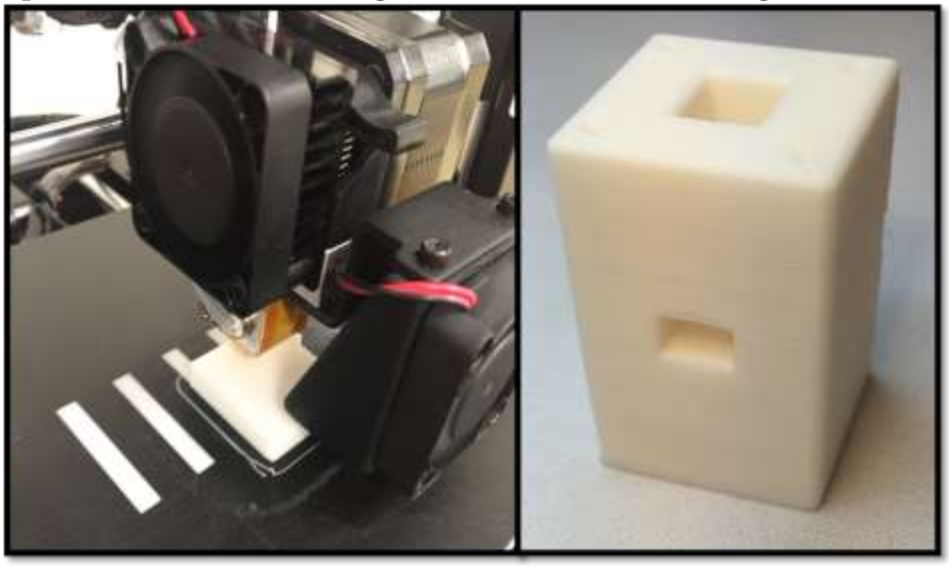


Figure 196 shows the tower base during and after print.

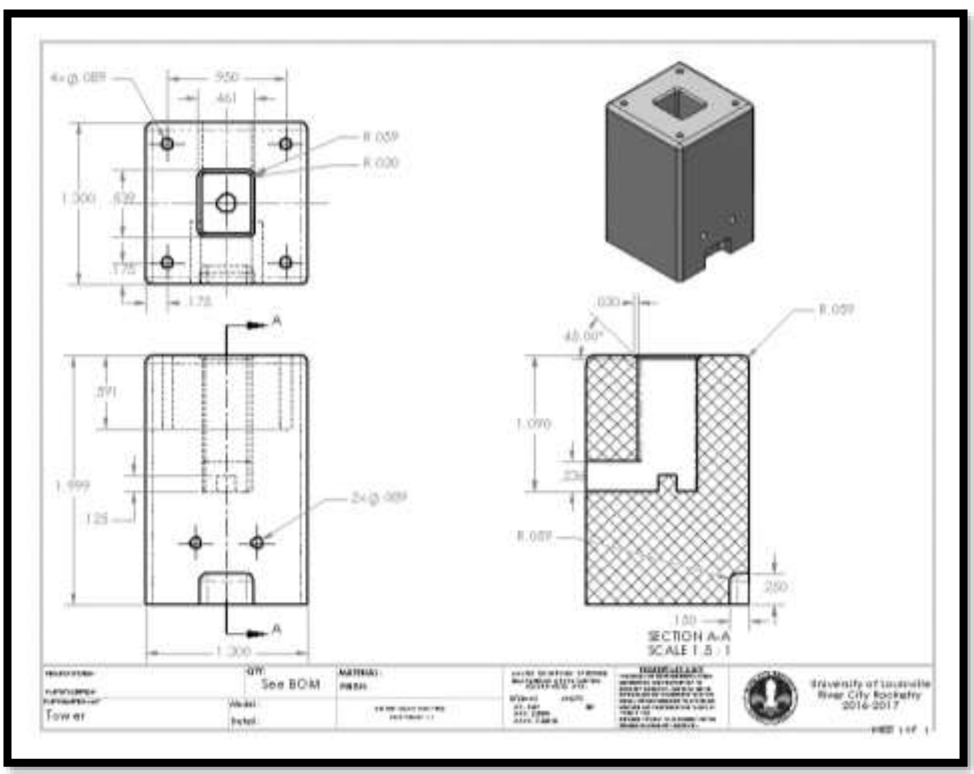


Figure 195: As built drawing of the tower base.

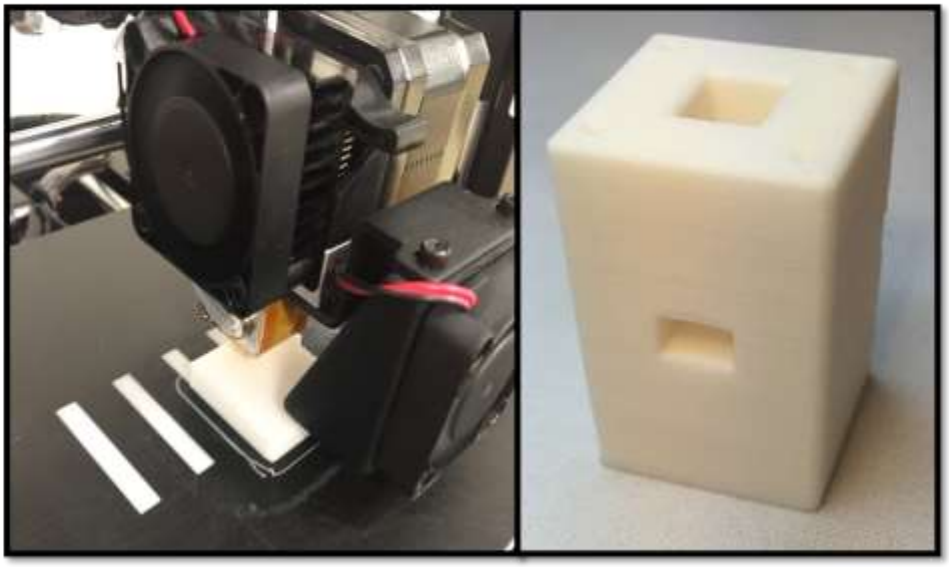


Figure 196: Tower base 3D print.

5.8.3.2 Spring Hinge

The spring hinge is an assembly of two hinge plates, a torsion spring, and a pin. The hinge was purchased and two additional holes were cut through one plate with a drill press. The tower base is mounted to the bottom of the rover with the spring hinge through 4 0.375 in. long 4-40 socket head cap screws. Two of the screws thread through the additionally cut holes and into the tower base. The other two screws thread through the original hinge holes into the bottom of the RBS, as shown in Figure 197.

Figure 197: The spring hinge mounted to the tower base and the RBS.

The hinge is mounted so the torsion spring raises the tower from its stowed flight position of 7.82° and keeps the tower in the upright deployed position of 91.80° after the locking motor, discussed in section 5.8.3.3, is released. The spring is relaxed at 275° from the bottom of the RBS, allowing the spring to be in torsion at the stowed and deployed states, ensuring that the tower remains in the deployed position. The team derived requirement Payload SAS-1 verified the performance of the spring hinge.

Figure 198 shows the as built dimensions of the spring hinge and the angles at the different hinge panel positions as measured from the panel that is fixed to the bottom of the RBS.

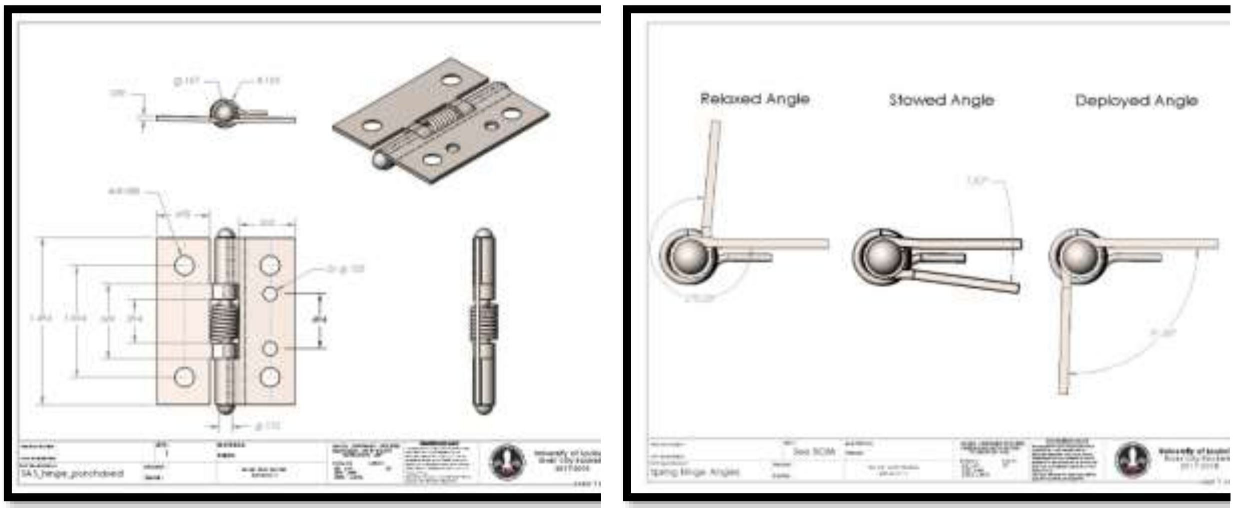


Figure 198: As built dawing of the spring hinge and the hinge angles.

5.8.3.3 Tower Locking Motor

The tower locking motor is the same motor as the deployment motor. The locking motor is mounted to the RBS with the custom mounting bracket shown below in Figure 199. The motor mount was 3D printed using PLA and 100% infill. The print was oriented with the hole for the motor shaft on the plate for maximum strength. Four 0.375 in. long 4-40 socket head cap screws thread into the RBS through the locking motor mount to fix the motor to the RBS.

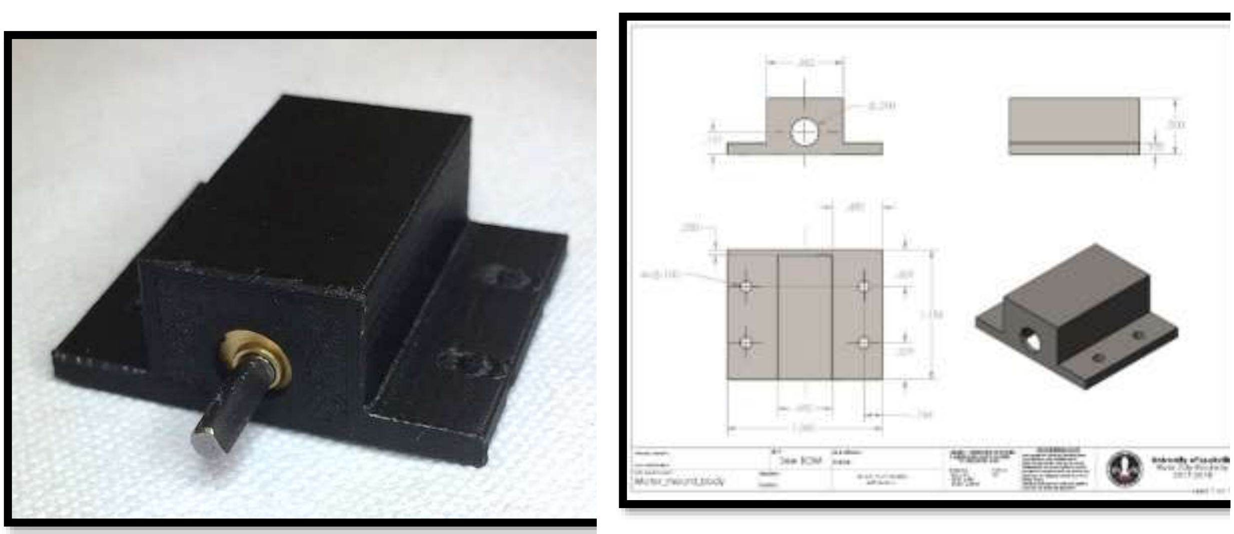


Figure 199: Tower locking motor mount and as built drawing.

An L-shaped attachment slides onto the locking motor's and it is held in place with a 0.175 in. long 4-40 socket head cap screw. The L tab attachment was water jet from 0.150 in. thick aluminum plate and the hole for the screw was drilled and tapped by hand.

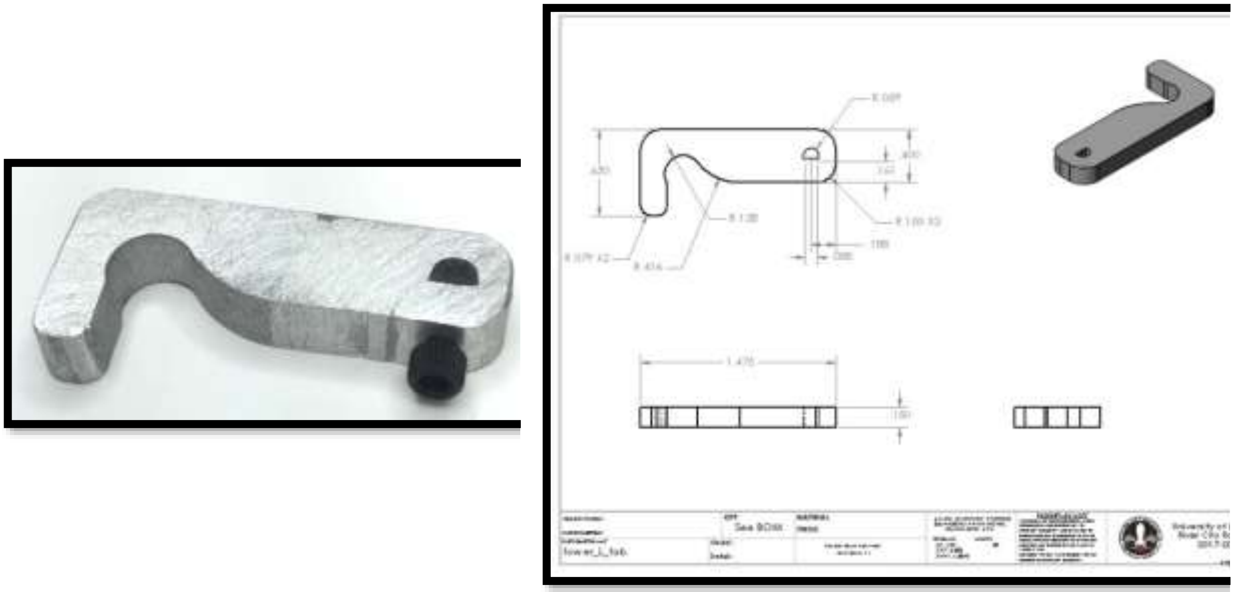


Figure 200: Locking motor L tab and the as built drawing.

The attachment hooks around the end of the deployment motor shaft extension, preventing the spring hinge from actuating and locking the tower base in the stowed configuration. The L tab attachment rotates 55° when the solar array is ready to deploy, allowing the torsion spring to actuate the tower into place. Figure 201 shows the L tab in the flight configuration then after the 55° rotation.

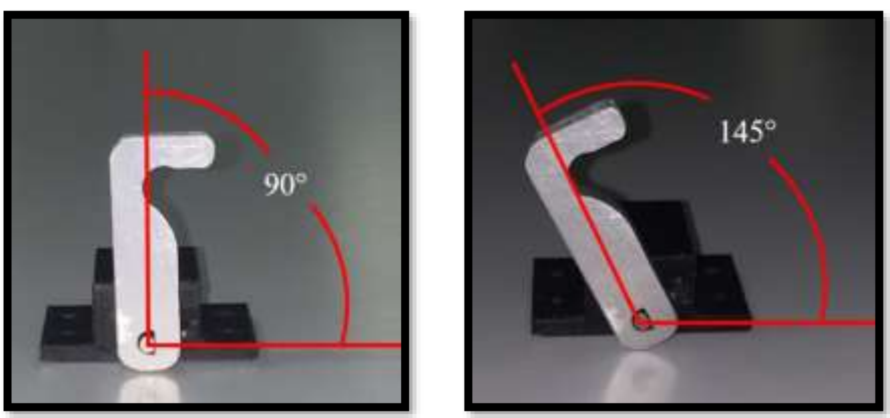


Figure 201: L tab attachment flight before and after release.

Figure 202 and Figure 203 show the solar tower and tower locking motor in their stowed flight and deployed configurations.

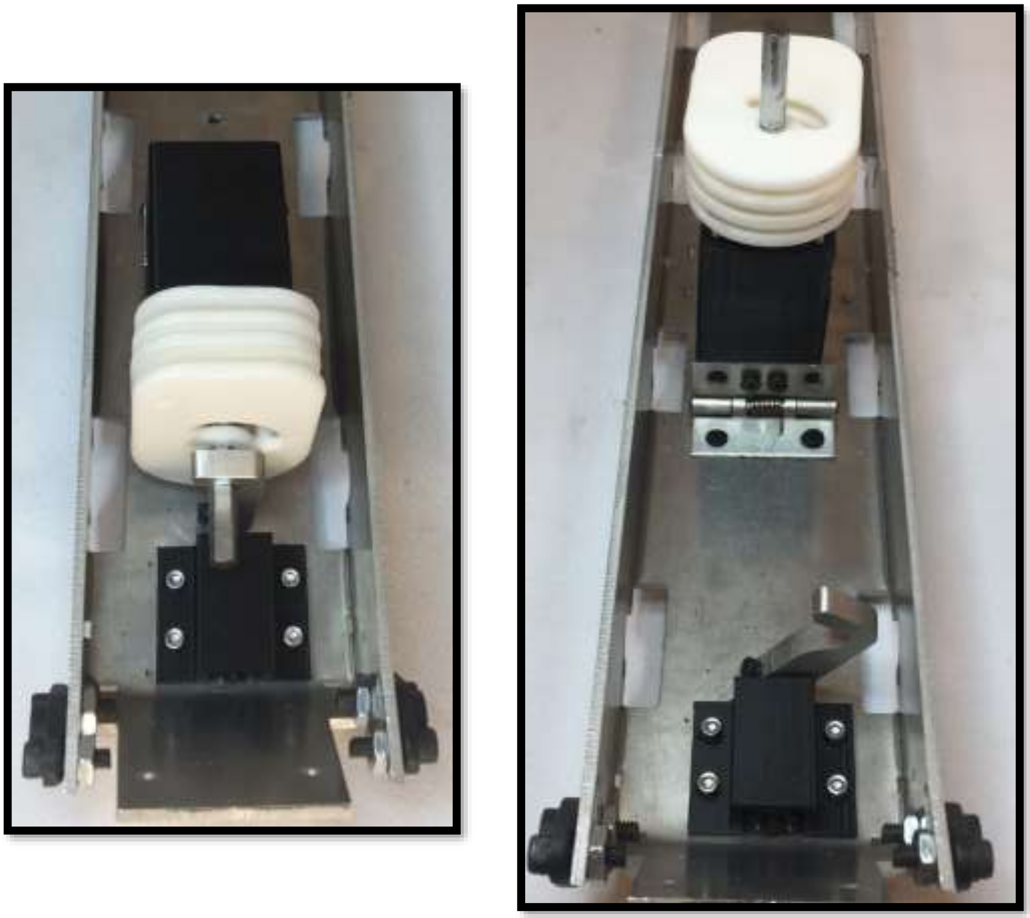


Figure 202: Top view of the towe assembly before and after locking motor rotation.

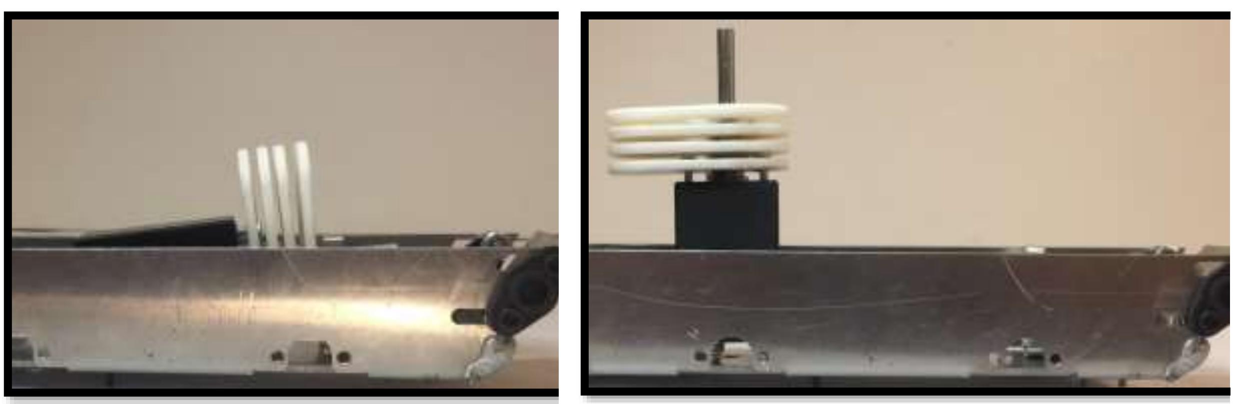


Figure 203: Side view of the towe assembly before and after locking motor actuation.

5.8.3.4 Panel Support Arm

The solar panels are fixed to the top of the panel support arms with epoxy and a screw, nut, and washer. The solar panels overhang the edges of the panel support arms to take advantage of the panel flexibility. The edges of the solar panels bend around the support arms while in the stowed position and the panels expand vertically after the Rover exits the vehicle. The bending allows the panels to fit inside the rover body while maintaining large surface area after deployment.

Each panel support arm consists of a central shaft hole, a peg slot, a towing peg on one face, a hole for a screw, and a counterbored hexagon for a nut for solar panel mounting. The screw threads through the solar panel and the panel support arm, threading through the nut that in the counterbore hole in the bottom of the panel. Each panel was 3D printed in PLA with 75% infill. The as build dimensions of Panel A, the upper support arm, are shown in Figure 204.

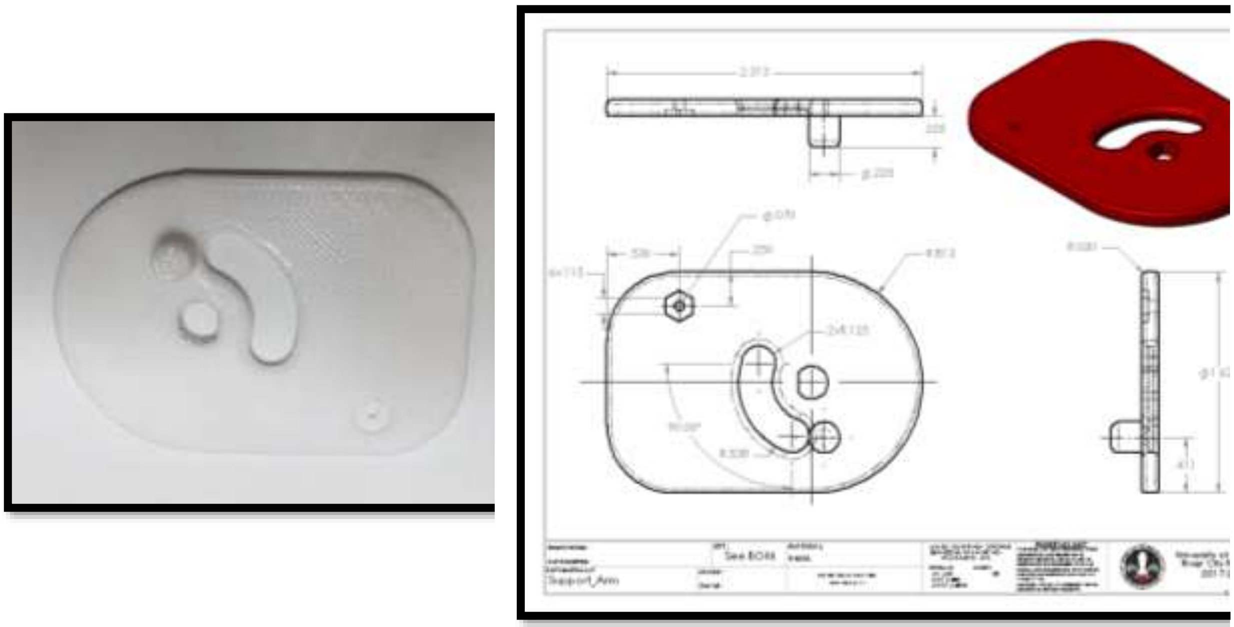


Figure 204: Top panel support arm.

The panel features must align with those of the panel below them, requiring some dimensions to vary across panels. The peg slots are rotated 35° further on each subsequent arm. The top arm has a 0.236 in. diameter D shaped hole for the deployment motor shaft to fit in and drive the support arm. The other support arms have holes of 0.425 in. diameter to fit over the shaft coupler. The counterbore hexagon holes are spaced 0.375 in. apart on each subsequent panel holes are spaced 0.375 in. apart on each subsequent panel. The bottom arm, panel D, is fixed to the tower base with four 4-40 screws that thread into the tower base and does not have a towing peg. The 3D printed panel support arms are shown in Figure 205 and the varied dimensions are shown in Figure 206.

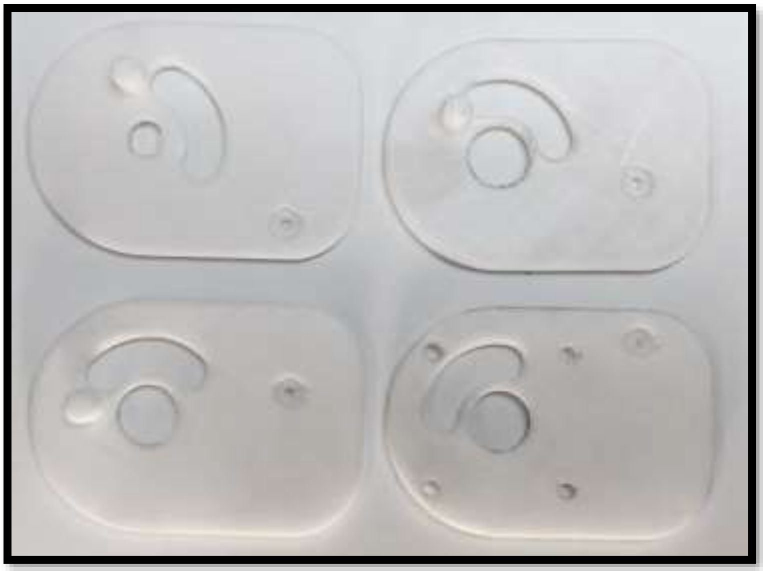
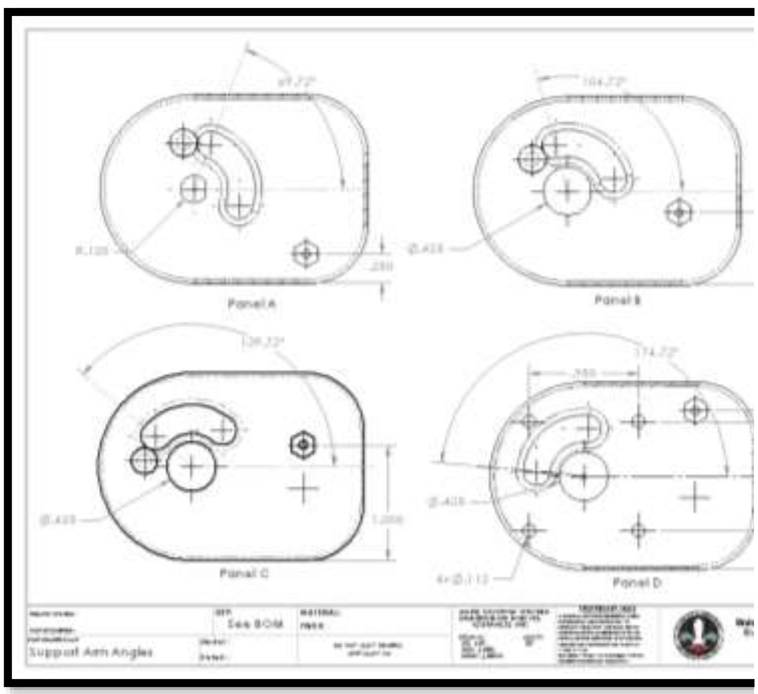


Figure 205: Panel support arms A through D.



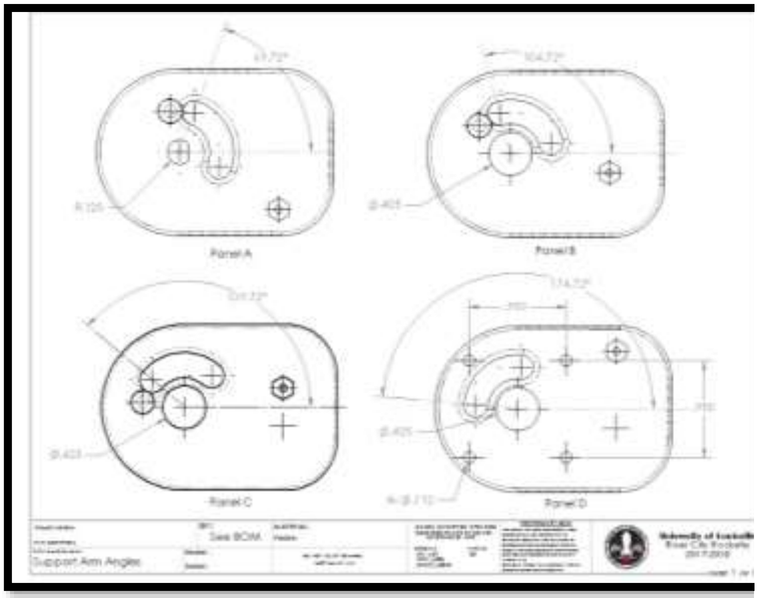


Figure 206: Suppor arm panels as built dimension variations.

The arms stack vertically and rest on the spacers that are pressed onto the shaft extension coupler, as discussed in section 5.8.2.1. The top panel is secured with a retaining ring and the arms stow as shown in Figure 207.

Figure 207: Support arm stowed configuration.

Figure 208 shows the support arms throughout actuation, beginning with the rotation of the top panel, panel A, that is driven by the deployment motor. The deployment then cascades down through the lower panels due to contact between the peg of the upper arm and the slot of the lower arm. The deployment is shown in Figure 208.

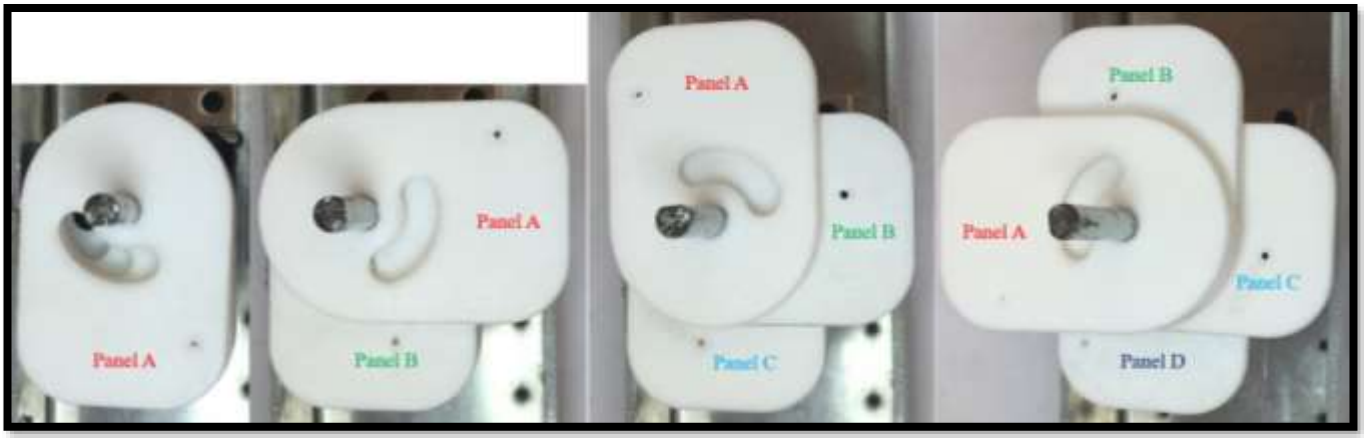


Figure 208: Support arm deployment order.

Figure 209 shows the towing peg locations of two stacked panels before and after deployment.

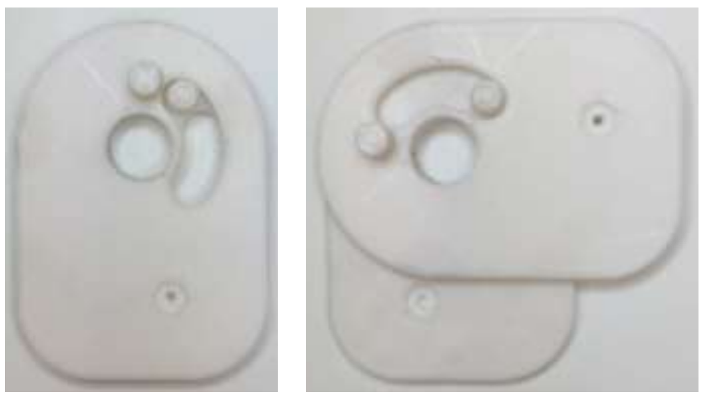


Figure 209: Bottom view of arm orientation before (left) and after deployment (right).

5.8.4 Interface with the CES

The four solar panels will be connected in parallel and the output of the panels connected directly to an input of the Control Electronics System control board discussed in section 5.10.1. The power level of the solar power generated will be read by the CES control board and a threshold set using a scaling factor to trigger the Surface Imaging System's camera module which is discussed below in section 5.9. The panels will be connected in parallel to allow the trigger to be set at a value lower than the maximum possible wattage of all four panels to account for weather conditions during the mission.

The SAS deployment motor is controlled by the CES motor driver board to maximize the power applied to the motor during deployment ensuring that all panels are able to successfully unfold.

5.8.5 Requirement Verifications

The SAS has been tested in accordance with the requirement verification methods outlined in section *8.2.3.* The results of the verifications are described below.

5.8.5.1 SAS-1 Verification

The tower successfully actuated via the spring hinge after being released and remained upright under its own power. The hinge and base of the tower assembly are shown before and after actuation below in Figure 210.

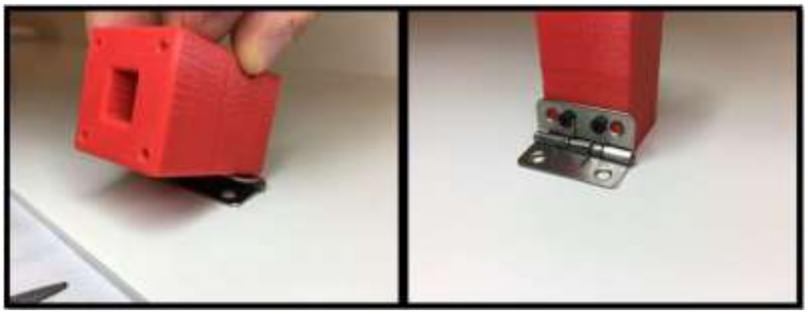


Figure 210: Tower assembly stowed (left) and actuated (right).

The panels and deployment motor were removed for the images to more closely show the actuation mechanism. These results successfully verify the requirement.

5.8.5.2 SAS-2 Verification

A test script was written to fold and unfold the solar panels using Bluetooth commands sent from a team members cellphone. The panels successfully deployed fully without any damage to the panels or panel support arms and were able to fold easily for resetting the test. The panels in their folded and unfolded states are shown below in Figure 211.

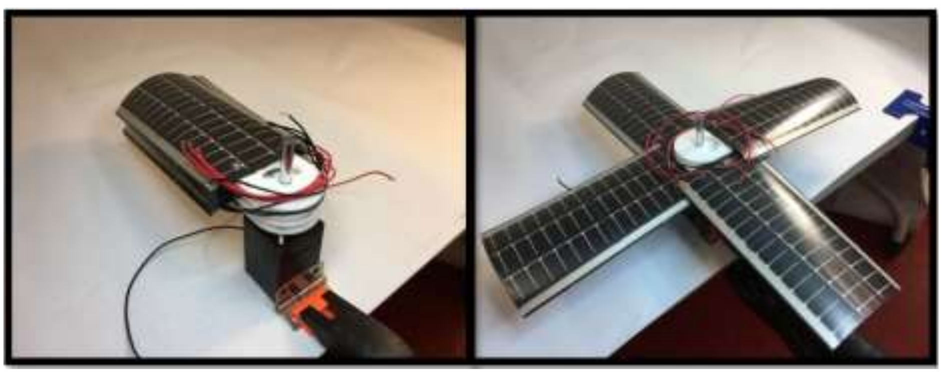


Figure 211: Solar panels folded (left) and unfolded (right).

This result successfully verifies the requirement as the surface area of exposed solar cells increased by a factor of four.

5.8.5.3 SAS-3 Verification

The solar panels were connected in parallel to conduct this demonstration as that is the configuration the panels will be in during the mission. The panels voltage and current were measured with a digital multimeter throughout the 30 second duration of the demonstration. The steady-state values characterizing the system are shown below in Table 50.

Voltage (V)	Current (mA)	Power (mW)

4.08	1.25	5.1

Table 50: Power characteristics of solar panels.

The continuous power measured of 5.1 mW exceeds the requirement of 4 mW successfully verifying the requirement.

5.8.5.4 SAS-4 Verification

Upon assembling the final rover, prior to stowing the panels for flight, the clearance with the other onboard rover structures was measured at 0.5 in. The clearance was measured using a digital caliper. This result successfully verifies the requirement.

5.8.5.5 SAS-5 Verification

See Flight Loads Testing Series._SAS-5

5.9 Surface Imaging System (SIS)

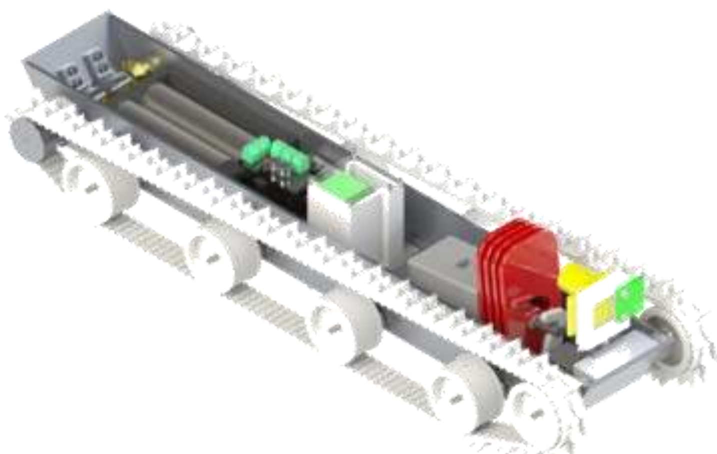


Figure 212: SIS Highlighted in Yellow.

The Surface Imaging System has been added to the payload as a secondary mission. This mission will not affect in any way the ability of the payload to complete its primary mission. The system has been added to embrace the mindset of the rover challenge of deploying an autonomous rover on another planet to collect data about that planet, of which images provide great scientific value. The SIS is responsible for using the power harvested by the SAS as a trigger to take images of the rover and surrounding ground area and storing the images on the CES data logging board's microSD card, for analysis after retrieval of the payload.

5.9.1 Camera Module

The camera module is responsible for taking the images and relaying them to the microSD card. The camera has \ be configured to take pictures at 1280x920 full HD resolution. This is not the highest resolution the camera is capable of but has been chosen due to its lower power consumption. The average time required for the module to both capture an image and send the image data to the microSD card has been determined experimentally and can be seen in the results of SIS-1 below. The camera module with a sample image taken using the camera is shown below in Figure 213.

Figure 213: OV5642 camera and sample picture.

5.9.2 Field of View Extension

The field of view, and thus data collected, has been increased by mounting the camera module on the back side of the OAS lidar sensor mount. By mounting the camera in the front of the rover with the lens facing the rear, the camera provides data on both the rover's state after completion of its primary mission and the ground in the surrounding area of the rover. By mounting the camera to the same OAS servo motor in section *5.7*, a single motor can provide a drastically increased field of view for both the lidar sensor and camera. The servo pans the camera 180 degrees allowing it to take images of a much wider range of the rover and surrounding ground. The increased field of view is represented in blue below in Figure 214 and shown in the results of SIS-2.

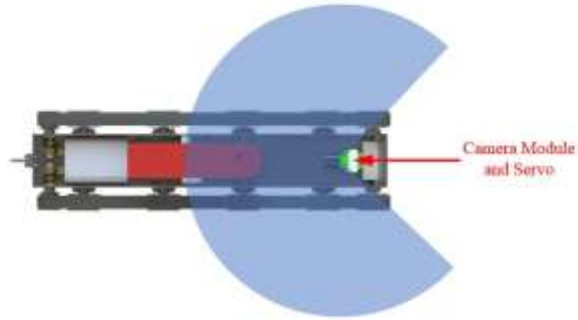


Figure 214: SIS field of view.

5.9.2.1 Mounting

The camera is secured to the lidar sensor and camera mount as described above in 3.7.1. The mount will feature a through-hole in the middle for the camera's heat sink to sit in, and it is designed and dimensioned to not interfere with the Lidar sensor. The heat sink configuration as well as a detailed drawing of the mount can be seen in Figure 182. The camera will be positioned sideways to prevent the wiring from interfering with the rotation of the OAS assembly. The mount is 3D printed out of PLA plastic by a MakerBot Replicator+. The configuration of the camera on the OAS mount assembly is shown below in Figure 215.

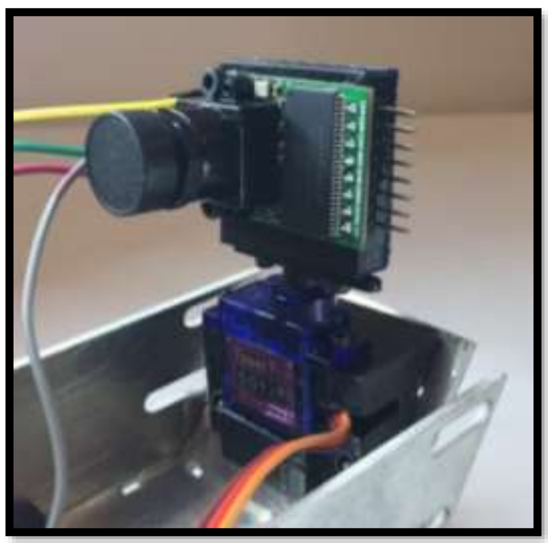


Figure 215: Camera Module Mount Assembly.

5.9.3 Interface with CES

The SIS camera module requires a 3-5V supply voltage and draws 390mA peak during operation. The "BAT" pin of the CES control board is directly taken from the controller battery which is 3.7V and can be used to power the camera module. This negates the need for a voltage regulator to power the camera.

The power generated by the solar panels will be fed into the control board as an input that will only be high if the panels have been deployed successfully as described in section 5.8.4. This input will be read by the CES control board as a voltage level and scaled to be within the range of 0 to 100,000 where 100,000 indicates all four panels exposed to intense, direct sunlight. A trigger will be set at 90,000 (to account for weather conditions) to initiate the SIS phase of the control scheme. An example of the trigger being surpassed is shown below in Figure 216.

```
Voltage = 87988.28 LOW
Voltage = 88183.59 LOW
Voltage = 87890.63 LOW
Voltage = 87792.97 LOW
Voltage = 91503.91 HIGH
Voltage = 99902.34 HIGH
Voltage = 99902.34 HIGH
Voltage = 99902.34 HIGH
```

Figure 216: Power level trigger.

5.9.4 Requirement Verifications

The SIS has been tested for functionality in accordance with the verification methods outlined in section 8.2.3. The verification results are described below leading to the confirmation of secondary mission success capability of the system.

5.9.4.1 SIS-1 Verification

Demonstration software was developed for the camera module to take and save images successively for 5 minutes continuously at a resolution of 1280 x 960. The script output data showing characteristics of each image taken, the time taken to perform key steps, and the battery voltage to the Arduino IDE serial monitor. This output is shown below in Figure 217.

```
Taking picture: 37 at time 294.55s
start capture.
The fifo length is :138392
OK
Capture Time: 194ms, Save Time: 2708ms
Pic ID: #612
VBat: 4.23V
------DONE------
```

Figure 217: SIS-1 serial monitor output.

The final image count was 37 resulting in a rate of just over 7.4 images per minute successfully verifying the requirement. Timing data at key steps of the image taking and saving process were compiled and averaged. The results are shown below in Table 51.

Pic #	Time Stamp (s)	Capture Time (s)	SaveTime (s)	Time Stamp Difference
1	0.00	0.174	3.095	
2	8.31	0.177	3.025	8.31
3	16.56	0.245	3.093	8.25
		•		

•
•

35	278.68	0.195	2.697	278.68
36	286.62	0.188	2.691	7.94
37	294.55	0.194	2.708	7.93
AVG.		**0.182**	**2.945**	**8.182**

Table 51: Image capture timing data.

5.9.4.2 SIS-2 Verification

The OAS servo motor demonstrated capability to increase the direct line of sight normal to the camera module's sensor to 180°. Objects were placed 180° apart from each other and the camera module was panned from one object to the other. The resulting images showed both objects directly in the center of the frame. These images taken of the objects are shown below in Figure 218.

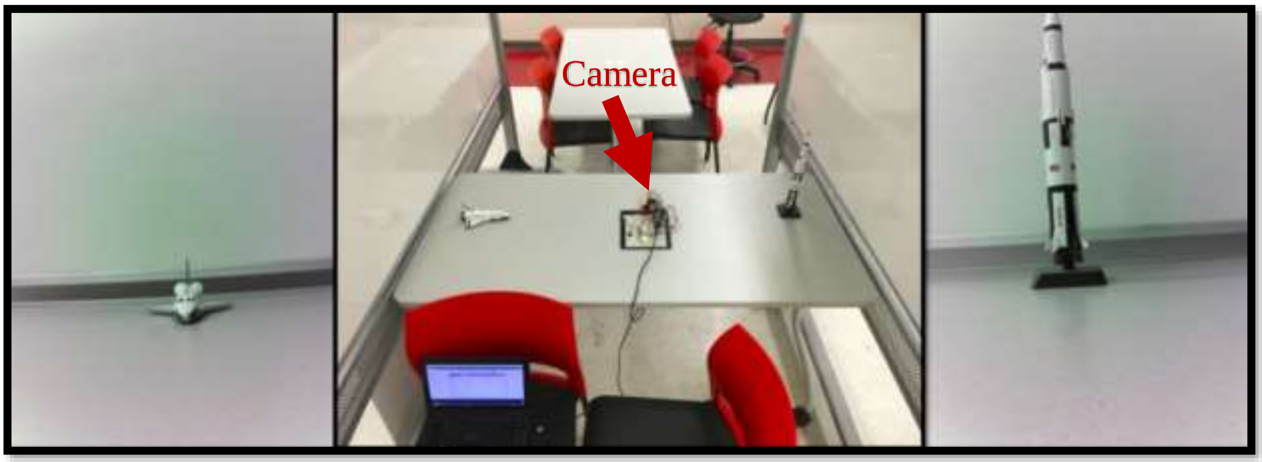


Figure 218: SIS field of view.

This result exceeds the required 156° successfully verifying the requirement.

5.9.4.3 SIS-3 Verification

The solar panels of the SAS were connected in parallel and a power level trigger set at 85,000. This level is representative of 3 of the 4 solar panels being fully exposed to direct light. The solar panels before and after the third panel was uncovered is shown below in FIGURE followed by the terminal output of the software indicating the camera beginning to take pictures after the trigger was exceeded in FIGURE.

Figure 219: Before and after 3rd panel covered removed.

```
Power generation too low. Trigger = 85000, Power Level =  84082.03
Time running = 15014
Power generation too low. Trigger = 85000, Power Level =  84570.31
Time running = 16016
Taking picture at 17016
start capture.
The fifo length is :175128
OK
Capture Time: 239ms, Save Time: 3589ms
Pic ID#: 419
---Done---
Power Level = 91308.59
```

Figure 220: SIS-3 terminal output.

The camera module beginning to take pictures after the trigger was exceeded as indicated by the terminal window successfully verifies the requirement.

5.10 Control Electronics System (CES)

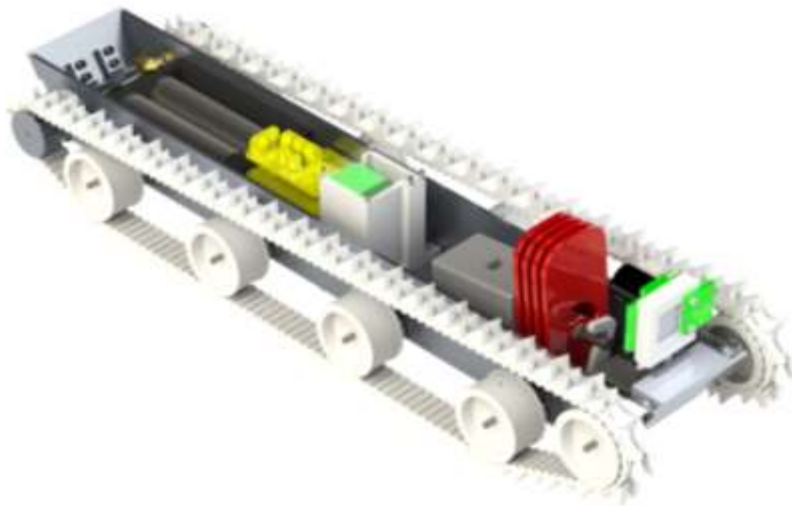


Figure 221: CES Highlighted in Yellow.

The Control Electronics System is responsible for controlling all payload electronics onboard the launch vehicle and storing any relevant data collected by the payload throughout the mission.

5.10.1 Hardware

The custom designed printed circuit board for the CES was prototyped using an LPKF ProtoMat S63 Milling Machine. The machine generates tool paths based on the gerber files generated using EagleCAD's cam processor. These paths are then milled using a variety of milling bits based on the type of cut being made for different features of the board. The machine milling the Control Electronics System PCB is shown below in Figure 222.

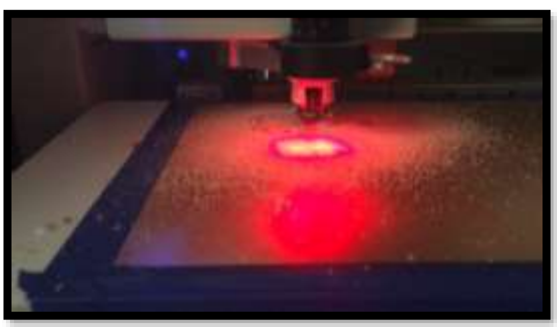


Figure 222: LPKF ProtoMat S63.

A double-sided copper sheet was used for prototyping the board as the design has components and traces on a top and bottom layer. The fully populated prototype board is shown below in Figure 223.

Figure 223: Prototype CES PCB.

This prototype was used for electrical and functionality testing. After confirmation that the design was capable of performing all necessary tasks, the design was sent to Advanced Circuits for professional manufacturing. The board received prior to and after populating is shown below in Figure 224.

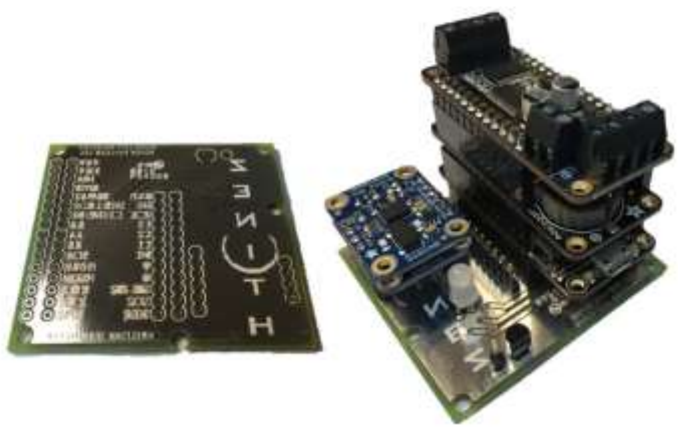


Figure 224: CES Printed Circuit Board.

This board has been electrically and functionality tested to satisfaction. The PCB was designed to allow the control stack consisting of the Feather M0 Bluefruit LE microcontroller, FeatherWing Adalogger, and FeatherWing Motor Driver to be easily mounted and removed from the PCB by using female headers on the PCB matching with male headers on the controller. This provides ease of access in the event that a board needs to be replaced or new software needs to be uploaded. The two gyroscopes have also been stacked and secured using headers for the same reason.

Male header pins are connected through the PCB to each I/O pin of the controller allowing all wiring to be separate from the control board. Again, this allows for ease of integration and removal of wiring or the control stack.

5.10.1.1 Batteries

The controller battery and motor battery have not changed since CDR. The controller battery is a single cell 500 mAh Lithium Polymer (LiPo) and the motor battery used to drive the 4 motors connected to the control stack's motor driver is a three cell 400 mAh LiPo. Both batteries are shown below in Figure 225.

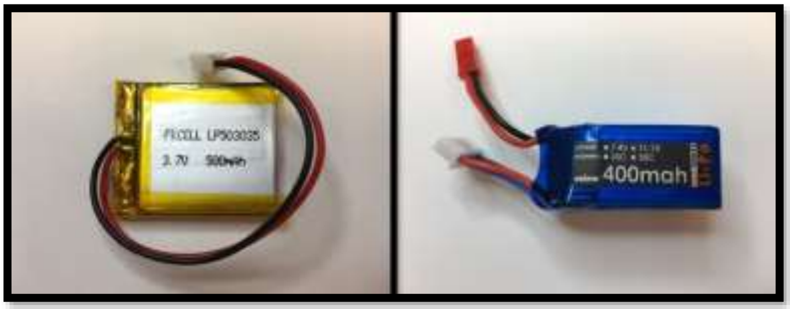


Figure 225: Controller (left) and motor (right) batteries.

5.10.1.2 Added Transistor

A transistor switch has been added to the board design to utilize the controller battery to power the SAS locking motor. The gate of this BS170 NMOS transistor will be controlled by a digital output of the control stack. The BS170 NMOS transistor was chosen for its normally open configuration ensuring safety and reducing power consumption. Additionally, the model has a short turn-on time of 4.0 ns with a maximum drain-source voltage of 60V, well above the 3.7~4.2V of the battery, and nominal 2V gate-threshold ensuring the Feather M0 is capable of controlling the switch.

5.10.1.3 Added LED

An RGB LED has been added to the board as a visual indicator of the state of the rover. During key phases of the mission, the LED will be illuminated according to the following Table 52.

Mission Phase	RGB Color	Meaning
Setup Completion	Sequence	A sequence of different colors flashing indicate that the setup for the program has completed and the rover is configured for flight.
DTS Phase	Red	No deployment signal has been received, but the system remains looping waiting for signal.
Deployment Signal Reception	Blue	Deployment signal has been successfully received and recognized, moving to orientation check.
Orientation Check	Green	Orientation check is successful, rover is safe to deploy and continue mission.
Error	Red (flashing)	If an error at any time occurs or the orientation check is unsuccessful, the LED will flash red until the system is powered down.

Table 52: Indicator LED states.

5.10.1.4 Added Power Switches

Two switches have been added to the rover that control the power from the controller battery and the motor battery. The switches have been mounted to the front of the rover to give access to them immediately prior to final assembly of the rocket. This maximizes the allowable pad, flight, and payload mission times by turning the switches to the on position as late as possible. The motor battery should be flipped before the controller battery to initialize the motor driver properly and as such the switches have been color coded. The switches mounted to the front of the rover integrated into the launch vehicle is shown below in Figure 226.

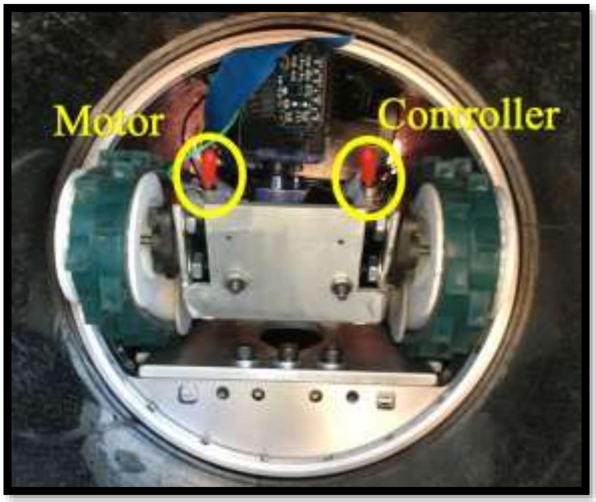


Figure 226: Power switches.

5.10.2 Software

Software has been constructed using the Arduino Integrated Development Environment (IDE) to match the process diagram of the control scheme shown in the Critical Design Review report as Figure 159. The software controlling the rover is function based and specifically designed to complete the payload's primary mission and secondary missions.

The controls have been written with safety as the highest priority by implementing a unique deployment signal and an orientation check prior to deploying the rover. Boolean variables "deployRover" and "orientation" are initialized to false on startup. The states of these variables must be changed due to meeting their respective condition in order for the payload to continue its mission. The conditions to change the state of these variables is described below in Table 53.

Variable	Condition
deployRover	The Deployment Trigger System's receiver module has received a packet of data from the transmitter that matches the predefined unique packet.
orientation	The average of 20 pitch and roll axis angle of inclination data points are below their respective threshold (pitch: 30°, roll: 50°)

Table 53: Key boolean variables and change state conditions.

While the condition to change the state of the "deployRover" variable is not met, the program will loop searching for the proper deployment signal. If an incorrect packet is received by the payload, the program will clear the received packet and continue waiting for the correct packet to be received. This ensures no other transmission devices are capable of deploying the rover.

If the orientation check fails based on the average of the 20 values of orientation data, the program will pass an error, log the error code and text, and loop within the error ensuring that it is no longer possible to deploy the rover.

5.10.2.1 Setup

During the setup() phase, the data logging file is created with a unique filename based on the time indicated by the real time clock onboard the control stack. The motor driver is then initialized to drive the motors at predefined speeds. Following this, both BNO055 IMU's are initialized and initial orientation data is taken. Finally, all I/O pins are configured as inputs or outputs and initial values of the pin are set.

5.10.2.2 DTS Phase

The DTSPhase() function of the software is the first operation after the setup to be called. This function loops waiting for the Deployment Trigger System's receiver module to pass a packet of data to the controller. The controller compares the packet received to a predefined packet. If and only if the packets are identical will the function change the variable "deployRover" to true and break out of the loop to call the next function.

5.10.2.3 Orientation Check

The OrientationCheck() phase queries the two BNO055 IMU's for gyroscope data to indicate the pitch and roll angles of inclination relative to the values initialized in the setup. The function takes 20 data points for each axis of rotation and determines an average of those values. If and only if the two averages are below (zero degrees being perfectly upright) the thresholds set will the function change the boolean "orientation" to true dropping out of the function. In the event that orientation is improper, an error will be logged and the payload will cease operation.

5.10.2.4 Unlock RLM

The UnlockRLM() phase of the software applies power to the Rover Locking Mechanism's motor, rotating the loading arm away from the latch on the rear of the rover, allowing the rover to translate.

5.10.2.5 Exit Bay

The ExitBay() phase has been separated from the drive phase of the rover due to the desire for the Obstacle Avoidance System to only become active after the rover has exited the airframe. Failing to exit the bay before the OAS actively searches for objects may cause the rover to remain in the airframe, although the algorithm written for the OAS should prevent this.

5.10.2.6 Drive Phase

The DrivePhase() operation of the controls collects data from the Obstacle Avoidance System while driving the rover forward. The algorithm of the OAS is discussed in section 5.7. The rover will continue driving forward until a calculated distance of 5 feet has been achieved or a timeout of 5 minutes of drive time has been reached exceeded. In the event that an obstacle has been detected, a method has been written allowing the rover to turn itself to a precise heading using the BNO055 IMUs yaw orientation data.

5.10.2.7 Deploy Array

The DeployArray() phase unlocks the solar tower assembly by applying a high signal to the gate of the MOSFET which allows power to flow from the controller battery to the Solar Array System's locking motor. This rotates the SAS locking bracket away from the shaft extension of the deployment motor allowing the spring hinge to raise the solar panels. The motor driver on the control stack is then commanded to drive the SAS deployment motor unfolding the solar array.

5.10.2.8 Camera Phase

The CameraPhase() function handles the secondary mission operation of the rover. The function continuously monitors the power generation level from the solar panels. When the generation is above a predetermined threshold, the controls will command the camera to begin taking pictures and save the pictures on a microSD card. The cameras will be taken at every 20 degrees of a 180 degree sweep of the servo motor. This sweep is controlled by a Pulse Width Modulation output to the servo by the controller.

5.10.3 Requirement Verifications

All requirement verifications of the Control Electronics System were determined to be verified by means of testing. As such, all results can be found in sections *8.1.2.6*, *8.1.2.7,* and *8.1.2.8.*

6 Safety

6.1 Safety Requirements

Maria Exeler is the Safety Officer for River City Rocketry during the 2017-2018 season. As Safety Officer, she is responsible for ensuring the overall safety of the team, students, and public throughout all team lead activities.

6.1.1 Statement of Work Requirements

The Statement of Work requirements were provided by NASA and are shown in Table 54

Requirement Number	Requirement	Verification
5.1	Each team will use a launch and safety checklist. The final checklists will be included in the FRR report and used during the Launch Readiness Review (LRR) and any launch day operations.	**Demonstration- Completed** Thorough checklists will be created prior to test launches that will require two member signatures for each step. The checklists will be updated after each test launch and will be finalized prior to FRR.
5.2	Each team must identify a student safety officer who will be responsible for all items in section 5.3.	**Demonstration- Completed** Maria Exeler was identified as the Safety Officer in the Proposal.
5.3	The role and responsibilities of each safety officer will include, but not limited to: Safety 5.3.1.- Safety 5.3.4.	**Demonstration- Completed** Revision G of the team Safety Manual and has been created to address these requirements.
5.3.1.	Monitor team activities with an emphasis on Safety during: design, construction, assembly, and ground testing of vehicle and payload, sub-scale and full-scale launch tests, launch day, recovery activities, and educational engagement activities.	**Demonstration- Continuous** Designs and construction progress will be reviewed weekly through subteam lead meetings. Mandatory safety briefings will be held prior to all construction and testing. Educational engagement activity safety will be reviewed prior to all team events.
5.3.2.	Implement procedures developed by the team for construction, assembly, launch, and recovery activities.	**Demonstration-** Completed Newly identified hazards will be reviewed prior to the construction, assembly, and testing of any components.
5.3.3.	Manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.	**Demonstration- Continuous** Maria has updated and reviewed these items with the team prior to FRR and will

		continue as new materials are used and processes are conducted.
5.3.4.	Assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.	**Demonstration- Continuous** The Safety Officer will meet with the lead of each subsystem to review and update the hazard and failure analyses and procedures prior to each test flight and major review.
5.4	During test flights, teams will abide by the rules and guidance of the local rocketry club's RSO. The allowance of certain vehicle configurations and/or payloads at the NASA Student Launch Initiative does not give explicit or implicit authority for teams to fly those certain vehicle configurations and/or payloads at other club launches. Teams should communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch.	**Demonstration- Completed** By agreeing to the Safety Manual, all team members agreed to follow decisions made by the RSO during all launches.
5.5	Teams will abide by all rules set forth by the FAA.	**Demonstration- Continuous** By signing the Safety Manual, all team members agreed to follow the regulations defined in FAR 14 CFR.

Table 54: Safety Statement of Work Requirements.

6.2 Safety Manual

6.2.1 Manual Contents

The team Safety Manual outlines the specific shop procedures including:

- Availability and location of emergency equipment including eyewash stations, fire extinguishers, and PPE.
- The need to understand the MSDS for materials used by the team and where all team MSDS are stored in the team cage.
- Proper waste disposal of hazardous waste like solvent contaminated rags and proper cleaning of machining chip and shavings.
- Required certification by Engineering Garage staff prior to use of the Electronic Bench and soldering irons
- Requirement that team members pass a mandatory safety quiz prior to accessing the Machine Cage and the heavy machining equipment that is stored inside

- The quiz covers topics from the [HSM Shop Safety handbook]
- All team members were warned about the penalty of being barred from the Engineering Garage if they do not conform to the Safety Manual

Since CDR, the required use of a hot surface warning sign has been implemented. The sign acts as a stand to prevent the hot elements, such as glue guns, from contacting or dripping on other materials. The sign is shown below in Figure 227.

Figure 227: Hot surface warning.

Table 55 outlines the requirements to use any equipment in the Machine Cage by Engineering Education Garage management.

Wear Safety Glasses- you must wear safety glasses AT ALL TIMES while in the shop area. You must wear safety goggles over prescription glasses unless your glasses have side shields and are ANSI safety approved.
Use hearing Protection- you will wear hearing protection as instructed during machine training
No jewelry- you will remove all rings, watches, necklaces, bracelets, and dangling earrings before operating any machinery or tools.
Proper Attire- you will wear ankle-length pants, loose hair and clothing are extremely dangerous. You must tuck in your shirt, roll up long sleeves, secure draw strings, tie back hair etc.
Clean up- before leaving the shop area, you must assist in cleaning all messes- metal chips, wood shavings, and splashed coolant) All liquids must be cleaned immediately to avoid slips
Return of tools and parts- all tools, instruments, bits, etc. must be returned to their proper location after use.
You must not operate equipment alone OR that you have not been trained to use. You must follow proper operating procedures detailed in the Job Safety and Sequence Instruction cards that are posted near all machinery.
You must not enter the shop area under the influence of drugs or alcohol, specifically over-the-counter drugs that include warnings against operating machinery. You must not consume alcohol within 8 hours of entering the shop area.

If the machine makes an unusual noise or acts in any suspicious manner, you must stop the machine and inform the Engineering Garage manager immediately.

Table 55: Engineering Education Garage requirements.

The Safety Manual is published on the team website so members always have access.

6.2.2 Manual Agreement

All of the topics mentioned above were covered in the mandatory Safety Briefing. All current team members signed the Safety Agreement Form following this briefing, saying that they agreed to follow all team rules covered in the Safety Manual. The signed Agreement Form is shown in Figure 228.

Safety Manual Agreement Form			•I agree to the rules and regulations detailed in the River City Rocketry Safety Manual. •I will report any concerns or safety violations to the Safety Officer •I will follow these rules and maintain safety as my highest concern when completing any work for the team	
Last Name	First Name	Participation and Release Form Received	I agree to the above statements	Date
Basil	Alex	Yes	Absent on co-op	2/26/18
Breville	Zach	Yes		10/26/17
Bloom	David	Yes		10/26/17
Bruncher	Austin	Yes		10/26/17
Cassady	Jake	Yes	Absent on co-op	2/26/18
Cockerline	Kevin	yes		10/26/17
Collins	Gabriel	Yes		10/26/17
Cosgrove	Matthew	Yes		10/26/17
Coyle	Jarett	Yes		10-26-17
Culver	James	Yes		10/27/17
Dannunzio	Blaise	Yes		10/28/17
Epps	Alex	Yes		10/27/17
Exeler	Maria	Yes		10/26/17
Fowler	James	Yes		10/26/17
Garcia	Erik	Yes		10/26/17
Holden	Nolan	Yes	Absent on co-op	3/2/18
Hsieh	Taylor	Yes		10-26-17
Huddleston	Luke	Yes		10/26/17
Johnson	Justin	Yes	Absent on co-op	
Joy	Denny	Yes		10/26/17
Ketron	Joellyn	Yes		10/26/17
Kindred	Micah	yes		10/26/17
Lewis	Eric	yes		10/26/17
Malone	Brody	Yes		10/26/17
Malone	Luke	Yes		10/26/17
Marcum	Jacob	Yes		10/26/17
Mazarakis	Alora	YES		10/26/17
McClain	Gloria	yes		10/26/17
Meier	Michael	yes		10/26/17
Meyer	Kristian	yes		10/26/17
Norvell	Kaylee	Yes		10/26/17
Pyle	Ryan	yes		10/27/17
Stringer	Ben	Yes	Absent on co-op	
Tran	Justin	Yes		10/26/17
Williams	Robert	yes		10/26/17
Williams	Samuel	yes		10/26/17
Young	Jeff	yes		10/26/17

Figure 228: Safety Agrement Form.

Updates were made to the Safety Manual concerning hearing protection and the use of a warning sign for hot elements including hot glue guns. The Safety Manual was updated and all members were required to agree to the updates. Team members that have returned from co-op were only required to agree to the most up to date version of the Safety Manual. All of the team members agreed to the current revision of the Safety Manual, Revision G, and the signed form is shown in Figure 229.

Revision Form		By initialling and dating the box below each Safety Manual revision, I agree to follow all updates of the manual.				
Last Name	First Name	F	G	H	I	J
[illegible]	Alex	Absent on co-op	[illegible]			
[illegible]	David	[illegible]	[illegible] 2/26/18			
[illegible]	Austin	[illegible]	Absent on co-op			
Cassady	Jake	Absent on co-op	[illegible]			
Cockerline	Kevin	KC [illegible]	Kevin Cockerline			
[illegible]	Gabriel	[illegible]	[illegible]			
Cosgrove	Matthew	[illegible]	Matthew Cosgrove			
[illegible]	[illegible]	JC [illegible]	[illegible]			
[illegible]	[illegible]	[illegible]	[illegible]			
[illegible]	[illegible]	[illegible]	[illegible]			
Epps	Alex	[illegible]	[illegible]			
[illegible]	[illegible]	[illegible]	[illegible]			
Fowler	[illegible]	JF [illegible]	[illegible]			
Garcia	Erik	EG [illegible]	EG			
[illegible]	Nolan	Absent on co-op	Nolan			
[illegible]	Taylor	TH [illegible]	[illegible]			
[illegible]	[illegible]	Absent on co-op	Absent on co-op			
[illegible]	[illegible]	DJ [illegible]	[illegible]			
[illegible]	[illegible]	[illegible]	[illegible]			
Lewis	Eric	EL 10/26/17	EL			
Malone	Luke	[illegible]	[illegible]			
Marcum	Jacob	[illegible]	[illegible]			
[illegible]	Alexis	[illegible]	[illegible]			
McClain	Gloria	[illegible]	Absent on co-op			
[illegible]	Michael	MM 10/26/17	[illegible]			
Meyer	Kristian	[illegible]	[illegible]			
Norvell	Kaylee	KN [illegible]	[illegible]			
Pyle	Ryan	RP [illegible]	RP			
Tran	Justin	JT [illegible]	[illegible]			
Williams	Robert	[illegible]	Absent on co-op			
Williams	Samuel	[illegible]	[illegible]			
Young	Jeff	[illegible]	JGY			

Figure 229: Revison G Agreement Form.

6.3 Hazard Analysis

The risk hazard tables were updated to better classify the risks before mitigations (RBM) and risks with mitigations (RWM).

6.3.1 Risk Assessment Matrix

By methodically examining each human interaction, environment, rocket system and component, hazards have been identified. However, hazards and risks will continue to be revised through the competition as new components are designed and manufactured. Risk assessment and mitigation are vital to the success of our project and team safety.

Each currently identified hazard has been evaluated through a risk assessment process that recognizes the hazard's potential causes and results, the severity and probability of the hazard, and how the hazard can be mitigated and how that mitigation can be verified.

A severity value between 1 and 4 has been assigned to each hazard with a value of 1 being the most severe. To determine the severity of each hazard, the outcome of the mishap was compared to an established set of criteria based on the severity of personal injury, environmental impact, and damage to the rocket and/or equipment.

The Severity Criteria was maintained from PDR and is shown in Table 56.

Severity		
Description	**Value**	**Criteria**
Catastrophic	1	Could result in death, significant irreversible environmental effects, complete mission failure, or monetary loss of $5k or more.
Critical	2	Could result in severe injuries, significant but reversible environmental effects, partial mission failure, or monetary loss of $500 or more but less than $5k.
Marginal	3	Could result in minor injuries, moderate environmental effects, complete failure of non-mission critical system, monetary loss of $100 or more but less than $500.
Negligible	4	Could result in insignificant injuries, minor environmental effects, partial failure of non-mission critical system, monetary loss of less than $100.

Table 56: Severity criteria.

A probability level between A and E has been assigned to each identified hazard with a level of A being most likely. The probability value was determined for each hazard based on an estimated percentage chance that the mishap will occur. The Probability Table is shown in Table 57.

Probability		
Description	**Level**	**Criteria**
Almost Certain	A	Greater than a 90% chance that the mishap will occur
Likely	B	Between 50% and 90% chance that the mishap will occur
Moderate	C	Between 25% and 50% chance that the mishap will occur
Unlikely	D	Between 1% and 25% chance that the mishap will occur
Improbable	E	Less than a 1% chance that mishap will occur

Table 57: Probability criteria.

Through the combination of the severity value and the probability level, an appropriate risk level has been assigned using the risk assessment matrix found in Table 58. The matrix identifies each combination of severity and probability values as either a high, moderate, low, or minimal risk. The team's goal is to have every hazard to a low or minimal risk level by the time of the competition launch. Hazards that are not currently at a low risk level will be readdressed with redesign, additional safety regulations, or other measures as required. Risk levels are also being reduced through verification systems.

Probability Level	Severity Value			
	1 - Catastrophic	2 - Critical	3 - Marginal	4 - Negligible
A–Almost Certain	1A	2A	3A	4A
B – Likely	1B	2B	3B	4B
C – Moderate	1C	2C	3C	4C
D – Unlikely	1D	2D	3D	4D
E – Improbable	1E	2E	3E	4E

Table 58: Risk Assessment Matrix.

The Risk Level Matrix was updated to match the Handbook and to better describe the effect of the assigned mitigation on each hazard's risk. A Risk Level Approval Matrix was created based on the risk level of a hazard to show what level of approval is required for each risk level to be acceptable. The required approvals of sub-team leads, the safety officer, and co-captains are listed in Figure 231 for the Low risks and Figure 231 for Moderate risks.

I, Matthew Cosgrove, approve of the hazards with Low Risk levels following final mitigations. These include risks are specifically associated with the Launch Vehicle, Propulsion, and the impacts of these systems on the overall success of the mission and team members.

X ______ Date: 3/4/18

I, Kristian Meyer, approve of the hazards with Low Risk levels following final mitigations. These include risks are specifically associated with the Payload systems and the impacts of these systems on the overall success of the mission and team members.

X ______ Date: 3-4-18

I, Jarett Coyle, approve of the hazards with Low Risk levels following final mitigations. These include risks are specifically associated with the Recovery systems and the impacts of this system on the overall success of the mission and team members.

X ______ Date: 3-4

I, Alora Mazarakis, approve of the hazards with Low Risk levels following final mitigations. These include risks are specifically associated with the Variable Drag System and the system's impacts on the launch vehicle and team members.

X ______ Date: 3.5.18

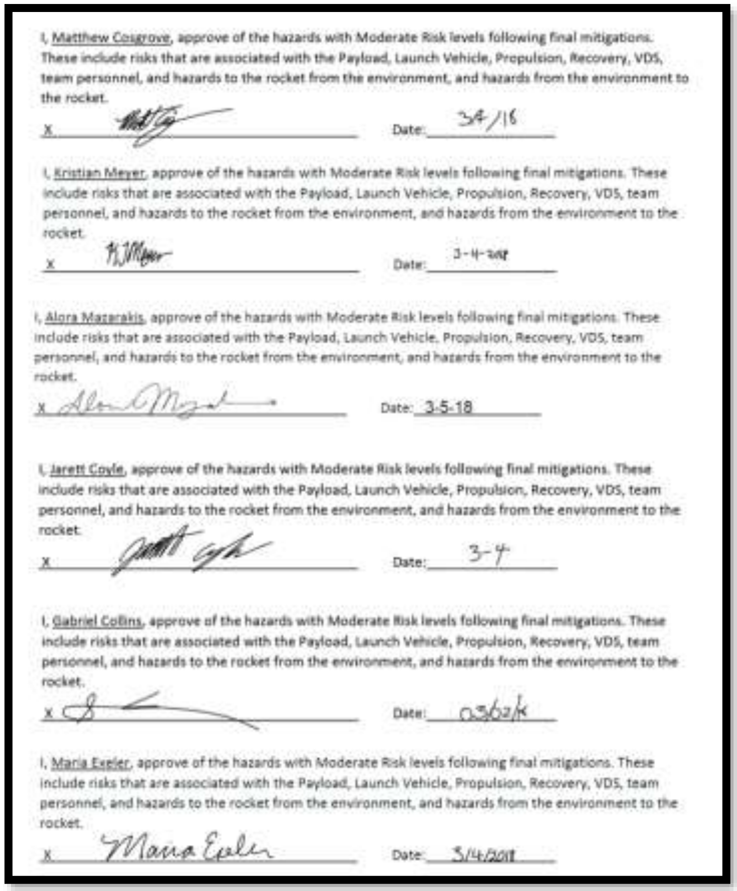
I, Gabriel Collins, approve of the hazards with Low Risk levels following final mitigations. These include risks that are associated with the Payload, Launch Vehicle, Propulsion, Recovery, VDS, team personnel, and hazards to the rocket from the environment, and hazards from the environment to the rocket.

X ______ Date: 03/02/18

I, Maria Exeler, approve of the hazards with Low Risk levels following final mitigations. These include risks that are associated with the Payload, Launch Vehicle, Propulsion, Recovery, VDS, team personnel, and hazards to the rocket from the environment, and hazards from the environment to the rocket.

X Maria Exeler Date: 3/4/18

Figure 230: Low risk approvals.



I, Matthew Cosgrove, approve of the hazards with Moderate Risk levels following final mitigations. These include risks that are associated with the Payload, Launch Vehicle, Propulsion, Recovery, VDS, team personnel, and hazards to the rocket from the environment, and hazards from the environment to the rocket.

X ______________________ Date: 3-4/18

I, Kristian Meyer, approve of the hazards with Moderate Risk levels following final mitigations. These include risks that are associated with the Payload, Launch Vehicle, Propulsion, Recovery, VDS, team personnel, and hazards to the rocket from the environment, and hazards from the environment to the rocket.

X ______________________ Date: 3-4-2018

I, Alora Mazarakis, approve of the hazards with Moderate Risk levels following final mitigations. These include risks that are associated with the Payload, Launch Vehicle, Propulsion, Recovery, VDS, team personnel, and hazards to the rocket from the environment, and hazards from the environment to the rocket.

X ______________________ Date: 3-5-18

I, Jarett Coyle, approve of the hazards with Moderate Risk levels following final mitigations. These include risks that are associated with the Payload, Launch Vehicle, Propulsion, Recovery, VDS, team personnel, and hazards to the rocket from the environment, and hazards from the environment to the rocket.

X ______________________ Date: 3-4

I, Gabriel Collins, approve of the hazards with Moderate Risk levels following final mitigations. These include risks that are associated with the Payload, Launch Vehicle, Propulsion, Recovery, VDS, team personnel, and hazards to the rocket from the environment, and hazards from the environment to the rocket.

X ______________________ Date: 03/6/18

I, Maria Exeler, approve of the hazards with Moderate Risk levels following final mitigations. These include risks that are associated with the Payload, Launch Vehicle, Propulsion, Recovery, VDS, team personnel, and hazards to the rocket from the environment, and hazards from the environment to the rocket.

X Maria Exeler Date: 3/4/2018

Figure 231: Moderate risk approvals.

The matrix is shown in Table 59.

Risk Level and Approval Matrix	
Risk Level	Level of Approval Required
High Risk	Highly undesirable. Documented approval of NASA SL team, RSO, team sub-team leads, team safety officer, and team co-captains required.
Moderate Risk	Undesirable. Documented approval of all team sub-team leads, team safety officer, and team co-captains required.
Low Risk	Acceptable. Documented approval from team sub-team lead overseeing the component's development.
Minimal Risk	Acceptable. Documented approval is not required. Sub-team lead will ensure that sub-team members are familiar with the hazard.

Table 59: Risk Level and Approval Matrix.

The risks evaluated were grouped initially by hazard to equipment, personnel, and the environment. The equipment hazards have been further divided by sub-teams.

Payload Risk Assessment

The payload will not be permanently fixed in the launch vehicle and will require multiple components to ensure proper deployment. These hazards contain the testing, assembly, and flight concerns associated with the payload. The hazards are listed in Table 81.

Vehicle Assembly Risk Assessment

The hazards outlined in Table 82 are risks that could potentially be encountered throughout the assembly phase and during launch preparations.

Propulsion Risk Assessment

The hazards outlined in are risks associated with stability and propulsion. The team has one member with certifications supporting that he can safely handle motors and design stable rockets the size of the competition rocket. Other members are currently working toward certifications as well. These assessments are listed in Table 83.

Recovery Risk Assessment

The hazards outlined in Table 84 are risks associated with the recovery. Since there are two recovery systems onboard, many of the failure modes and results will apply to all the systems but will be stated only once for conciseness.

VDS Actuation Risk Assessment

The hazards outlined in this section discuss the risks associated with testing and flight of the VDS. The VDS interfaces with the main structure of the vehicle with potential risk from manufacturing, assembly, and installment. The VDS hazards are outlined in Table 85.

Personnel Safety Risk Assessment

Construction and manufacturing of parts for the rocket will be performed in on-campus labs, the Engineering Garage and Sackett Lab. The hazards assessed in associated with machinery, tools, and chemicals in the lab are assessed in Table 86.

Environmental Hazards to Launch Vehicle Risk Assessment

The hazards outlined in Table 87 are risks from the environment that could affect the rocket or a component of the rocket. These hazards are the exception for needing to achieve a low risk level. This is because several of these hazards are out of the team's control, such as the weather. In the case that environmental hazards present themselves on launch day, putting the team at a moderate risk, the launch will be delayed until a low risk level can be achieved. The hazards that the team can control will be mitigated to attain a low risk level.

Launch Vehicle Hazards to Environment Risk Assessment

The hazards outlined in Table 88 are risks that construction, testing or launching of the rocket can pose to the environment.

7 Safety Checklists and Launch Procedures

7.1 Checklists and Launch Procedures Overview

The Safety Officer is responsible for writing, enforcing, and maintaining all Safety Checklists and Launch Procedures. These lists are critical to ensure the safety of personnel, spectators, equipment, and success of the team.

The checklists are broken up into checklists for each subsystem for pre-launch preparations and launch day. This allows the team to maintain organization and ensures a quick and efficient preparation for launch day. Each subsystem checklist must be 100% complete and signed by a representative of that subsystem. Checklists will be verified and collected by the Safety Officer. Overall final assembly checklist can be started once all subsystems are prepared. After completion of the final assembly, all sub-team leads, captains, and the Safety Officer must approve the rocket as being a go for launch. The “at the launch pad” checklist can be started and personnel are assigned tasks of tracking each section of the rocket during recovery. Maria maintains the right to call off a launch at any time if she determines anything to be unsafe or at too high of a risk level.

7.2 Safety Checklists and Launch Procedures

Full Scale Launch Safety Checklists

The following checklists were written to prepare the team for a safe and successful launch. Each checklist includes the following features to ensure that assemblers are well equipped, safe, and able to recognize all existing hazards:

- Required hardware, equipment, and PPE for each process
- Labels to indicate explicit safety precautions:

CAUTION -label used to identify where PPE must be used

WARNING -label used to signify importance of procedure by clearly identifying a potential failure and the result if not completed correctly

DANGER -label to signal the use of explosives and to indicate specific steps that should be taken to ensure safety

7.2.1 General Materials and Safety Checklist

To be checked and signed by a River City Rocketry team member and co-captain when the General Materials are prepared.		
1. ______________________	2. ______________________	
Prior to leaving for launch site		
Equipment to Pack		
☐ 5-minute epoxy	☐ Dremel	☐ Garbage bag (x2)
☐ Allen wrench set	☐ Dremel bit kit	☐ Hammer
☐ Assorted zip tie container	☐ Drill	☐ Hot glue gun

☐ Black Gorilla Tape	☐ Drill bit set	☐ Large tarp
☐ Black powder kit	☐ Electrical tape	☐ Paper towels
☐ Black powder measuring	☐ E-matches (x4)	☐ Red supply tackle box (x2)
☐ Box of nitrile gloves	☐ Folding chair (x3)	☐ Scissors
☐ Clear black powder capsules (x4)	☐ Folding table (x3)	☐ Tent (x2)
Personal Protective Equipment to Pack		
☐ Air horn		
☐ First Aid Kit	☐ Nitrile gloves	☐ Safety glasses (x25)
☐ Fire extinguisher	☐ Respirator (x2)	☐ Water bottles (x18)
☐ Sunscreen	☐ Set of earplugs (x5)	

Fire extinguisher check	
___________	1. Check the fire extinguisher charge level prior to packing.
___________	2. If the gage does not show a full level, obtain a different extinguisher.
WARNING	A fire extinguisher will not be effective if it is not fully charged, rendering it useless.
Pre-launch safety briefing and driver identification	
___________	1. Update team members about any newly identified personal hazard risks.
___________	2. Inform all team members about anticipated launch day weather conditions.
Note:	A launch will not be attended if there are hazardous weather conditions on the day of launch.
___________	3. Identify team members who will be driving to the launch field.
WARNING	Failing to identify drivers prior to launch day may endanger team members or team materials due to lack of sleep.

7.2.2 Vehicle Safety Checklist

To be checked and signed by Vehicle Lead and team member when *all* steps are completed, indicating that Vehicle team is **PREPARED FOR LAUNCH.**		
1. _________________________________ 2. _________________________________		
Prior to leaving for launch site: Vehicle		
Equipment to Pack or Prepare		
☐ Precision flathead screwdriver	☐ Multimeter	☐ Nosecone altimeter sled
☐ Standard Philips head screwdriver	☐ Skytraq	☐ StratoLogger altimeter (x4)
☐ Duracell 9V battery (x4)	☐ AIMXTRA nose cone	☐Battery clips (x2)
☐ Eggfinder sled	☐4-40 shear pins (x24)	☐Battery holster cover
☐ Trackimo outside of bulk plate		☐ PVC rocket stands

Vehicle Inspection Prior to Launch	
_____	1. Place airframe on rocket stand.
WARNING	If rocket stands are not used, the airframe could roll off the work surface.
_____	2. Inspect all fins for damage.
_____	3. Inspect nosecone for damage.
_____	4. Inspect airframe for damage.
_____	5. Inspect permanent internal airframe components for damage.
_____	6. Inspect all electronic sleds for damage.
_____	7. Inspect all couplers and shear pin holes, and threads for damage.
_____	8. Inspect motor centering ring epoxy and retainer for damage.
_____	9. Inspect carbon fiber components for signs of delamination or structural weakness.
_____	10. Ensure that all sections and screw holes align without forcing them together. There should also not be extra room between the coupler and airframe.

WARNING	If sections are too tight, they may not be able to separate with black powder. Sections that are too Loose may cause an unstable flight.
WARNING	Any damage must be reported to Vehicle lead and Safety officer to mitigate possible impact on later launches.
Black powder charge preparation	
DANGER	E-matches are explosive and must be kept clear of batteries, sparks, and open flames to avoid premature firing. No open flames are allowed within 25 feet of black powder.
CAUTION	Safety glasses must be worn when using a drill and while handling e-matches.
____	1. Drill a 1/8" hole in the bottom of each black powder capsule.
____	2. Unwind an e-match and remove the protective cap from the pyrotechnic end.
____	3. Feed the wire end of the e-match through the top of the capsule and through the hole in the base of the capsule until the pyrotechnic end is against the bottom of the inside of the capsule.
	4. Secure the e-match to the capsule and close the hole with Gorilla tape.
WARNING	Ensure that black powder does not leak out of the capsule. Leakage could cause a failed vehicle separation or failed recovery, leading to a catastrophic vehicle failure. Any spilled powder must be cleaned up with painter's tape, lint roller, or other non-sparking/non-static producing tools.
____	5. Two people are required to measure and handle black powder
WARNING	Two people are needed to ensure the intended amounts of black powder are used in charges and black powder should only be handled outdoors to provide proper ventilation.
____	5. Fill each capsule with the calculated number of cc's of black powder.
____	6. Fill excess capsule space with cellulose insulation to ensure that the pyrotechnic end of the e-match is submerged in the powder regardless of capsule orientation.
WARNING	An unsubmerged e-match may not ignite the black powder and could cause a failed vehicle separation or failed recovery, leading to a catastrophic vehicle failure.
____	7. Close the capsule with the lid, checking that there is a tight fit.
____	8. Repeat steps 1 through 7 for each required charge.
	9. Unwind 2 e-matches for each ARRD and remove the protective caps from the pyrotechnic ends.
	10. Insert 2 modified e-matches into the ARRDs.
____	11. Assemble the ARRDs according to the manufacturer's instructions.
	12. Store all created charges and ARRDs in the explosive's box.
Vehicle Avionics Preparation	
____	1. Charge all 4 GPS units prior to the day of launch.
____	2. Verify proper avionic shielding.
WARNING	Ensure that the entire inside of the avionics bay is properly shielded to protect from Interference. In the incident that interference occurs, pyrotechnic devices may be actuated Prematurely, causing potential harm to personnel and/or mission failure.
____	3. Verify StratoLogger CF altimeters are properly programmed.
____	4. Identify altimeter that will be used to record an official apogee measurement.
Note:	A NASA official will mark the official competition altimeter during LRR.
____	5. Verify 9V battery has a minimum charge of 8.7 V.
____	6. Mount StratoLoggers onto standoffs on sustainer altimeter sled using #4-40 shear pins
____	7. Attach batteries to battery clips and install into holster.
____	8. Attach battery holster cover using 4, #4-40 shear pins
____	9. Ensure screw switches are turned off and wire screw switches to switch terminal on the StratoLogger.
DANGER	Altimeters must remain in the OFF position until the vehicle is upright on the launch pad. Skipping this step could lead to premature black powder detonation and serious danger to all personnel.
____	10. Wire battery to +/- terminal on StratoLogger.
____	11. Wire main and drogue terminals on StratoLogger to terminal blocks on the nosecone.
____	12. Install altimeter sled into avionics bay

WARNING	Ensure that the sled is fixed properly to eliminate damage that could prevent recovery from being properly deployed.
_____	13. Verify proper screw switch alignment with access hole
WARNING	If the alignment hole and screw switch do not align, the altimeters will not be able to be engaged at the launch pad, possibly delaying the launch.
_____	14. Install AIM XTRA into 3D printed sled.
_____	15. Install the AIM XTRA sled onto the nosecone all thread and tighten the sled down with nuts.
_____	16. Install the Eggfinder into 3D printed sled.
_____	17. Install the Eggfinder sled into the Payload recovery coupler.
_____	18. Mount the Trackimo in the Payload coupler.

Prior to leaving for launch site: Propulsion

Equipment to Pack or Prepare

☐ Gorilla Glue ☐ Grease	☐ Booster bay ☐ Booster stand	☐ AeroTech L2200-G motor ☐ Motor retainer ☐ #10-32 shoulder bolt (x3)

Motor Preparation

CAUTION	Protective gloves must be worn while applying grease to the motor.
_____	1. The vehicle lead, Matthew Cosgrove, will be responsible for fully preparing the motor and installing it within the casing. Only members with Level 2 certification may assist.
_____	2. Slide motor casing fully into the motor mount tube.
_____	3. Attach the motor retainer to the fin retainer via #10-32 shoulder bolts
_____	4. Set the completely assembled bay on the stand, ensure that the bay is not resting on the fins
Note:	If any damage is identified, immediately inform each co-captain and the safety officer. The launch vehicle will be deemed safe to fly or a corrective action will be decided upon.

To be checked and signed by Vehicle Lead and team member when all *prior to leaving* steps are completed, indicating that Vehicle team is **PREPARED TO DEPART FOR LAUNCH**

1. ______________________________ **2.** ______________________________

At the Launch Site

7.2.3 Recovery Safety Checklist

To be checked and signed by Recovery Lead and team member when *all* steps are completed, indicating that Recovery team is **PREPARED FOR LAUNCH**.

1. ____ 2. ____

Prior to leaving for launch site

Equipment to Pack

☐ ARRD (x2) ☐ Shock cord (x6) ☐ Booster main parachute ☐ Payload bay main parachute ☐ E-Match (x4)	☐ Drogue parachute (x2) ☐ Spare drogue parachute (x2) ☐ Deployment bag (x2) ☐ No Burn fire retardant spray ☐ Parachute packing hook (x2)	☐ Masking tape ☐ Nomex cloth (x3) ☐ Quick link (x10) ☐ Recovery insulation (Dog barf) ☐ Opening force reduction ring (x4)

Main Parachute Packing

The same packing checklist is to be used for both Booster main and Payload main parachutes.

Booster	Payload	
_____	_____	1. Inspect canopies, shroud lines, and shock cords for any cuts, burns, fraying, loose stitching and any other visible damage.
	Note:	*If any damage is identified, immediately inform each co-captain and the safety officer. The launch*

		ehicle will be deemed safe to fly or a corrective action will be decided upon and implemented.
_____	_____	2. Spray shroud lines with No Burn fire retardant spray.
_____	_____	3. Lay parachute canopy out flat.
_____	_____	4. Ensure shroud lines are taut and evenly spaced and not tangled.
_____	_____	5. Slide opening force reduction ring to where the shroud lines meet the canopy.
_____	_____	6. Attach quick link to shroud lines.
_____	_____	7. Fold parachute per the folding procedures.
_____	_____	8. Daisy chain shroud lines and place folded parachute(s) into respective zip lock bags.
_____	_____	9. Attach quick links to shock cord via bowline knot.
_____	_____	10. Verify all recovery equipment is packed.

To be checked and signed by Recovery Lead and team member when all *prior to leaving* steps are completed, indicating that Recovery team is **PREPARED TO DEPART FOR LAUNCH**

1. ______________________________ 2. ______________________________

Launch day procedures

Parachute Assembly

The same packing checklist is to be used for both Booster main and Payload main parachutes through step 5.

CAUTION	Safety glasses must be worn while handling black powder
__________	1. Properly assemble the ARRD and perform a force test with a minimum of 400 lbs. Tape E-matches into the base.
DANGER	E-matches and black powder are explosive. The cartridges and leads of the ARRD must be kept clear of batteries, sparks, and open flames to avoid accidental firing.
Note:	*If any damage is identified, immediately inform each co-captain and the safety officer. The launch vehicle will be deemed safe to fly or a corrective action will be decided upon and implemented.*
__________	2. Secure ARRD to payload bay coupler.
_____ Booster / _____ Payload	3. Properly place folded booster main parachute in deployment bag with shroud lines coming directly out of the bag. Ensure that the shroud lines are not wrapped around the parachute inside the deployment bag.
WARNING	If the shroud lines are not wrapped around the parachute, the parachute getting stuck in the deployment bag. Verify that the parachute fits loosely in the deployment bag.
_____ Booster / _____ Payload	4. Secure deployment flaps using shroud lines. Use hook to assist in securing extra length of shroud lines through loops stitched in deployment bag. Continue this pattern in the same direction around the deployment bag to prevent tangling.
__________	5. Repeat steps 3 and 4 for payload bay main parachute
__________	6. Properly fold drogue parachute and insert in respective Nomex cloth. Use masking tape to secure the Nomex cloth.
__________	7. Inspect the inside of the vehicle for carbon fiber splinters or corners that could cause parachutes To be caught during separation.
WARNING	If edges are not identified prior to packing, the parachute may not deploy and could cause to a total mission failure.
__________	8. Attach shock cord to payload bay coupler and main parachute.
__________	9. Secure shock cord slack using masking tape.
__________	10. Tether deployment bag to payload bay ARRD.
__________	11. Connect shock cord from drogue parachute to ARRD and nosecone.

___________	12. Attach shock cord to booster coupler and main parachute.
___________	13. Secure shock cord slack using masking tape.
___________	14. Tether deployment bag to payload bay coupler.

7.2.4 Variable Drag System (VDS) Safety Checklist

To be checked and signed by VDS Lead and team member when *all* steps are completed, indicating that VDS team is **PREPARED FOR LAUNCH**.

1. ______________________________ 2. ______________________________

Prior to leaving for launch site

Equipment to Pack or Prepare

☐ Precision flathead screwdriver	☐ Fuse shunt	☐ Nosecone altimeter sled
☐ Standard Philips head screwdriver	☐ Electronics Assembly	☐ StratoLogger altimeter (x4)
☐ Duracell 9V battery (x4)	☐ Extra 22 AWG wires	☐Battery clips (x2)
☐4-40 shear pins (x24)	☐ Teensy 3.6	☐Battery holster cover
☐ Multimeter	☐ Neverrest40 DC motor	☐ SD Card
☐ Black Tool box	☐ Encoder cable	☐ Wire Cutters/Strippers
☐ VDS connector cable	☐ Laptop	☐ 7.4V LIPO battery (stored in insulated battery bag)
☐ SD adapter	☐ Banana Plug Cables	☐ 11.1V LIPO battery (stored in insulated battery bag)
	☐ USB micro B cable	☐ Fuse
	☐ Electronics Enclosure	

Hardware Preparations

____	1.Before handling VDS electronics, ensure that you are properly grounded. This can be done at Launch by touching the chassis of a car and removing extra layers of clothing.
____	2. Check battery connector for frayed or loose wires and check battery for any damage.
WARNING	The use of damaged batteries could cause failure of the VDS or environmental harm if the battery leaks.
____	3. Verify that all traces have correct continuity and are not shorted to any grounds.
_	4. Verify Battery Charge of both 7.4 and 11.1 li-Po batteries. If more than .2V below specified voltage, charge.
WARNING	If the batteries are below the specified charge level, the VDS may not have enough battery life to remain powered during pad wait times.
____	5. Plug in Teensy 3.6 into top board.
____	6. Plug top board into bottom board, assure that al header pins are making adequate contact with bottom female headers.
____	7. Assemble stand offs into boards. The top board should have nuts screwed into them, and the bottom will be screwed in after assembly into sled.
____	8. Insert boards into sled with Teensy in the direction of cable insert hole. Place screws into bottom stand offs.
____	9. Verify that both batteries are inserted into the correct places. Plug in batteries with correct polarity.
WARNING	Ensure that the batteries are plugged in with CORRECT POLARITY
____	10. Flip switches on to verify that LEDs are illuminated.
____	11. Insert sled into coupler with correct all-thread orientation
____	12. Plug in motor D-sub, and feed through USB wire for Teensy computer connectivity, and intermittent charging.

Software Preparations

____	1. Begin by booting up VDS_Software_V2. Load program, and verify that it is “built” onto Teensy 3.6.
____	2. Open serial port.

____	3. Begin program in Serial monitor with “s” command.
____	4. Verify the bmp is “GO”.
____	5. Calibrate BNO by rotating at 25 degree angles until sensors reads all “3s”.
____	6. Perform preemptive motor test with “M” command.
____	7. Check status of all components with “D” command.
____	8. If all components are “GO”, confirm assembly in rocket. Install coupler and keep VDS Powered until flight readiness.
____	9. Remove USB when launch ready
	After Recovery
____	1. Remove cover from sled.
____	2. Shut down motor power.
____	3. Plug USB B into Teensy.
____	4. Launch Putty.
____	5. Press ‘E’ (or any character other than ‘F’) to end flight mode.
____	6. Remove SD card.
____	7. Shut down power to board
____	8. Store electronics in ESD-safe bag

7.2.5 Payload Safety Checklist

To be checked and signed by Payload Lead and team member when *all* steps are completed, indicating that Payload team is **PREPARED FOR LAUNCH**.

1. ______________________________ 2. ______________________________

Prior to leaving for launch site

Equipment to Pack or Prepare

☐ ROCS Assembly ☐ Socket Head Cap Screws (x30) ☐ DTS Receiver Module ☐ DTS Antenna ☐ DTS Transmitter Module	☐ Rover ☐ Extra Controller Batteries (x2) ☐ Extra Motor Battery ☐ LiPo Voltage Indicator ☐ LiPo Battery Charger	☐ Allen Key Set ☐ Multimeter ☐ Electrical Wire ☐ Wire Stripper ☐ Laptop ☐ DTS Transmitter Yagi	☐ MicroSD Card (x2) ☐ M-2 Screws (x10) ☐ 4-40 Screws (x30) ☐ 8-32 Screws (x30) ☐ Pliers ☐ Extra CES Components

Rover Orientation Correction System (ROCS)	
____	1. Inspect ROCS assembly for damage or loss of material
Note:	*If any damage is identified, inform Payload Lead to determine degree of damage and if corrective action is necessary.*
____	2. Roll ROCS assembly to verify functionality
Rover Locking Mechanism (RLM)	
____	1. Verify functionality of RLM by applying 12V to RLM motor using power supply
____	2. Fit test rover with the RLM
Deployment Trigger System (DTS)	
____	1. Verify transmitter power source is fully charged
____	2. Wire receiver module through slip ring flange

_____	3. Attach receiver antenna to exterior of airframe
Rover Body Structures (RBS)	
_____	1. Install battery mount
_____	2. Install motor mount
_____	3. Install OAS/SIS mount
_____	4. Verify locking bracket is secured to rear of rover
WARNING	*Failure to verify locking bracket is secure could lead to premature deployment of the rover.*
Rover Drive System (RDS)	
_____	1. Verify functionality of main drive motors by applying 12V to each motor using power supply
WARNING	*Bevel gears rotating can cause injury to personnel and should be avoided*
_____	2. Mount all wheel bearings with shafts to the RBS
_____	3. Mount idler and drive wheels to shafts
_____	4. Clean tread thoroughly
_____	5. Install tread onto wheels
Obstacle Avoidance System (OAS)	
_____	1. Secure lidar to mount and fully tighten all screws
_____	2. Install lidar mount onto servo motor
_____	3. Install servo motor onto mount inside the RBS
Solar Array System (SAS)	
_____	1. Mount spring hinge to tower assembly
_____	2. Install assembly into RBS by screwing spring hinge into RBS and fully tightening all screws
_____	3. Verify spring hinge functionality by allowing it to actuate the tower assembly
_____	4. Verify deployment motor functionality by applying 12V to the motor using a power supply
_____	5. Verify locking motor functionality by applying 3.3V to the motor using a power supply
Surface Imaging System (SIS)	
_____	1. Secure camera module to mount and fully tighten all screws
Control Electronics System (CES)	
_____	1. Load flight ready software onto Feather M0 Bluefruit LE
_____	2. Install PCB into RBS
_____	3. Route lidar sensor, camera module, servo motor, SAS locking motor, and solar panel wires to indicated header pins on CES PCB
Note:	*Use tape to secure wires and ensure no tangling can occur. Cut excess wire to ensure wires cannot be crossed*
_____	4. Route main drive motor (x2) and SAS deployment motor to FeatherWing motor driver and screw down terminal blocks
Note:	*Use tape to secure wires and ensure no tangling can occur. Cut excess wire to ensure wires*

	cannot be crossed. Connect wires in polarity according to colors (Red–Positive, Black–Negative)
_____	5. Install switches for motor and controller batteries
_____	6. Verify full charge of motor and controller batteries
WARNING	*Failure to fully charge batteries can cause loss of power to electronics and failure of the mission*
To be checked and signed by Payload Lead and team member when *all* steps are completed, indicating that Payload team is **PREPARED TO DEPLART FOR LAUNCH.**	
1. ______________________ 2. ______________________	
Final Assembly	
_____	1. Integrate rover with ROCS/RLM assembly
_____	2. Connect RLM motor to FeatherWing motor driver and screw down terminal blocks
_____	3. Route slip ring flange wires for DTS receiver module to indicated header on CES PCB
_____	4. Press payload into payload bay of the launch vehicle aligning ROCS with drilled screwholes
_____	5. Screw all 20 Socket Head Caps Screws into ROCS securing the payload inside the airframe
Launch Site Procedure	
_____	1. Flip motor battery switch to on position
_____	2. Flip controller battery switch to on position
_____	3. Flip DTS transmitter power source to on position
_____	4. Hand-off payload to vehicle team for final launch vehicle assembly
To be checked and signed by Payload Lead and team member when *all* steps are completed, indicating that Payload team is **PREPARED FOR LAUNCH**.	
1. ______________________ 2. ______________________	
After Recovery	
_____	1. Walk DTS transmitter to designated deployment location
_____	2. Query RSO for permission to initiate payload mission
_____	3. Send deployment trigger to the payload
_____	4. Inspect each phase of the rover's mission for unexpected performance characteristics
_____	5. Allow SIS to take pictures for 2 minutes
_____	6. Flip all switches to off position, powering down all electronics
_____	7. Remove and inspect ROCS/RLM assembly
_____	8. Remove microSD card from FeatherWing Adalogger
_____	9. Log all data from microSD card for analysis and controls modifications

7.2.6 Full Vehicle Assembly Safety Checklist

To be checked and signed by Payload Lead and team member when *all* steps are completed, indicating that ASSEMBLED VEHICLE is **PREPARED TO LAUNCH**.
1. ______________________ 2. ______________________
Equipment Required

☐ Payload Assembly ☐ VDS Assembly ☐ RFS Assembly	☐ Allen Key Set ☐ ROCS Assembly ☐ All recovery hardware	☐ Multimeter ☐ Nose cone assembly ☐ Lone coupler assembly	☐ Payload recovery coupler assembly

Final Assembly	
_____	1. Integrate payload bay to payload recovery coupler.
_____	2. Integrate payload recovery bay to payload recovery coupler.
_____	3. Integrate nose cone to payload recovery bay.
_____	4. Integrate lone coupler to payload bay.
_____	5. Integrate lone coupler to booster recovery bay.
_____	6. Integrate VDS coupler into booster section.
_____	7. Integrate VDS coupler to booster recovery bay.
_____	8. Insert motor into motor mount tube and secure with motor retainer.
To be checked and signed by Vehicle Lead, Recovery Lead, and a captain when *all* steps are completed, indicating that the vehicle is **PREPARED FOR LAUNCH**.	
1. ______________________________ 2. ______________________________ 3. ____________________	

7.2.7 Launch Pad Safety Checklist

To be checked and signed by Vehicle Lead and Safety Officer when *all* steps are completed, indicating that the rocket is a **GO FOR LAUNCH**.		
1. ______________________________ 2. ______________________________		
Prior to launch setup		
Equipment Required		
☐ TPL-72 Tank launch pad ☐ 1515 launch rail	☐ Multimeter ☐ Wind vane	☐ Wind vane display ☐ Zip ties
Launch Pad Setup		
_____	1. Assemble the launch pad with the 1010 launch rail.	
_____	2. Position the assembled launch pad a minimum of 1,500 feet away from any occupied building And 300 feet away from any personnel.	
WARNING	Ensure that the tripod launch pad does not tilt more than 20° from vertical. If the launch pad is not stable, the vehicle flight may be negatively impacted.	
_____	3. Clear dry grass within 100 feet of the launch pad	
	4. Fix the wind vane to the launch pad	
_____	5. Confirm that the wind vane display shows the wind speed.	
Vehicle Setup on Launch Pad		
Equipment to Pack or Prepare		
☐ Assembled vehicle ☐ Philips head screw driver ☐ Level	☐ Rocket perch ☐ Launch box ☐ Pencil	☐ Checklist ☐ Level 2 certification card
_____	1. Verify flight card has been properly filled out and launch permission has been granted by RSO.	
CAUTION	Safety glasses are required to be worn at the launch pad.	
_____	2. Select 3 team members to transport the assembled vehicle from the preparation area to the launch pad	
WARNING	Confirm the members can comfortably carry the vehicle together to eliminate the risk of a dropped vehicle.	
Note:	Only required personnel should accompany the rocket to the launch pad to eliminate distraction	
_____	2. Slide the vehicle onto the rail. If the section of airframe does not slide freely up and down the	

	entire length of the launch rail, see the trouble shooting section.	
WARNING	This step cannot be considered completed until the airframe moves freely. If the airframe is caught on the launch rail, the vehicle will experience too much friction, jeopardizing successful flight.	
_____	3. Ensure that the vehicle does not rest on the fins. Install a rocket perch if required.	
_____	4. Tilt and rotate the launch pad as directed by RSO. Use the level to ensure desired angle.	
_____	5. Arm all electronics in the following order:	
	___1. Payload ___2. Cameras	___3. Altimeters ____ StratoLoggers in nosecone ____ StratoLoggers in lower airframe
_____	6. Check for continuity between the launch box and launch pad.	
_____	7. Clear launch pad area and do not return until range has been reopened by the RSO.	
Igniter Installation		
Equipment to Pack or Prepare		
☐ Vehicle ☐ Igniter	☐ Masking tape ☐ Modified nozzle cap	
CAUTION	Safety glasses are required during igniter installation.	
_____	1. Insert the coated end of igniter through motor nozzle throat until it stops against the smoke charge element.	
DANGER	Igniters are explosive and must be kept clear of batteries, sparks, and open flames to avoid accidental firing.	
_____	2. Secure the igniter to the nozzle with a piece of masking tape or the modified nozzle cap.	

7.2.8 Troubleshooting Safety Checklist

Problem: The motor does not ignite after engaging launch button for 5 seconds	
Immediate steps:	
_____	1. Disengage safety interlock
_____	2. Do not begin to approach vehicle for a minimum of 60 seconds.
WARNING	The rocket may still launch in the case of a hang fire. Prematurely approaching the vehicle may endanger the team member.
Identify Situation	
Igniter no longer installed connected	
Definition: The igniter is no longer properly inserted against the smoke charge element of the motor.	
Identifier: The igniter is visibly outside of the motor.	
Igniter clips are no longer connected	
Definition: The igniter is no longer connected to the igniter clips and continuity is lost	
Identifier: Igniter is visibly disconnected from the igniter clips.	
Misfire or Hang Fire	
Definition: A misfired motor never ignites while a hang fire ignites after a substantial delay.	
Identifier: The igniter is visually intact and connected to the igniter clips but the motor never ignited	
Steps to Follow	
CAUTION	Safety glasses are required at the launch pad.
_____	3. Disconnect the igniter clip from the igniter.
WARNING	Do not place fingers or hands underneath the vehicle or any part of your body in front of the Vehicle. In the event of a hang fire, exhaust may still exit the motor nozzle.
	4. Remove the vehicle from the launch rail.
WARNING	Keep the motor nozzle pointed away from all handler faces and bodies
_____	5. Remove igniter

DANGER	Igniters are explosive and must be kept clear of batteries, sparks, and open flames to avoid accidental firing.
	6. Repeat motor preparation, igniter installation, and vehicle setup on launch pad.

7.2.9 Post Flight Inspection Safety Checklist

To be checked and signed by Vehicle Lead, Recovery Lead, Payload Lead, and Safety Officer when *all* steps are completed, indicating that the rocket has been completely EVALUATED POST FLIGHT.	
1. ______________________________	2. ______________________________
3. ______________________________	4. ______________________________
Altitude Achieved: ______________________________	
Motor Used: __________________________________	
Launch Location: _______________________________	
Launch Time: __________________________________	
Ground Wind Speed: ____________________________	
Estimated Shear Wind Speed: ____________________	
Launch Site Altitude: ____________________	
Launch Site Temperature: ____________________	
Post Launch Recovery Assessment	
2 Recovery team members must inspect the following components following every launch.	
Requirements	
☐ Vehicle	☐ 2 Recovery team members
____	1. Inspect all shroud lines for any damage or burn marks.
Damage: Y / N	Notes: ____
____	2. Inspect all shroud attachment points for damage.
Damage: Y / N	Notes: ____
____	3. Inspect *booster drogue* canopy for damage like holes, burns, or stretching.
Damage: Y / N	Notes: ____
____	4. Inspect *booster main* canopy for damage like holes, burns, or stretching.
Damage: Y / N	Notes: ____
____	5. Inspect *payload bay drogue* canopy for damage like holes, burns, or stretching.
Damage: Y / N	Notes: ____
____	6. Inspect *payload bay main* canopy for damage like holes, burns, or stretching.
Damage: Y / N	Notes: ____
____	7. Inspect *booster main* deployment bag for torn fabric that would indicate a snag.
Damage: Y / N	Notes: ____
____	8. Inspect *payload bay main* deployment bag for torn fabric that would indicate a snag.
Damage: Y / N	Notes: ____
____	9. Inspect ARRDs and altimeters for signs of damage or unacceptable wear.
Damage: Y / N	Notes: ____
WARNING	Any damage must be reported to Recovery lead and Safety officer to mitigate possible impact on later launches.
Repair Plan: ____ ____ ____	
Recovery team signatures for post launch inspection completion.	
1. ____________________________________	2. ____________________________________
Post Launch Vehicle Assessment	
2 Vehicle team members must inspect the following components following every launch.	
Equipment Required	
☐ Vehicle ☐ Sealable bag	☐ Acetone ☐ 2 Vehicle team members

_____	1. All fins for damage.
Damage: Y / N	Notes: ____
_____	2. Inspect nosecone for damage.
Damage: Y / N	Notes: ____
_____	3. Inspect airframe for damage.
Damage: Y / N	Notes: ____
_____	4. Inspect permanent internal airframe components for damage.
Damage: Y / N	Notes: ____
_____	5. Inspect all electronic sleds for damage.
Damage: Y / N	Notes: ____
_____	6. Inspect all couplers and shear pin holes for damage.
Damage: Y / N	Notes: ____
_____	7. Inspect motor centering ring epoxy and retainer for damage.
Damage: Y / N	Notes: ____
_____	8. Inspect carbon fiber components for signs of delamination or structural weakness
Damage: Y / N	Notes: ____
_____	9. Inspect all bolts and threads for signs of galling or deformation.
Damage: Y / N	Notes: ____
_____	9. Inspect all epoxied joints for cracks or edge peeling.
Damage: Y / N	Notes: ____
WARNING	Any damage must be reported to Vehicle lead and Safety officer to mitigate possible impact on later launches.
Repair Plan: ____	
Vehicle team signatures for post launch inspection completion.	
1. ______________________________________ 2. ______________________________________	
Motor casing cleaning and inspection	
_____	1. Carefully disassemble the motor casing.
WARNING	Ensure that no casing components are dropped or lost. The threaded components could be significantly damaged if dropped, requiring a new casing for a safe launch. Also ensure that the O-ring seal is not thrown away during disassembly.
_____	2. Remove used motor grains from casing.
_____	3. Place grains in a sealable back and place in an inert garbage can.
_____	4. Soak the forward seal in acetone.
_____	5. Dip a paper towel in acetone and wipe down the rest of the motor casing
_____	5. Inspect all components for damage following cleaning.
WARNING	Any damage must be reported to Vehicle lead and Safety officer to mitigate possible impact on later launches.
Vehicle team signatures for post launch motor cleaning and inspection.	
1. ______________________________________ 2. ______________________________________	
Payload Post Launch Assessment	
1. Walk DTS transmitter to within 50 feet of payload bay	
2. Query RSO for permission to initiate payload mission	
3. Send deployment trigger to the payload	
4. Inspect each phase of the rover's mission for unexpected performance characteristics	
5. Allow SIS to take pictures for 2 minutes	
6. Flip all switches to off position, powering down all electronics	
7. Remove and inspect ROCS/RLM assembly	
Damage: Y / N	Notes: ____
8. Remove microSD card from FeatherWing Adalogger	

9. Log all data from microSD card for analysis and controls modifications
Payload team signatures confirming post launch assessment completion.
1. ____ 2. ____

8 Project Plan

8.1 Testing

8.1.1 Launch Vehicle Test Campaign

Test	Test Description	Requirements Verified	Status
Subscale Vehicle Separation Test	The separation of the subscale vehicle will be tested by igniting pyrotechnic charges inside the vehicle on the ground to ensure proper separation of the vehicle to allow successful recovery of the vehicle.	2.24	Completed 11/10/17 and 12/1/17. Outcome: Pass
Subscale Vehicle November 11th Flight	A subscale vehicle flight will be used to estimate the coefficient of drag of the full-scale launch vehicle, verify construction techniques, and confirm simulation accuracy.	2.18, 2.18.2, 2.18.2.1	Completed 11/11/17. Outcome: Fail
Subscale Vehicle December 2nd Flight	A subscale vehicle flight will be used to estimate the coefficient of drag of the full-scale launch vehicle, verify construction techniques, and confirm simulation accuracy.	2.18, 2.18.2, 2.18.2.1	Completed 12/2/17. Outcome: Pass
Nose Cone Drop Test	A nose cone drop test will occur to verify that the additively manufactured nose cone can structurally withstand hitting the ground while falling under its parachute.	2.23	Completed 12/21/17. Outcome: Pass
Parachute Drop Test	A main parachute drop test will occur to verify opening force, time, stability, landing force and nominal drag force under freefall. A drogue parachute drop test will occur to verify opening force, vertical velocity, and stability.	3.3	Completed 12/26/17 Outcome: Pass

Reefing Ring Drop Test	A main parachute drop test with reefing ring will occur to verify deployment time retardation.	3.3.1	Completed 12/26/17 Outcome: Pass
CO_2 Mock Payload Bay Separation Test	A separation test will occur using a previously manufactured airframe tube modified to simulate the payload bay in size and weight. This test serves to verify the size CO_2 charge needed to separate the payload bay during flight	2.23	Completed 1/3/18. Outcome: Fail
Payload Bay Black Powder Containment Test	To verify that a black powder separation test will not damage the rover payload, a test will be conducted with a mock payload and black powder separation setup.	2.23	Completed 1/6/18 Outcome: Pass
Bulkplate Assembly Test	The bulkplate assemblies will be placed at least twice the maximum forces applied by the parachutes during descent to verify they will not fail.	2.22, 2.23	Incomplete. Scheduled for late January.
Fin Material Tensile Test	A tensile test will be used to determine material properties of the quasi-isotropic carbon fiber sheet the team manufactured for use in the fins.	2.23	Canceled
Vehicle Separation Test	The separation of the vehicle will be tested by igniting pyrotechnic charges inside the vehicle on the ground to ensure proper separation of the vehicle to allow successful recovery of the vehicle.	2.24	Completed 2/15/18 Outcome: Pass
Control Vehicle Flight Test	A full-scale launch vehicle test flight will be used to test the stability of the vehicle and the integrity of the mechanical design of the	2.2, 2.6, 2.9, 2.19, 2.19.1, 2.19.2	Completed 2/17/18 Outcome: Fail

	vehicle. The VDS will be inactive during this flight.		

8.1.1.1 Subscale Vehicle Separation Test

This test will demonstrate the system's ability to separate sections of the subscale vehicle to allow the recovery equipment to deploy during flight.

Items to be tested

- Ejection charges are properly sized to successfully separate the subscale launch vehicle during recovery.

Pass/Fail Criteria

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria
Subscale Vehicle Separation Test	2.6, 2.24	This test will be considered a pass if all sections of the subscale launch vehicle separate flawlessly. The nose cone must separate from the recovery bay and deploy the drogue parachute. The ARRD must release its pin and deploy the main parachute. If any section does not separate flawlessly the test is considered a failure.

Table 60: Pass/Fail criteria.

Pre-Test

Equipment

- The subscale launch vehicle shall be utilized to ensure proper volume of the recovery bay.
- An electronic ignition station shall be utilized in order to ignite the ejection charge from a safe distance.
- Prepared black powder ejection charges shall be utilized in order to separate the section.

Setup

Ejection charges shall be inserted into the recovery bay. The recovery bay shall be attached to the corresponding sections of the electronics bay in accordance with the launch vehicle.

Safety Notes

All spectators and testers shall be a minimum of 12 feet from the subscale launch vehicle during testing. No person or object shall be directly in front of or behind the subscale launch vehicle during ejection charge testing. All spectators shall wear safety goggles during preparation of charges and during separation testing.

Procedure

1) Prepare ejection charge using the specified amount of black powder measured using the black powder measuring kit located in the explosives box.
2) Connect the prepared ejection charge to the drogue terminal block.

3) Assemble the electronics bay and recovery bay using the #4-40 UNC nylon shear pins.
4) Connect the electronic ignition station to the terminal block.
5) Ensure the area is clear around the subscale launch vehicle.
6) Fire the ejection charge using the electronic ignition station.
7) After nose cone separation, repeat steps 4-6 for the ARRD.

Results

After completion of the subscale launch vehicle separation test, the test resulted in a pass. The nose cone separated from the recovery bay and deployed the drogue. The ARRD released its pin and allowed the main parachute to be deployed.

8.1.1.2 Subscale Vehicle November 11th Test Flight

To comply with Statement of Work Requirement 2.18, a subscale model of the full-scale launch vehicle was designed, manufactured, and flown. The subscale model was designed to resemble and perform as similarly as possible to the full-scale design.

Items to be tested

- The subscale vehicle shall be utilized to ensure proper volume of the recovery bay.
- An electronic ignition station shall be utilized in order to ignite the ejection charge from a safe distance.
- Prepared black powder ejection charges shall be utilized in order to separate the section.
- StratoLogger altimeters will be used on the subscale to verify their validity for use on the full-scale launch vehicle.

Items not tested

- The VDS, Payload, and GPS devices will not be tested due to the size constraints of the subscale vehicle.

Pass/Fail Criteria

The following table describes the requirements that are being tested and the specifications to be able to accept tested requirements as a verified requirement.

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria
Subscale Vehicle November 11th Flight	2.18, 2.18.2, 2.18.2.1	The launch of the subscale vehicle is considered a success if the exit rail velocity and the achieved apogee altitude is within 10% of the simulated apogee altitude. The recovery of the subscale vehicle is considered a success if the subscale vehicle is undamaged upon recovery.

Table 61: Pass/Fail criteria.

Pre-Test

The following sections describe information about the setup and approach being used for this test.

Equipment

- Subscale vehicle
- Two PerfectFlite StratoLogger Altimeters
- Two Duracell 9 volt batteries
- Altimeter Sled
- ARRD assembly
- Launch Controls
- Aerotech I300 Motor
- Ejection charge equipment
- Cruciform Drogue
- Toroidal Main
- Shock Chord

Setup

The recovery equipment for the subscale vehicle was inserted into a single recovery bay with a separation point at the avionics bay located in the center of the vehicle.

Safety Notes

All spectators and launch attendees shall be at the appropriate distance from the launch vehicle as outlined by the NAR Safety Code.

Procedure

Subscale Vehicle Preparation

1. Program the two PerfectFlite Stratologger CF altimeters to ignite an ejection charge at apogee and at a lower specific altitude.
2. Mount altimeters to altimeter sled and connect each altimeter to a Duracell 9 volt battery.
3. Create two ejection charges by inserting an appropriate amount of black powder into an ejection charge canister with a e-match and seal them off with electrical tape.
4. Check continuity between terminal barrier blocks and altimeters.

Subscale Recovery Preparation

1. Inspect shroud lines, panels, and stitching for compromising damage.
2. Fold drogue arms under center overlap of panels. Neatly fold shroud lines and wrap assembly in nomex.
3. Fold main parachute panels sequentially in half on top of each other.
4. Fold shroud lines into S folds.
5. Stow main parachute in deployment bag with S folded shroud lines tucked neatly inside bag.
6. Inspect and clean ARRD of any black powder residue.
7. Install redundant E-matches through hole in black canister.
8. Fill black powder canister to line with black powder and cover with retaining sticker.
9. Install shackle pin, ball bearings, spring, and piston into red ARRD body.
10. While depressing piston just past threads and holding shackle in place, screw black powder canister into ARRD body. Test integrity by pulling and twisting shackle.
11. Install ARRD onto bulkplate.
12. Connect drogue and main to their respective shock cords.
13. Carefully slide recovery bay tube over assembly for transportation to launch field.

Launch Site Subscale Preparation

1. Insert motor into motor mount and secure using the motor retainer.
2. Insert altimeter sled into the avionics coupler and secure to propulsion bay by using three 6-32 SCHS fasteners.
3. Seal avionics coupler with bulkplate, which holds the terminal barrier blocks, ARRD, and eye bolt for attaching recovery equipment.
4. Connect ejection charge and ARRD to its respective terminal barrier block.
5. Connect main shock cord to eyebolt. Connect drogue shock cord to ARRD shackle.
6. Connect main deployment bag tether to ARRD shackle.
7. Insert dog barf under main bag and slide airframe over coupler.
8. Connect nose cone to vehicle via a friction fit.
9. Setup launch pad 100 feet away from spectators. For more detail, reference see the NAR Safety Code.
10. Attach 12 foot rail to launch pad and prepare launch system.
11. Transport subscale vehicle to launch pad location and attach subscale vehicle to launch rail by sliding rail buttons into the rail.
12. Arm each altimeter by turning each screw switch to the on position, which are accessible via the vent hole in the avionics bay.
13. Insert the igniter into the motor, ensuring that the igniter tip is inserted far enough into the motor.
14. Connect to the igniter to the launch system via alligator clips.
15. Check continuity between the igniter and the launch system.
16. Launch subscale vehicle.

Results

After conducting the subscale flight test on November 11th, the outcome resulted in a failed test. The full details on the results of this test can be found in 8.1.1.1.

8.1.1.3 Subscale Vehicle December 2nd Test Flight

To comply with Statement of Work Requirement 2.18, a subscale model of the full-scale launch vehicle was designed, manufactured, and flown. The subscale model was designed to resemble and perform as similarly as possible to the full-scale design. This test served to test new recovery subsystem designs implemented after the failed test launch on November 11th.

Items to be tested

- The subscale vehicle shall be utilized to ensure proper volume of the recovery bay.
- An electronic ignition station shall be utilized in order to ignite the ejection charge from a safe distance.
- Prepared black powder ejection charges shall be utilized in order to separate the section.
- StratoLogger altimeters will be used on the subscale to verify their validity for use on the full-scale launch vehicle.

Items not tested

- The VDS, Payload, and GPS devices will not be tested due to the size constraints of the subscale vehicle.

Pass/Fail Criteria

The following table describes the requirements that are being tested and the specifications to be able to accept tested requirements as a verified requirement.

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria
Subscale Vehicle December 2nd Flight	2.18, 2.18.2, 2.18.2.1	The launch of the subscale vehicle is considered a success if the exit rail velocity and the achieved apogee altitude is within 10% of the simulated apogee altitude. The recovery of the subscale vehicle is considered a success if the subscale vehicle is undamaged upon recovery.

Table 62: Pass/Fail criteria.

Pre-Test

The following sections describe information about the setup and approach being used for this test.

Equipment

- Subscale vehicle
- Two PerfectFlite StratoLogger Altimeters
- Two Duracell 9 volt batteries
- Altimeter Sled
- ARRD assembly
- Launch Controls
- Aerotech I300 Motor
- Ejection charge equipment
- Cruiciform Drogue
- Toroidal Main
- Shock Chord

Setup

The recovery equipment for the subscale vehicle was inserted into a single recovery bay with a separation point at the avionics bay located in the center of the vehicle.

Safety Notes

All spectators and launch attendees shall be at the appropriate distance from the launch vehicle as outlined by the NAR Safety Code.

Procedure

Subscale Vehicle Preparation

1. Program the two PerfectFlite Stratologger CF altimeters to ignite an ejection charge at apogee and at a lower specific altitude.
2. Mount altimeters to altimeter sled and connect each altimeter to a Duracell 9 volt battery.

3. Create two ejection charges by inserting an appropriate amount of black powder into an ejection charge canister with a e-match and seal them off with electrical tape.
4. Check continuity between terminal barrier blocks and altimeters.

Subscale Recovery Preparation

1. Inspect shroud lines, panels, and stitching for compromising damage.
2. Fold drogue arms under center overlap of panels. Neatly fold shroud lines and wrap assembly in nomex.
3. Fold main parachute panels sequentially in half on top of each other.
4. Fold shroud lines into S folds.
5. Stow main parachute in deployment bag with S folded shroud lines tucked neatly inside bag.
6. Inspect and clean ARRD of any black powder residue.
7. Install redundant E-matches through hole in black canister.
8. Fill black powder canister to line with black powder and cover with retaining sticker.
9. Install shackle pin, ball bearings, spring, and piston into red ARRD body.
10. While depressing piston just past threads and holding shackle in place, screw black powder canister into ARRD body. Test integrity by pulling and twisting shackle.
11. Install ARRD onto bulkplate.
12. Connect drogue and main to their respective shock cords.
13. Carefully slide recovery bay tube over assembly for transportation to launch field.

Launch Site Subscale Preparation

1. Insert motor into motor mount and secure using the motor retainer.
2. Insert altimeter sled into the avionics coupler and secure to propulsion bay by using three 6-32 SCHS fasteners.
3. Seal avionics coupler with bulkplate, which holds the terminal barrier blocks, ARRD, and eye bolt for attaching recovery equipment.
4. Connect ejection charge and ARRD to its respective terminal barrier block.
5. Connect main shock cord to eyebolt. Connect drogue shock cord to ARRD shackle.
6. Connect main deployment bag tether to ARRD shackle.
7. Insert dog barf under main bag and slide airframe over coupler.
8. Connect nose cone to vehicle via a friction fit.
9. Setup launch pad 100 feet away from spectators. For more detail, reference see the NAR Safety Code.
10. Attach 12-foot rail to launch pad and prepare launch system.
11. Transport subscale vehicle to launch pad location and attach subscale vehicle to launch rail by sliding rail buttons into the rail.
12. Arm each altimeter by turning each screw switch to the on position, which are accessible via the vent hole in the avionics bay.

13. Insert the igniter into the motor, ensuring that the igniter tip is inserted far enough into the motor.
14. Connect to the igniter to the launch system via alligator clips.
15. Check continuity between the igniter and the launch system.
16. Launch subscale vehicle.

Results

After conducting the subscale flight test on December 2nd, the outcome resulted in a passed test. The full details on the results of this test can be found in 8.1.1.

8.1.1.4 Nose Cone Drop Test

This test will demonstrate the ability of the additively manufactured nose cone to structurally withstand the impact force from hitting the ground while descending under parachute. The nose cone design is further discussed in 8.1.1.

- Full scale nose cone 3D printed at the University of Louisville Rapid Prototyping Center.

Pass/Fail Criteria

The following table describes the requirements that are being tested and the specifications to be able to classify the results of the tested requirement as a "pass".

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria
Nose Cone Drop Test	2.23	The force that the nose cone experiences impacting the ground after descending under fully deployed parachute must not cause any structural damage to the nose cone.

Table 63: Pass/Fail criteria.

Pre-Test

The following sections describe information about the setup and approach being used for the test.

Equipment

- The nose cone to be used on the full-scale launch vehicle will be utilized to ensure that the test results do not deviate from the system's actual performance.
- A parachute with the exact dimensions to be used for the nose cone section on the full-scale launch vehicle shall be utilized to ensure accurate descent velocity.
- A 6 in. diameter carbon fiber coupler will be utilized to simulate the mass of the nose cone avionics coupler, and to serve as point of attachment for the parachute.

Setup

The nose cone avionics coupler will be temporarily fastened to the nose cone. The parachute shall be securely fastened to a bulk-plate at the base of the nose cone avionics coupler.

Safety Notes

All spectators must be a minimum of 100 ft. from the drift radius of the nose cone at ground level.

Procedure

1) Assemble the coupler and bulk plates using ¼"-20 all-thread rods and a single U-bolt.
2) Fasten the nose cone and coupler together.
3) Secure the parachute's shock cord to the U-bolt in the center of the coupler bulk plate.
4) Ensure that the drop zone area surrounding the elevated platform is clear for a safe test.
5) Drop the nose cone assembly.

Results

After conducting the nose cone drop test, the test resulted in a pass. The additively manufactured nose cone will be used on the full-scale launch vehicle and is discussed in detail in 4.1.3.7.

Parachute Drop Test

This test will demonstrate the ability of the laser cut parachutes to fully deploy, verifying opening force, vertical velocity, and stability.

Items to be tested

- Main Toroidal Parachute Booster
- Main Toroidal Parachute Payload
- Drogue Cruciform Parachute Booster
- Drogue Cruciform Parachute Payload

Pass/Fail Criteria

The following table describes the requirements that are being tested and the specifications to be able to classify the results of the tested requirement as a "pass".

Test Name	**Requirement(s) to be Verified**	**Pass/Fail Criteria**
Parachute Drop Test	3.3	Opening force will not exceed structural capabilities of the bulk plate. Parachute will fully deploy and shroud lines will not twist. Maintain appropriate terminal velocity.

Table 30: Pass/Fail criteria.

Pre-Test

The following sections describe information about the setup and approach being used for the test.

Equipment

- AIM XTRA accelerometer
- 2.2 lb. & 18.96 lb. Ballast
- Shock cord
- Parachutes

Setup

The parachute to be tested was attached to the ballast with shock cord.

Safety Notes

All spectators must be a minimum of 100 ft. from the drift radius of the ballast at ground level.

Procedure

1) Attach the parachute to the ballast
2) Engage accelerometer
3) Ensure that the drop zone area surrounding the elevated platform is clear for a safe test.
4) Drop the parachute assembly.
5) Repeat for all parachutes

Results

After conducting the parachute drop test, the test resulted in a pass. Both the toroidal and cruciform parachutes will be used on the full-scale launch vehicle and is discussed in detail in 8.1.1.

8.1.1.5 Reefing Ring Test

This test will demonstrate the ability of the reefing ring to retard the deployment duration of the main parachute.

Items to be tested

- Main Toroidal Parachute Reefing Ring

Pass/Fail Criteria

The following table describes the requirements that are being tested and the specifications to be able to classify the results of the tested requirement as a "pass".

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria
Reefing Ring Test	3.3.2	Opening force will not exceed structural capabilities of the bulk plate. Parachute will fully deploy over a 20-30% greater period of time than without a reefing ring

Table 30: Pass/Fail criteria.

Pre-Test

The following sections describe information about the setup and approach being used for the test.

Equipment

- AIM XTRA accelerometer
- 5 lb Ballast
- Shock cord
- Parachute
- Reefing Ring

Setup

The parachute to be tested was attached to the 5lb ballast with shock cord.

Safety Notes

All spectators must be a minimum of 100 ft. from the drift radius of the ballast at ground level.

Procedure

1) Attach the parachute with reefing ring to the ballast
2) Engage accelerometer
3) Ensure that the drop zone area surrounding the elevated platform is clear for a safe test.
4) Drop the parachute assembly.

Results

After conducting the reefing ring test, the test resulted in a pass. The reefing ring will be used on the full-scale launch vehicle and is discussed in detail in 4.2.1.

8.1.1.6 Payload Bay Black Powder Containment Test

This test will determine an effective way to shield the rover payload from the black powder charge needed to separate the payload bay from the payload coupler. The black powder charge will be wrapped in a custom sewn nomex charge well that ct the charge away from the rover.

Items to be tested

- Nomex charge well
- Black powder charge

Pass/Fail Criteria

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria

Payload Bay Black Powder Containment Test	2.6	This test will be considered a pass if no excessive amount of black powder residue or particulate is expelled from the nomex charge well. This test will be considered a failure if there is an excessive amount of residue, or if the nomex charge well is burned excessively.

Table 64: Pass/Fail criteria.

Pre-Test

Equipment

- Nomex
- Black powder
- Black powder charge canister
- Sewing machine
- E-match and igniter

Setup

- Place precisely 4.5 grams of black powder into a black powder charge canister
- Insert e-match into black powder charge canister
- Place black powder charge into nomex charge well

Safety Notes

All spectators must stand at least 15 ft. from the black powder charge while wearing safety glasses.

Procedure

1. Ignite black powder charge within nomex charge well.
2. Inspect area surrounding charge well for excess residue.
3. Inspect charge well for excess burning/damage.

Results

After completing the payload bay black powder charge containment test, the test resulted in a pass. The nomex charge well contained the black powder successfully and suffered minimal burning. The nomex charge well design will be tweaked and tested further in late January.

8.1.1.7 Bulkplate Assembly Test

The bulkplate assembly test will prove the integrity of the design with the expected load from the opening force of the recovery equipment. This test will verify that the carbon fiber plate, wood plate, and U-bolt together can withstand 412 lbs, the maximum opening force of the parachute during decent.

Items to be tested.

- Carbon Fiber Plate
- Wood Plate
- U-Bolt and Washer

Pass/Fail Criteria

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria
Bulkplate Assembly Test	2.22	The bulkplate assembly must not permanently deform in any way under loading of 412 lbs.

Table 65: Pass/Fail criteria.

Pre-Test

Equipment

- Bulkplate Assembly
- Test Fixture
- Test Load

Setup

1. The wooden plate is placed on top of the carbon fiber plate.
2. The u-bolt is inserted, from the bottom, through the carbon fiber plate and wooden plate, with the washers and nuts installed on top of the wooden plate.
3. The assembly is then suspended, carbon fiber side down, from the all thread on the test fixture with nuts and washers installed on the carbon fiber side.

Safety Notes

Keep all body parts clear of test fixture and potential falling objects.

Procedure

1) Assemble bulkplate.
2) Install bulkplate in test fixture, with carbon fiber side down.
3) Check that u-bolt and all nuts are properly secured.
4) Suspend load from bulkplate.
5) Gradually increase load to 412 lbs, checking for signs of failure.

8.1.1.8 Fin Material Tensile Test

NOTE: Due to a material change, this test was canceled.

This test will determine ultimate tensile strength of the fin material.

Items to be tested.

- In-house manufactured carbon fiber fin material

Pass/Fail Criteria

The following table describes the requirements that are being tested and the specifications to be able to accept tested requirement as a passed requirement.

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria

Fin Material Tensile Test	2.22	Test data shall provide the team with a clear understanding of the material properties of the fin material.

Table 66: Pass/Fail criteria.

Pre-Test

Equipment

20,000 Lbs MTS

Laptop with MTS software

1"x12" fin material sample

Setup

Airframe Samples

1. Cut 1"x12" strips from fin material.
2. Sample strips shall be cut.
3. Reinforce 1" from both ends of sample strips, front and back, to distribute clamping force.

Procedure

1) Connect laptop to MTS.
2) Enter sample specs into MTS program.
3) Set MTS gap to match sample length.
4) Secure sample in MTS clamp.
5) Run program/tensile test.
6) Record material properties.

Cancellation

The fin material tensile test was cancelled upon the completion of the first full scale test flight on February 17th. Due to the motor CATO that was experienced, the fins experienced significant damage and it was determined that a new set of fins would be needed to produce. Due to time constraints and the lengthy manufacturing time associated with the fin material, the new fins are cut from store-bought carbon fiber sheet. The carbon fiber sheet has been used for fins on similar launch vehicles in the past and is therefore trusted to be used as fin material with no additional testing. In addition, testing data for the material was obtained from the manufacturer verifying that the material is strong enough to withstand the loads from flight. This data can be seen in Table 67 below.

Youngs Modulus	**5 msi**
Tensile Strength	**50 ksi**

Table 67: Fin Material Data

8.1.1.9 Full-Scale Vehicle Separation Test

This test will demonstrate the system's ability to separate sections of the vehicle to allow the recovery equipment to deploy during flight.

Items to be tested

- Ejection charges are properly sized to successfully separate the launch vehicle during recovery.

Pass/Fail Criteria

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria
Full-Scale Vehicle Separation Test	2.6, 2.24	This test will be considered a pass if all sections of the launch vehicle separate flawlessly. The payload bay must separate from the payload coupler and deploy the drogue parachute. The nose cone must separate from the payload recovery bay and deploy the drogue parachute. The payload coupler must separate from the booster and deploy the main parachute. The ARRD must release its pin and deploy the main parachute. If any section does not separate flawlessly the test is considered a failure.

Table 68: Pass/Fail criteria.

Pre-Test

Equipment

- The full scale launch vehicle shall be utilized to ensure proper volume of the booster recovery bay and payload recovery bay.
- An electronic ignition station shall be utilized in order to ignite the ejection charge from a safe distance.
- Prepared black powder ejection charges shall be utilized in order to separate the section.

Setup

Ejection charges shall be inserted into the appropriate terminal block of their associated recovery bay. Recovery bays shall be attached to the corresponding sections of the electronics bay in accordance with the launch vehicle.

Safety Notes

All spectators and testers shall be a minimum of 12 feet from the launch vehicle during testing. No person or object shall be directly in front of or behind the launch vehicle during ejection charge testing. All spectators shall wear safety goggles during preparation of charges and during separation testing.

Procedure

1) Prepare ejection using the specified amount of black powder measured using the black powder measuring kit located in the explosives box.
2) Connect the prepared ejection charge to the drogue terminal block.
3) Assemble the electronics bay and recovery bay using the #4-40 UNC nylon shear pins.
4) Connect the electronic ignition station to the terminal block.
5) Ensure the area is clear around the launch vehicle.

6) Fire the ejection charge using the electronic ignition station.
7) After nose cone separation, repeat steps one through six for the main deployment instead of the drogue deployment.

Results

After conducting the full-scale vehicle separation test, the test resulted in a pass.

8.1.1.10 Control Vehicle Flight Test

This test will demonstrate the flight characteristics, recovery, and structural integrity of the full-scale vehicle. It will also serve as a benchmark to show what apogee altitude the vehicle can achieve with an inactive VDS.

Items to be tested

- The full-scale launch vehicle shall be utilized to ensure proper volume of the recovery bay.
- An electronic ignition station shall be utilized in order to ignite the ejection charge from a safe distance.
- Prepared black powder ejection charges shall be utilized in order to separate the section.

Items not tested

- The payload will not be tested and instead a payload mass simulator shall be used in its place.

Pass/Fail Criteria

The following table describes the requirements that are being tested and the specifications to be able to accept tested requirement as a passed requirement.

Test Name	Requirement(s) to be Verified	Pass/Fail Criteria
Control Vehicle Flight Test	2.2, 2.6, 2.9, 2.19, 2.19.1, 2.19.2	The launch vehicle control test flight shall be considered a pass if the vehicle ascends stably, does not exceed 5,600ft. AGL, is +/- 10% of the expected apogee altitude, and recovers safely within the predicted drift radius.

Table 69: Pass/Fail criteria.

Pre-Test

Equipment

- Full scale launch vehicle
- Four PerfectFlite Stratologger CF altimeters
- Steel ballasts to simulate the weight of the payload
- VDS and VDS electronics
- 12-foot rail and launch pad
- Launch system
- ARRD
- Booster Main and Drogue
- Booster Main and Drogue shock cords

- Ejection charges
- AeroTech L2200-G motor
- Fins
- Multimeter

Results

After completing a full-scale vehicle flight test, the test resulted in a failure. The results of this test are further discussed in 4.4.1.

8.1.2 Payload Master Test Plans

This section will describe the tests required to prove the integrity of the final payload design. Each test will be conducted to verify requirements intended to confirm the performance of a designated system of the designed payload and confirm flight readiness of the entire payload. Tests to be performed, requirements each test will verify, and the scheduled date of the test is shown below in Table 70.

Test	Requirement to be Verified	Scheduled date
Rover Performance Test	4.5.3 of the NASA SOW	Complete
ROCS Roll Test	ROCS-3	Postponed
DTS 50 foot Radius Test	DTS-4	Complete
RDS Sloped Driving Test	RDS-3	Complete
OAS Accuracy Test	OAS-2	Complete
CES Orientation Accuracy Test	CES-1	Complete
CES Autonomous Control Testing Series	4.5.3 of the NASA SOW CES-2 CES-3 CES-4 CES-5 CES-6	Complete
Battery Life Testing Series	CES-8 CES-9	Postponed
Flight Loads Testing Series	ROCS-4 RLM-4 RBS-3 SAS-5	Postponed
Full Flight Performance Testing Series	DTS-6 CES-7	Postponed

Table 70: Payload testing plan.

8.1.2.1 Rover Performance Test

<u>Objective</u>

The objective of this test is to ensure that the payload can successfully complete its primary mission. This will be the final performance test of the rover to determine any changes to interaction between systems and mechanical adjustment. The requirement to be verified by this test is requirement 4.5.3 of the NASA Statement of Work. SOW453SOWreq

Items/Variable to be Tested

- Distance of travel after exiting the airframe
- Interaction between all systems in flight configuration

Methodology

This test will be an acceptance level test conducted to analyze the system's performance as it is intended to be used and affirm its capability to perform the intended tasks. The environment of the test will simulate the conditions in which the system is expected to perform during the mission by integrating the payload into the payload bay of the launch vehicle, running flight ready software, and deploying the rover as will be done during flight. The pretest setup, test procedure, post-test operations, and suspension criteria are described below.

Pretest Setup

- Load flight ready software onto Feather M0 Bluefruit LE microcontroller
- Integrate electronics into the rover
- Integrate the rover into the ROCS
- Integrate the ROCS into the payload bay of the launch vehicle and secure with set screws
- Ensure that the DTS antenna is installed on exterior of payload bay
- Configure transmitter electronics and mount on Yagi antenna

Test Procedure

____ 1.) Inform all bystanders of testing
____ 2.) Place payload bay section on the ground in an open area
____ 3.) Power up electronics
____ 4.) Walk within a 50 foot radius of the payload bay
____ 5.) Trigger deployment of the rover using the transmitter module
____ 6.) Inspect rover during autonomous operation
____ 7.) Allow rover to stop operating
____ 8.) Power down electronics

Post-test Operations

- Measure linear distance from rover to payload bay
- Log distance measurement and compare to 5 foot minimum required

Suspension Criteria

- Any safety risk not accounted for is encountered
- Rover does not reach 5 foot minimum distance from payload bay
- Rover does not deploy
- Loss of power to electronics

Success Criteria

The test will be considered successful only if the rover deploys from the payload bay after the deployment signal has been sent and comes to rest at least 5 feet from the payload bay from which it deployed. This test does not require the rover to deploy the solar array to be considered successful. The test will be considered a failure if the rover does not deploy or is not capable of reaching at least 5 feet away from the payload bay.

Safety Considerations

Proper safety precautions will be taken to avoid injury. Point points will be identified prior to any work being done. All bystanders will be cleared prior to testing to avoid collision and tripping hazards. The testing area will be cleared to avoid collision. No person will be allowed within 3 feet of the rotating parts while they are operating. All circuits will be continuity checked for shorts prior to any power being applied to avoid harm to personnel or components.

Results

This verification has been partially completed due to not using the deployment signal that will be used during the mission to conduct this test. All other items have been proven functional. The deployment signal has been proven reliable in the payload's mission configuration and as such, the requirement is being considered verified. The rover can be seen exiting the airframe section during this test below in Figure 232.

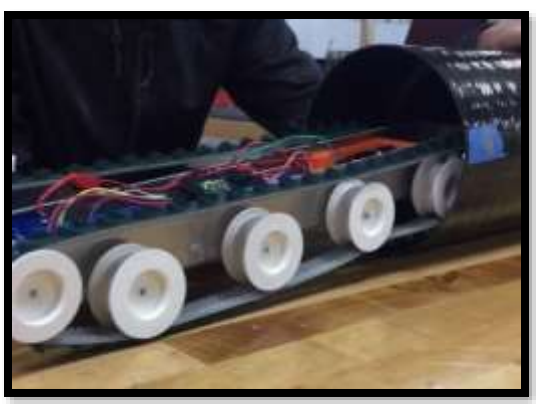


Figure 232: Rover exiting payload bay.

The payload had been integrated into the ROCS and airframe prior to beginning the test. The rover was deployed using a team member's cellphone to send a Bluetooth command to the rover to deploy. The rover then drove straight forward over two 1 inch tall obstacles coming to rest 5 feet from the bay.

8.1.2.2 ROCS Roll Test

Objective

The objective of this test is to ensure that the Rover Orientation Correction System will reliably bring the rover to rest upright inside the payload bay regardless of the landing orientation of the launch vehicle. The results of this test will determine if any changes need to be done to the ROCS before flight. The requirement to be verified by this test is ROCS-3.ROCS3ROCS3req

Items/Variable to be Tested

- Angle of inclination along the roll axis of the rover
- Consistency of performance of the system

Methodology

This test will be a system level test conducted to analyze the system's performance as it is intended to be used. The environment of the test will simulate the conditions in which the system is expected to perform during the mission. The pretest setup, test procedure, post-test operations, and suspension criteria are described below.

Pretest Setup

- Construct ramp out of wood with a 20° angle of inclination to provide consistent test platform
- Place ramp in large, flat, open area with no obstructions in front of the slope
- Load test script onto Feather M0 Bluefruit LE microcontroller
- Integrate electronics into the rover
- Integrate the rover into the ROCS
- Integrate the ROCS into the payload bay of the launch vehicle and secure with set screws

Test Procedure

____ 1.) Inform all bystanders of testing
____ 2.) Place payload bay section at the peak of the ramp
____ 3.) Power up electronics
____ 4.) Visually confirm orientation data is being collected by inspecting the
____ LEDs
____ 5.) Perform countdown prior to releasing the payload bay
____ 6.) Release payload bay
____ 7.) Allow payload bay to come to rest
____ 8.) Inspect and log the color of the LEDs as either green or red
____ 9.) Power down electronics
10.) This concludes a trial. Repeat procedure to obtain 10 trials

Post-test Operations

- Remove set screws
- Remove ROCS from payload bay
- Remove rover from ROCS
- Remove electronics from the rover
- Extract gyroscope data from all 10 trials from microSD card
- Plot roll axis data and 50° upper limit vs. time
- Compare steady-state gyroscope data to 50° upper limit to confirm LED inspection results

Suspension Criteria

- Any safety risk not accounted for is encountered
- Either LED is red after the payload bay comes to rest
- Loss of power to electronics
- Failure of a trial

Success Criteria

Each trial will be considered successful only if both LEDs are seen to be green after the payload bay comes to rest. The test will be considered successful only if 10 consecutive trials yield successful results and graphical data is consistent with the LED data. Any deviation from these criteria will render the trial and test a failure at which point the test will be suspended, a solution will be determined and implemented, and the test will be conducted again.

Safety Considerations

Proper safety precautions will be taken to avoid injury. Point points will be identified prior to any work being done. Power tool safety will be adhered to while constructing the ramp. All bystanders will be cleared prior to testing to avoid collision and tripping hazards. The testing area will be cleared to avoid collision. All circuits will be continuity checked for shorts prior to any power being applied to avoid harm to personnel or components.

Results

This test has been postponed due to unsuccessful flight of the launch vehicle and the need to rebuild the payload entirely.

8.1.2.3 DTS 50 Foot Radius Test

Objective

The objective of this test is to ensure that the complex RF emission pattern of the receiver module backed by a rounded conductive body is capable of maintaining communication with the transmitter module anywhere within close proximity. The requirement to be verified by this test is DTS-4. DTS4req

Items/Variable to be Tested

- Integrity of communication at short range
- Communication rate

Methodology

This test will be a system level test conducted to analyze the system's performance as it is intended to be used. The environment of the test will simulate the conditions in which the system is expected to perform during the mission. The pretest setup, test procedure, post-test operations, and suspension criteria are described below.

Pretest Setup

- Integrate receiver antenna with receiver module
- Acquire 6 in. carbon fiber airframe section
- Mount receiver antenna to exterior of airframe section
- Integrate transmitter module with Yagi antenna
- Establish communication output to computer terminal

Test Procedure

____ 1.) Inform all bystanders of testing
____ 2.) Place airframe section on the ground in open area
____ 3.) Power up electronics
____ 4.) Stand 50 feet away from receiver with transmitter in hand
____ 5.) Confirm communication link on computer terminal
____ 6.) Walk transmitter slowly directly towards airframe section
____ 7.) Monitor communication link at all times
____ 8.) Walk transmitter directly over and past airframe section until reaching
____ 50 feet away
____ 9.) Walk transmitter 90° along perimeter of 50 foot radius centered on
____ airframe section
10.) Walk transmitter toward, over, and past airframe section until reaching 50 feet away
11.) Power down electronics

Post-test Operations

- Collect airframe section and electronics
- Analyze communication rate and integrity based on timestamps on each data point

Suspension Criteria

- Any safety risk not accounted for is encountered

- Communication downlink occurs at any point
- Loss of power to electronics

Success Criteria

The test will be considered successful only if no downlink in communication occurs at any point during the test. The communication must maintain a consistent rate measured by the time stamps on each data point to be considered successful. The test will be considered a failure if there is any loss of communication or inconsistent, lagging communication occurs.

Safety Considerations

Proper safety precautions will be taken to avoid injury. The transmitter module and computer will be operated by separate team members. Each team member will keep their eyes on the ground in front of them while walking to avoid tripping hazards. All circuits will be continuity checked for shorts prior to any power being applied to avoid harm to personnel or components.

Results

The transmitter Yagi antenna was used to transmit data continuously to the receiver module that had been placed inside of an airframe section and placed on the ground with the mud-flap antenna adhered to the exterior of a carbon fiber airframe section as it is during flight. Instead of walking the transmitter around the receiver, the receiver airframe section was rotated giving the same effect. The test being conducted is shown below in Figure 233.

Figure 233: 50 foot radius test.

At no point during the testing was the connection between the transmitter and receiver lost successfully passing the test and verifying the requirement.

8.1.2.4 RDS Sloped Driving Test

Objective

The objective of this test is to evaluate the Rover Drive System design's ability to maintain forward motion of the rover up an inclined terrain. The requirement to be verified by this test is RDS-3.RDS3RDS3req

Items/Variable to be Tested

- Maximum incline surmountable by RDS
- Rate at which the RDS allows the rover to climb each slope angle

Methodology

This test will be a system level test conducted to analyze the system's performance in extreme conditions and determine limit of design. After meeting the success criteria, the test will continue to analyze the system in extreme conditions to expose any apparent design issues. The pretest setup, test procedure, post-test operations, and suspension criteria are described below.

Pretest Setup

- Assemble RDS system onto the body structure of the rover
- Build ramp with adjustable incline
- Place ramp on the ground in an open area
- Mark preset angles on adjustable ramp
- Mark one foot increments of distance up the ramp
- Set initial incline of ramp at 20°
- Load test script on Feather M0 Bluefruit LE microcontroller
- Confirm functionality of test script on flat ground

Test Procedure

____ 1.) Inform all bystanders of testing
____ 2.) Place rover at base of ramp facing upward
____ 3.) Power on electronics
____ 4.) Begin driving rover forward using Bluetooth controls and begin timer
____ 5.) Once rover has reached one foot marker, stop driving and stop timer
____ 6.) Remove rover from ramp
____ 7.) Log time taken to reach one foot and incline of ramp
____ 8.) Increment ramp angle
____ 9.) Repeat trial

Post-test Operations

- Plot drive time to reach one foot vs ramp angle as bar graph
- Determine upper inclination angle limit of system's capability

Suspension Criteria

- Any safety risk not accounted for is encountered
- Rover is not capable of reaching one foot up the ramp
- Ramp angle is not accurate
- Rover has not reached one foot up the ramp within one minute of driving
- Loss of power to electronics

Success Criteria

The test will be considered successful if the rover is able to climb at least one foot up the inclined surface of the ramp while the ramp is set at 20°. The rover must be able to reach this marker within one minute of driving. The test will be considered a failure if the rover is not capable of reaching at least one foot up the ramp within one minute at which point the design will be evaluated and a solution determined.

Safety Considerations

Proper safety precautions will be taken to avoid injury. Point points will be identified prior to any work being done. Power tool safety will be adhered to while constructing the ramp. All bystanders will be cleared prior to testing to avoid collision and tripping hazards. The testing area will be cleared to avoid collision. All circuits will be continuity checked for shorts prior to any power being applied to avoid harm to personnel or components.

Results

The RDS successfully completed the one foot drive up an inclined ramp of 20° in a time of 7.02s. The Ramp constructed as well as the starting position and inclination of the ramp to conduct this test are shown below in Figure 234.

Figure 234: Ramp at 20 degrees.

At this point, the requirement was considered successfully verified. The test continued per the procedure increasing the incline of the ramp in 5° increments. The maximum angle of inclination before slipping back down the ramp was 44.60° achieved in a time of 16.50 seconds. The system after completion of this climb is shown below in Figure 235.

Figure 235: Max inclination climb.

The complete set of data accumulated by this test is shown below in Figure 236.

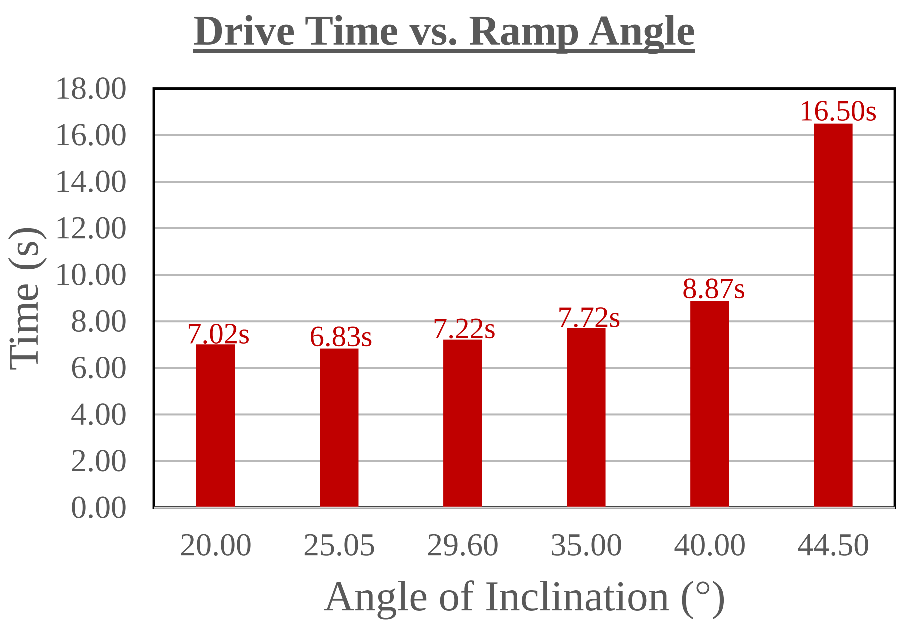


Figure 236: Slope angles and drive times.

8.1.2.5 OAS Accuracy Test

Objective

The objective of this test is to evaluate the range finding accuracy of the VL53L0X lidar sensor of the Obstacle Avoidance System and ensure that the minimum accuracy meets the minimum requirement. The requirement to be verified by this test is OAS-2._Obstacle_Avoidance_System_1OAS2req

Items/Variable to be Tested

- Accuracy of the VL53L0X Time of Flight lidar sensor

Methodology

This test will be a unit/component level test conducted to analyze the sensor's accuracy the low and high end of the documented range of the sensor. The results of this test will determine the range of reliable operation of the lidar sensor to use for the control scheme. The pretest setup, test procedure, post-test operations, and suspension criteria are described below.

Pretest Setup

- Acquire object large enough to be placed in front of the sensor
- Load test script on Feather M0 Bluefruit LE microcontroller
- Place ruler below lidar sensor with zero mark in line with the sensor
- Confirm distance data is being displayed on computer terminal

Test Procedure

____ 1.) Inform all bystanders of testing
____ 2.) Power on electronics
____ 3.) Place object 5 in. away from sensor
____ 4.) Record trial number, location data from lidar, and location data from
____ ruler
____ 5.) Move object away from sensor by 2 in.
____ 6.) Repeat steps 4 and 5 until 5 trials have been completed
____ 7.) Move object 40 in. away from sensor
____ 8.) Record trial number, location data from lidar, and location data from
____ ruler
____ 9.) Move object closer to sensor by 2 in.
10.) Repeat steps 8 and 9 until 10 trials have been completed
11.) Power down electronics

Post-test Operations

- Analyze data to determine accuracy of every trial
- Determine average accuracy over low end of the range
- Determine average accuracy over high end of the range
- Determine average accuracy over the whole range

Suspension Criteria

- Any safety risk not accounted for is encountered
- Lidar does not sense object in front of sensor
- Loss of power to electronics

Success Criteria

The test will be considered successful only if the lidar sensor distance data is within 1 in. of the measured ruler data for all of the 10 data points taken. The test will be considered a failure if any data point displays an accuracy outside of +/- 1 in. even in the case of an average accuracy being below +/- 1 in. In the event of a failed test, a different object will be chosen to evaluate the effect of object color, geometry, and size on the readings.

Safety Considerations

Proper safety precautions will be taken to avoid injury and damage to electronics. Grounding mats will be used to avoid electrostatic discharge when handling electronics. All circuits will be continuity checked for shorts prior to any power being applied to avoid harm to personnel or components.

Results

A series of 5 tests were conducted, each containing 10 trials to obtain enough data to consider the results consistent. The test was successful at the low end of the range (5-13 in.) for multiple objects, but failed at the high end of the range (32-40 in.) for multiple objects. An example of the data collected is shown below in Table 71.

TEST 2					
TRIAL #	RULER DISTANCE (in.)	LIDAR DISTANCE (in.)	DEVIATION (in.)	%ERROR	ACCURACY
Short Range					+/- 0.128 in.
1	5.00	4.96	0.04	0.80%	
2	7.00	7.13	0.13	1.86%	
3	9.00	9.02	0.02	0.22%	
4	11.00	11.18	0.18	1.64%	
5	13.00	13.27	0.27	2.08%	
Long Range					+/- 1.574 in.
6	40.00	41.46	1.46	3.65%	
7	38.00	39.72	1.72	4.53%	
8	36.00	37.56	1.56	4.33%	
9	34.00	35.67	1.67	4.91%	
10	32.00	33.46	1.46	4.56%	

Table 71: OAS-2 Accuracy Test 2.

The accuracy for the low and high end of the range was determined by taking the average of the deviations across all 5 tests. The results of the accuracy calculations are shown below in Table 72.

TOTALS	
Avg. Accuracy (Short Range)	+/- 0.131 in.
Avg. Accuracy Long Range)	+/- 1.415 in.

Table 72: OAS-2 Accuracy Test accuracies.

The results of this test have shown an unacceptable reliability in the data collected at the high end of the range of the VL53L0X sensor, but an accuracy well within the acceptable limit of +/- 1 in. for the low end of the range. Due to these results, the CES controls will only use the data collected from the sensor at ranges shorter than 13 in. to manage obstacle avoidance.

8.1.2.6 CES Orientation Accuracy Test

Objective

The objective of this test is to validate the orientation check as a high reliability risk mitigation for premature deployment. The requirement to be verified by this test is CES-1.CES1req

Items/Variable to be Tested

- Accuracy of the BNO055 9DOF IMUs
- The drift of the BNO055 9DOF IMUs

Methodology

This test will be a unit/component level test conducted to analyze the sensor's accuracy and drift over long duration. The results of this test will be used to set the orientation angles determined to be safe to deploy the rover. The pretest setup, test procedure, post-test operations, and suspension criteria are described below.

Pretest Setup

- Acquire section of 6 in. airframe
- Load test script on Feather M0 Bluefruit LE microcontroller
- Confirm orientation data is being logged on FeatherWing Adalogger's microSD card
- Confirm LEDs are indicating orientation of the sensors properly
- Breadboard 2 BNO055 sensors, 1 microcontroller, and 1 data logger
- Tape breadboard to interior of the 6 in. airframe

Test Procedure

____ 1.) Inform all bystanders of testing
____ 2.) Ensure sensors are flat to the surface
____ 3.) Power up electronics
____ 4.) Log all orientation angles at startup
____ 5.) Roll airframe section one complete revolution while watching changes
____ in LEDs color
____ 6.) Log angles at each color change
____ 7.) Log orientation angles once the full revolution is complete
____ 8.) Repeat steps 5, 6, and 7 until 10 trials have been completed

9.) Power down electronics

Post-test Operations

- Remove breadboard from airframe
- Compare angles set to change the LEDs' color with measured angles when LEDs changed color
- Analyze data to determine sensor accuracy
- Compare angles measured at the end of each full revolution to the angles measured at startup to determine drift of the sensor

Suspension Criteria

- Any safety risk not accounted for is encountered
- Either LED does not change color when breadboard passes set threshold
- Data accuracy exceeds +/- 1°
- Loss of power to electronics

Success Criteria

The test will be considered successful only if the two BNO055s maintain an accuracy of +/- 0.1°, the LEDs change color appropriately after crossing the threshold, and the drift stays within 1° over the testing period of 10 trials. The test will be considered a failure if any of these criteria are not met at which point a solution will be determined to ensure accuracy and reliability.

Safety Considerations

Proper safety precautions will be taken to avoid injury and damage to electronics. Grounding mats will be used to avoid electrostatic discharge when handling electronics. All circuits will be continuity checked for shorts prior to any power being applied to avoid harm to personnel or components.

Results

The BNO055 sensors showed adequate accuracy and drift over the testing period to verify the requirement. The IMUs and indicator LED can be seen below in both a safe-to-deploy and unsafe-to-deploy angle in Figure 237.

Figure 237: Orientation check in safe and unsafe condition.

The data was analyzed to indicate a sensor accuracy of +/- 0.1° and a drift of 0.5°. Both values are below the thresholds required. The sensors were then subjected to random noise during the test to confirm the accuracy and drift in an erratic situation. The plot of the data is show below in FIGURE.

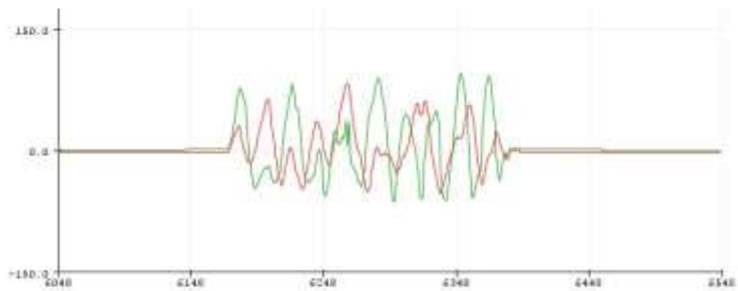


Figure 238: Orientation data with noise.

The data was collected for both the pitch and roll axis and indicated the sensor's accuracy and low drift.

8.1.2.7 CES Autonomous Control Testing Series

Objective

The objective of this testing series is to validate the autonomous controls of each system of the rover and refine the control scheme to achieve mission success. The requirements to be verified by this testing series are the following which are linked to their respective description: 4.5.3, CES-2, CES-3, CES-4, CES-5, CES-6. SOW453CES2CES3CES4CES5CES6SOWreqCES2reqCES3reqCES4reqCES5reqCES6req

Items/Variable to be Tested

- Autonomous control scheme
- Precision of desired operation

Methodology

Each test will be a system level test conducted to validate the autonomous control scheme. The results of these tests will determine changes to the autonomous controls of each system needed before integration of all autonomous controls into one program. The pretest setup, post-test operations, and suspension criteria common among all tests are described below. The test procedure for each test is described individually in detail.

Pretest Setup

- Integrate subsystem or component to be tested with Control Electronics System
- Load flight ready autonomous control for that subsystem or component onto Feather M0 Bluefruit LE microcontroller
- Confirm Bluetooth link in case of override
- Clear testing area of anything not necessary for testing

Test Procedure for SOW Verification (4.5.3)

____ 1.) Inform all bystanders of testing
____ 2.) Integrate Rover into ROCS
____ 3.) Integrate ROCS into payload bay of launch vehicle
____ 4.) Integrate DTS into launch vehicle
____ 5.) Power up electronics
____ 6.) Send deployment signal to rover using DTS
____ 7.) Measure distance traveled of the rover
____ 8.) Note distance at which the rover stops moving
____ 9.) Power down electronics

Test Procedure for RLM Control (CES-2)

____ 1.) Inform all bystanders of testing
____ 2.) Integrate CES into rover
____ 3.) Integrate Rover with RLM
____ 4.) Confirm Bluetooth link with Feather M0 Bluefruit LE
____ 5.) Send lock trigger over Bluetooth using cellphone
____ 6.) Inspect state of the locking mechanism
____ 7.) Send unlock trigger over Bluetooth using cellpnone
____ 8.) Inspect state of the locking mechanism
____ 9.) Repeat steps 5, 6, 7, and 8 until 10 trials have been completed
____ 10.) Power down electronics

Test Procedure for SAS Locking Motor Control (CES-3)

____ 1.) Inform all bystanders of testing
____ 2.) Power on electronics
____ 3.) Confirm Bluetooth link with Feather M0 Bluefruit LE
____ 4.) Send lock trigger over Bluetooth using cellphone
____ 5.) Inspect the state of the SAS Locking Motor
____ 6.) Send unlock trigger over Bluetooth using cellphone

____ 7.) Inspect the state of the SAS Locking Motor
____ 8.) Repeat Steps 4, 5, 6, and 7 until 10 trials have been completed
____ 9.) Power down electronics

Test Procedure for SAS Deployment Motor Control (CES-4)

____ 1.) Inform all bystanders of testing
____ 2.) Power on electronics
____ 3.) Confirm Bluetooth link with Feather M0 Bluefruit LE
____ 4.) Send unfold trigger over Bluetooth using cellphone
____ 5.) Inspect the state of the Solar Panel Support Arms
____ 6.) Send fold trigger over Bluetooth using cellphone
____ 7.) Inspect the state of the Solar Panel Support Arms
____ 8.) Repeat Steps 4, 5, 6, and 7 until 10 trials have been completed
____ 9.) Power down electronics

Test Procedure for OAS Control (CES-5)

____ 1.) Inform all bystanders of testing
____ 2.) Place objects of at least 4 in. tall at random locations in front of the rover
____ 3.) Power up electronics
____ 4.) Confirm Bluetooth link with Feather M0 Bluefruit LE
____ 5.) Place rover in front of field of objects
____ 6.) Send "Begin test" command using cellphone
____ 7.) Note performance as rover drives around objects
____ 8.) After the rover is at least 5 feet from any object, send "Stop test" command using cellphone
____ 9.) Power down electronics
____ 10.) Repeat steps 2 through 9 until 5 trials have been completed

Test Procedure for RDS Control (CES-6)

____ 1.) Inform all bystanders of testing
____ 2.) Mark setpoint locations on the ground
____ 3.) Place rover at start location
____ 4.) Power up electronics
____ 5.) Confirm Bluetooth link with Feather M0 Bluefruit LE
____ 6.) Send "Begin test" command using cellphone
____ 7.) Note the location of the rover at each point the rover attempts to change direction vs the location of the setpoints
____ 8.) Once the rover has reached the end setpoint, send "Stop test" command
____ using cellphone
____ 9.) Power down electronics

10.) Repeat steps 3 through 9 until 5 trials have been completed

Post-test Operations

- Analyze data from test to determine precision of control scheme
- Use data to refine control scheme if necessary
- Store data in secure locations for referencing

Suspension Criteria

- Any safety risk not accounted for is encountered
- Loss of power to electronics
- Error encountered in software leads to test abort

Success Criteria

Each test will be considered successful if the end of the test is reached without any intervention from team members and data collected is consistent with expected performance characteristics. Failure of any test will require a solution to be determined before restarting the test.

Safety Considerations

Proper safety precautions will be taken to avoid injury and damage to electronics. Grounding mats will be used to avoid electrostatic discharge when handling electronics. Pinch points will be identified prior to any work being done. No person will be allowed within 3 feet of rotating parts while they are operating. Tripping hazards will be identified and mitigated. All circuits will be continuity checked for shorts prior to any power being applied to avoid harm to personnel or components.

Results

8.1.2.7.1 SOW 5.4.3

Flight ready software has shown the ability to perform all autonomous tasks of the payload mission. A full run through of the mission has been conducted to analyze the performance of the software. Each phase of the mission performed nominally without any outside intervention confirming autonomy.

8.1.2.7.2 CES-2

Once integrated onto the ROCS and RLM, the rover was pulled vigorously and held in flight orientation to confirm that the RLM was retaining the rover as it does in flight. The RLM is shown locked during the test below in Figure 239.

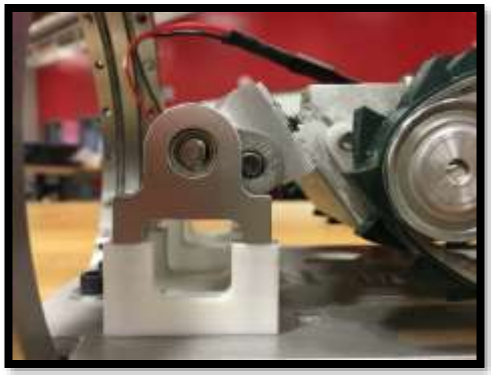


Figure 239: RLM locked.

The magnetic connector was being used to power the RLM during this test. After the final unlock was achieved, the rover was commanded to exit the ROCS. The magnetic connector successfully detached without impeding the motion of the rover.

8.1.2.7.3 CES-3

The SAS locking motor control circuit was wired as it is during flight using the CES PCB. A command was given via Bluetooth to begin a test of the system. The motor was successfully powered and rotated the latch away from the shaft extension of the SAS deployment motor. No outside intervention was required. This results successfully verifies the requirement.

8.1.2.7.4 CES-4

The SAS deployment motor wired to the motor driver of the control stack. A command was given via Bluetooth to begin a test of the system. At the conclusion of the test, all four solar panels were fully exposed. No outside intervention was required. This result successfully verifies the requirement.

8.1.2.7.5 CES-5

This test was conducted with the sensor attached to a breadboard being pushed to simulate the driving of the rover as the rover was in the process of reconstruction after an unsuccessful flight. The board was halted and turned according to data collected and analyzed from the Obstacle Avoidance System. The field of obstacles and path chosen by the system for all 5 trials are shown below in Figure 240.

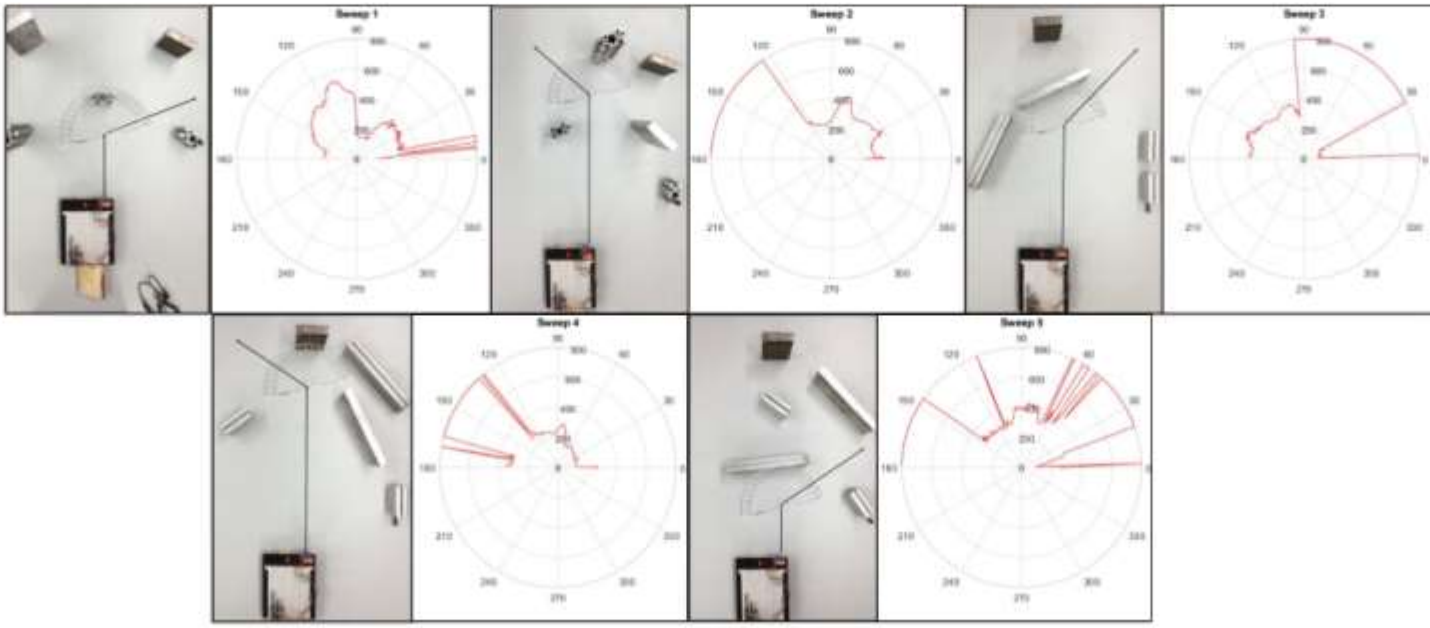


Figure 240: OAS path finding results.

The output of the script used for the detection of obstacles is a degree to turn to the left or right of the rover based on the pathfinding algorithm discussed in section *5.7*. This output angle can then be used by the control electronics to turn the rover the precise number of degrees to the left or right using the gyroscopes as discussed in section *5.10.2.6.* Additionally, Figure 240 shows a tilt in the protractor which compensates for a deviation of true north for the servo during the test due to mounting. To counter this team members rotated the board to match this inaccuracy. This mounting has been corrected for flight. The result of this test successfully verifies the requirement.

8.1.2.7.6 CES-6

A test script was written to perform the operation described by the verification method. A command was given via Bluetooth to initiate the test. The rover successfully performed both right and left turns of 90 degrees using the gyroscopes to indicate the heading, as well as successfully completed all forward and reverse driving to arrive at the end location 5 times consecutively. The course that the rover drove to perform the maneuvers required to verify this test is shown below in Figure 241.

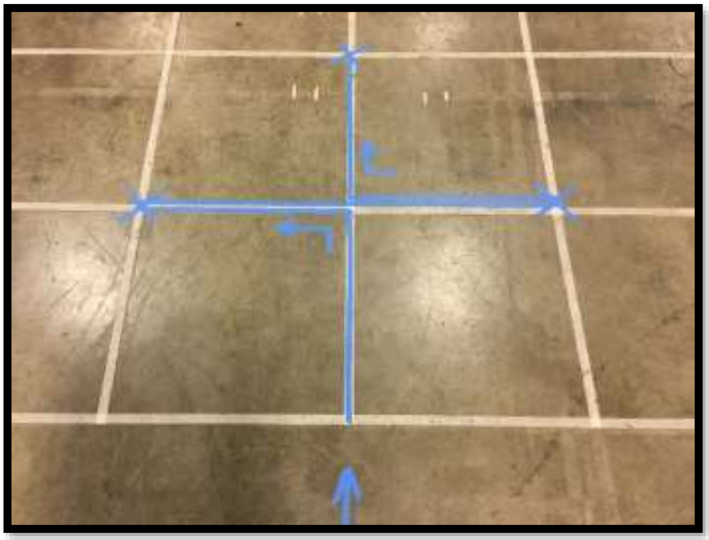


Figure 241: Driving course.

Blue arrows, tape, and Xs mark the driving direction, path, and setpoint markers respectively. The rover successfully reaching the end marker 5 times consecutively verifies this requirement.

8.1.2.8 Battery Life Testing Series

Objective

The objective of this testing series is to ensure that the capacity of the chosen batteries matches the runtime calculated based on current draw from electronics. The requirements to be verified by this testing series are the following which are linked to their respective description: CES-8, CES-9.CES8CES9CES8reqCES9req

Items/Variable to be Tested

- Controller Battery Lifetime
- Motor Batter Lifetime

Methodology

These tests will be unit/component level tests conducted analyze power consumption of the payload electronics. The results of these test will determine if larger or smaller capacity batteries are necessary for the mission. The pretest setup, post-test operations, and suspension criteria common among both tests are described below. The test procedure for each test is described individually in detail.

Pretest Setup

- Integrate all payload electronics with CES
- Load flight ready software on to the Feather M0 Bluefruit LE microcontroller
- Acquire timer

Test Procedure for Controller Battery Lifetime (CES-8)

____ 1.) Inform all bystanders of testing
____ 2.) Take voltage of battery using voltage monitor
____ 3.) Power up electronics and begin timer
____ 4.) Record voltage level on 10 minute increments
____ 5.) After 3 hours of continuous runtime, confirm electronics are still powered
____ 6.) Take voltage of battery using voltage monitor
____ 7.) Power down electronics

Test Procedure for Motor Battery Lifetime (CES-9)

____ 1.) Inform all bystanders of testing
____ 2.) Plug voltage monitor into battery and take initial reading
____ 3.) Power up electronics and start timer
____ 4.) Record voltage level on 15 second increments
____ 5.) After 5 minutes of total motor runtime, confirm motors are still being
____ powered
____ 6.) Power down electronics
7.) Record final voltage level using voltage monitor

Post-test Operations

- Plot data point of each voltage reading vs time at which reading was taken
- Analyze battery life trend

Suspension Criteria

- Any safety risk not accounted for is encountered
- Loss of power to electronics

Success Criteria

The tests will be considered successful only if the battery being tested outlasts the time frame allotted for its runtime. If at the completion of the controller battery test, the voltage has not dropped below 3.7V and is still powering the electronics, the test will be successful. If at the completion of the motor battery test, the voltage has not dropped below 6V and is still powering the motors, the test will be successful. The test will be considered a failure if power loss occurs at which point a larger capacity battery will be obtained and the test restarted.

Safety Considerations

Proper safety precautions will be taken to avoid injury and damage to electronics. Grounding mats will be used to avoid electrostatic discharge when handling electronics. All circuits will be continuity checked for shorts prior to any power being applied to avoid harm to personnel or components.

Results

8.1.2.8.1 CES-8

This test has been postponed due to unsuccessful flight of the launch vehicle and the need to rebuild the payload entirely.

8.1.2.8.2 CES-9

This test has been postponed due to unsuccessful flight of the launch vehicle and the need to rebuild the payload entirely.

8.1.2.9 Flight Loads Testing Series

Objective

The objective of this testing series is to ensure that all load bearing systems of the rover are capable of sustaining high loads experienced during flight of the full-scale launch vehicle. The requirements to be verified by this testing series are the following which are linked to their respective description: ROCS-4, RLM-4, RBS-3, SAS-5.ROCS4RLM4RBS3SAS5ROCS4RLM4RBS3SAS5ROCS4reqRLM4reqRBS3reqSAS5req

Items/Variable to be Tested

- Fidelity of Rover Orientation Correction System assembly under flight loads
- Fidelity of Rover Locking Mechanism assembly under flight loads
- Fidelity of Rover Body System assembly under flight loads
- Fidelity of Solar Array System solar panel support arms under flight loads

Methodology

These tests will be system level tests conducted corroborate analysis that has been done on systems and confirm the load bearing capabilities of these systems under full-scale flight loads. The results of this testing series will determine if any design changes need to be made in the interest of safety. The pretest setup, post-test operations, test procedure and suspension criteria common among all tests are described below.

Pretest Setup

- See payload preflight checklist in launch procedures

Test Procedure

____ 1.) Follow payload launch procedures

Post-test Operations

- Inspect systems for any deformation or damage

Suspension Criteria

- N/A

Success Criteria

The tests will be considered successful only if no deformation or impedance to performance of a system is seen after full-scale flight and recovery of the launch vehicle. A failure of these tests will indicate a safety risk and a necessary change to the design of the system to mitigate the risk.

Safety Considerations

Proper safety precautions will be taken to avoid injury. Adhere to all risk mitigation and safety procedures associated with full-scale flights. All circuits will be continuity checked for shorts prior to any power being applied to avoid harm to personnel or components.

Results

8.1.2.9.1 ROCS-4

This test has been postponed due to unsuccessful flight. The ROCS successfully sustained the loads experienced during the first full-scale flight, however non-nominal flight results in this verification not being considered fully confirmed.

8.1.2.9.2 RLM-4

This test has been postponed due to unsuccessful flight. The RLM successfully sustained the loads and retained the rover inside the airframe of the launch vehicle during the first full-scale flight, however non-nominal flight results in this verification not being considered fully confirmed.

8.1.2.9.3 RBS-3

This test has been postponed due to unsuccessful flight. The RBS successfully sustained the loads experienced during the first full-scale flight, however non-nominal flight results in this verification not being considered fully confirmed.

8.1.2.9.4 SAS-5

Postponed due to unsuccessful flight.

8.1.2.10 Flight Full Performance Testing Series

Objective

The objective of this testing series is to validate the flight performance of the DTS receiver antenna and the data logging capability of the CES. The requirements to be verified by this testing series are the following which are linked to their respective description: DTS-6, CES-7.DTS6CES7DTS6reqCES7req

Items/Variable to be Tested

- Integrity of DTS receiver antenna
- Data logging capacity of the CES

Methodology

These tests will be unit/component level tests conducted verify a robust design has been implemented. The pretest setup, post-test operations, and suspension criteria common among both tests are described below. The test procedure for each test is described individually in detail.

Pretest Setup

- See payload preflight checklist in launch procedures

Test Procedure for DTS Receiver Antenna Fidelity (DTS-6)

____ 1.) Follow payload launch procedures
____ 2.) At landing, send deployment signal to receiver module
____ 3.) Inspect color of LED indicator to determine functionality of receiver antenna

Test Procedure for CES Data logging (CES-7)

____ 1.) Follow payload launch procedures
____ 2.) At landing, deploy rover
____ 3.) After rover has completed its mission, recover all data from CES microSD card

Post-test Operations

- Analyze data gathered to determine success of test

Suspension Criteria

- N/A

Success Criteria

The tests will be considered successful only if the DTS receiver recognizes the deployment signal for DTS-6 and the CES microSD card successfully logged data from the DTS deployment signal, two gyroscopes, OAS lidar sensor, autonomous drive commands, solar power generation levels, and SIS images for CES-7. A failure of DTS-6 will require minor modification to the exterior antenna. Failure of CES-7 will require minor changes to software.

Safety Considerations

Proper safety precautions will be taken to avoid injury. Adhere to all risk mitigation and safety procedures associated with full-scale flights. All circuits will be continuity checked for shorts prior to any power being applied to avoid harm to personnel or components.

Results

8.1.2.10.1 DTS-6

After landing, the deployment transmission signal was able to receive the unique deployment signal from the transmission station. The system then turned the indicator LED green signaling the correct signal was received. Through the flight and landing the antenna maintained its location on the outside of the airframe. All connections between the antenna, receiving module, and receiving microcontroller were maintained throughout the flight and landing. Once the payload bay reached its final location and position, the receiving system was able to receive the unique signal.

8.1.2.10.2 CES-7

This verification has been postponed due to unsuccessful flight of the launch vehicle. Operation to verify this requirement has been ground tested successfully.

8.2 Requirements Verification

8.2.1 Launch Vehicle Requirements

Requirement ID	Requirement Description	Method of Verification	Status
2.1	The vehicle will deliver the payload to an apogee altitude of 5,280 feet above ground level (AGL)	Analysis: The launch vehicle shall be designed to reach an apogee altitude of 5,280 feet AGL. Several OpenRocket simulations as well as hand calculations will be performed to ensure the ideal motor is selected.	Complete: See OpenRocket Flight Simulations section.
2.1.1 TDR	The launch vehicle will reach an apogee of 5,500 feet AGL with an inactive VDS	Analysis: The launch vehicle shall be designed to use lightweight materials and the proper motor to overshoot the target altitude with an inactive VDS.	Complete: See OpenRocket Flight Simulations section.
2.1.1.1 TDR	The launch vehicle's mass will not exceed 50 pounds.	Analysis: The launch vehicle shall be designed to use lightweight materials and the masses of each component shall be recorded during the design phase.	Complete: See OpenRocket Flight Simulations section.
2.1.1.2 TDR	Hand calculations must be performed to verify OpenRocket simulations are accurate	Analysis: Hand calculations shall be performed prior to CDR to ensure the OpenRocket simulations are accurate.	Complete: See OpenRocket Flight Simulations section.
2.1.1.3 TDR	The ascent of the launch vehicle shall be safe and stable.	Analysis: the launch vehicle shall be designed to ascend safely. Safety checklists shall be written to ensure that no assembly steps will be missed.	Complete: See CDR
2.1.1.4 TDR	The launch vehicle's overall coefficient of drag shall not exceed 0.50.	Analysis: CFD simulations shall simulate flight conditions and compute the coefficient of drag of the entire launch vehicle.	Complete: See CDR.
2.2	The vehicle will carry one commercially available, barometric altimeter for recording the official altitude used in determining the altitude award winner. Teams will receive the maximum number of altitude points (5,280) if the official scoring altimeter reads a value of exactly 5280 feet AGL. The team will lose one point for every foot above or below the required altitude	Inspection: A PerfectFlite StratoLogger CF altimeter will be used to record the official apogee altitude for the competition flight.	N/A
2.2.1 TDR	All separation events will have two altimeters for redundancy.	Inspection: Two PerfectFlite StratoLogger CF altimeters will be used to initiate separation evens during recovery. The altimeters will be programmed to be delated relative to each other to prevent over pressurization of the airframe.	Complete: See Avionics section.
2.2.2 TDR	All altimeters will be secured in the launch vehicle via a 3D printed sled.	Analysis: The launch vehicle shall be designed to accept 3D printed sleds for holding each altimeter. All 3D printed sleds will be designed prior to CDR.	Complete: See Avionics section.
2.3	Each altimeter will be armed by a dedicated arming switch that is accessible from the exterior of the rocket airframe when the	Inspection: Each altimeter will be equipped with a Featherweight screw arming switch. These switches shall be accessible from the exterior of the airframe through the barometric vent holes.	Complete: See Avionics section.

	rocket is in the launch configuration on the launch pad		
2.4	Each altimeter will have a dedicated power supply.	Inspection: Each StratoLogger altimeter shall be powered by a dedicated 9-Volt battery.	Complete: See Avionics section.
2.4.1 TDR	All altimeters will be powered by a Duracell 9-Volt battery	Inspection: Each altimeter shall be powered by a Duracell brand 9-Volt battery. Due to their internally welded contact points, Duracell brand batteries are well suited for the high accelerations experienced during flight.	Complete: See Avionics section.
2.4.1.1 TDR	All batteries will be brand new and the voltage will be measured to be greater than 9.3 volts.	Test: each battery will be new and measured with a digital multi-meter to assure that the voltage is greater than 9.3 volts.	Complete: See Avionics section.
2.4.2 TDR	All batteries will be secured onto their 3D printed sled.	Inspection: Each battery will be secured to its 3D printed sled using a cover secured to the sled via four screws.	Complete: See Avionics section.
2.5	Each arming switch will be capable of being locked in the ON position for launch (i.e. cannot be disarmed due to flight forces).	Demonstration: Each Featherweight screw switch will be tightly secured to the sled and will be tested in full-scale test launches to eliminate the possibility of disarmament due to flight forces.	Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.
2.6	The launch vehicle will be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications.	Analysis: The launch vehicle shall be designed to be fully recoverable and reusable. Several test launches will be conducted before competition to verify recoverability and reusability of the launch vehicle.	Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.
2.6.1 TDR	The launch vehicle will utilize the Removable Fin System (RFS).	Analysis: The launch vehicle will be designed to accommodate the RFS and to remove and install fins from the launch vehicle.	Complete: See Removable Fin System section.
2.6.1.1 TDR	There will be two extra fins available for use on launch day if any fins are broken during transportation or launch of the launch vehicle.	Inspection: The team will prepare a minimum of two extra fins before launches and account for the added expense in the team budget. This will be in conjunction with requirement 2.6.1.	Completed February 2018.
2.7	The launch vehicle will have a maximum of four (4) independent sections. An independent section is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute.	Demonstration: The launch vehicle will be comprised of four independent sections: the nose cone, the Payload section, the lone coupler, and the Booster section.	Complete: See Launch Vehicle Overview section.
2.8	The launch vehicle will be limited to a single stage.	Analysis: The fuss-scale launch vehicle will be designed to achieve all necessary altitude requirements on a single stage.	Complete: See Launch Vehicle Overview section.
2.9	The launch vehicle will be capable of being prepared for flight at the launch site within 3 hours of the time the Federal Aviation Administration flight waiver opens.	Demonstration: Assembly of the launch vehicle shall take less than 3 hours. A comprehensive checklist will be prepared by the team to assist in accurate and expedited vehicle assembly while preparing for flight.	Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.
2.9.1 TDR	The launch vehicle will be capable of being assembled in two hours independent of the payload.	Demonstration: The launch vehicle shall be designed to be assembled in less than two hours. A comprehensive checklist will be prepared by the team to assist in	Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.

		accurate and expedited vehicle assembly while preparing for flight. The team shall practice assembling the launch vehicle prior to competition to ensure Requirement 2.9.1 is met. This will be in accordance with Requirement 2.9.	
2.9.2 TDR	The payload subsystem will be capable of being assembled independent of the launch vehicle.	Analysis: The launch vehicle shall be designed so that the rover payload can be assembled separate of the launch vehicle.	Completed on 3/3/18.
2.9.2.1 TDR	The payload subsystem will be capable of being integrated into the launch vehicle within 30 minutes.	Demonstration: The launch vehicle shall be designed so that the rover payload can be integrated into the launch vehicle within 30 minutes. The team shall practice integrating the payload into the launch vehicle to verify Requirement 2.9.2.1 is met.	Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.
2.9.3 TDR	The launch vehicle will utilize witness triangles.	Inspection: The launch vehicle shall utilize witness triangles on each coupler.	Complete: See Airframe section.
2.9.4 TDR	The motor will be packed at least 24 hours prior to launch.	Demonstration: A minimum of 24 hours prior to launch, the launch vehicle's motor shall be packed.	Completed on 2/16/18
2.10	The launch vehicle will be able to remain in launch-ready configuration at the pad for a minimum of 1 hour without losing the functionality of any critical on-board components.	Demonstration: The power supplies for the VDS and recovery electronics shall demonstrate the capability to exceed Requirement 2.10.	Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.
2.10.1 TDR	All electronics onboard the launch vehicle will be capable of remaining in launch-ready configuration at the pad for a minimum of 1.5 hours without losing functionality of any on-board components.	Demonstration: The power supplies for the VDS and recovery electronics shall demonstrate the capability to exceed Requirement 2.10.	Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.
2.10.2 TDR	All electronics onboard the launch vehicle will be capable of remaining in launch-ready configuration at temperatures of 120 ° F.	Analysis: The components chosen for the systems shall be considered for their ability to withstand high temperatures while still retaining functionality.	Complete: See CDR
2.11	The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system. The firing system will be provided by the NASA-designated Range Services Provider.	Inspection: The chosen motor shall allow for the use of the standard 12-volt direct current firing system provided by the NASA-designated Range Services Provider.	Complete: See CDR
2.11.1 TDR	The launch vehicle will be capable of being launched using a firing system that complies with the NAR high Power Rocket Safety Code requirement 4.	Inspection: The launch vehicle shall be designed to be launched by a firing system complying to NAR high Power Rocket Safety Code requirement 4. This is in accordance to Requirement 2.11.	Complete: See CDR
2.12	The launch vehicle will require no external circuitry or special ground support equipment to initiate launch (other than what is provided by Range Services).	Analysis: The launch vehicle shall be designed for launch to be initiated only by an external source and shall not require any external support equipment. This is in accordance to requirement 2.11.	Complete: See CDR

2.12.1 TDR	The Variable Drag System (VDS) will require no external circuitry.	Analysis: The Variable Drag System (VDS) shall be designed to not require any external circuitry and shall be a self-contained system.	Complete: See Variable Drag System (VDS) section.
2.12.2 TDR	The payload subsystem will require no external circuitry.	Analysis: The payload subsystem shall be designed to not require any external circuitry and shall be a self-contained system.	Complete: See CDR
2.13	The launch vehicle will use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and the Canadian Association of Rocketry (CAR).	Demonstration: The team will use an AeroTech L2200-G motor for its full-scale launch vehicle.	Complete: See CDR
2.13.1	Final motor choices must be made by the Critical Design Review (CDR).	Analysis: The full-scale launch vehicle will utilize an AeroTech L2200-G motor for the competition launch.	Completed in January 2018
2.13.2	Any motor changes after CDR must be approved by the NASA Range Safety Officer (RSO), and will only be approved if the change is for the sole purpose of increasing the safety margin.	Demonstration: The current design for the launch vehicle utilizes an AeroTech L2200-G motor for the competition launch. If a safety issue arises, authorization for a motor change will be requested from the NASA RSO.	Completed in January 2018
2.14	Pressure vessels on the vehicle will be approved by the RSO and will meet the following criteria:	Demonstration: The launch vehicle has been designed to not require the use of any pressure vessels. If the design changes due to such a system, NASA and the RSO will be notified, and the criteria mentioned in the Statement of Work will be met.	Completed in October 2017
2.14.1	The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) will be 4:1 with supporting design documentation included in all milestone reviews.	Demonstration: The launch vehicle has been designed to not require the use of any pressure vessels. If the design changes due to such a system, NASA and the RSO will be notified, and the criteria mentioned in the Statement of Work will be met.	Completed in October 2017
2.14.2	Each pressure vessel will include a pressure relief valve that sees the full pressure of the valve that is capable of withstanding the maximum pressure and flow rate of the tank	Demonstration: The launch vehicle has been designed to not require the use of any pressure vessels. If the design changes due to such a system, NASA and the RSO will be notified, and the criteria mentioned in the Statement of Work will be met.	Completed in October 2017
2.14.3	Full pedigree of the tank will be described, including the application for which the tank was designed, and the history of the tank, including the number of pressure cycles put on the tank, by whom, and when.	Demonstration: The launch vehicle has been designed to not require the use of any pressure vessels. If the design changes due to such a system, NASA and the RSO will be notified, and the criteria mentioned in the Statement of Work will be met.	Completed in October 2017
2.15	The total impulse provided by a College and/or University launch vehicle will not exceed 5,120 Newton-seconds (L class).	Demonstration: The total impulse of the AeroTech L2200-G is 5,104 Newton-seconds.	Complete
2.16	The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail	Analysis: the launch vehicle shall be designed to have a stability of 2.0 at the point of rail exit. OpenRocket simulations shall be used to design the launch vehicle	Complete: See Simulation Results section.

	exit. Rail exit is defined at the point where the forward rail button loses contact with the rail.	to the stability margin required and hand calculations shall be used to verify the stability.	
2.16.1 TDR	The launch vehicle will have a stability margin at rail exit of 2.2.	Analysis: The launch vehicle shall be designed to have a stability margin of 2.2 upon rail exit.	Complete: See Simulation Results section.
2.17	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.	Analysis: The launch vehicle shall be designed to have a minimum velocity of 52 fps at the point of rail exit. OpenRocket simulations shall be used to select a motor to meet the requirements and hand calculations shall be used to verify.	Complete: See Flight Characteristics section.
2.17.1 TDR	The launch vehicle will have an exit rail velocity greater than 75 fps.	Analysis: the launch vehicle shall be designed to have an exit velocity of 75 fps at rail exit. OpenRocket simulations shall be used to select a motor to meet the requirement and hand calculations shall be used to verify.	Complete: See Flight Characteristics section.
2.18	All teams will successfully launch and recover a subscale model of their rocket prior to CDR. Subscales are not required to be high power rockets.	Test: The team shall design, build, and test a subscale model of the rocket prior to CDR.	Complete: See Subscale Vehicle November 11th Test Flight section.
2.18.1	The subscale model should resemble and perform as similarly as possible to the full-scale model, however, the full-scale will not be used as the subscale model.	Analysis: The subscale model of the rocket shall be designed to closely follow the design of the full-scale model to ensure similar performance and flight characteristics.	Complete: See Subscale Vehicle December 2nd Test Flight section.
2.18.1.1 TDR	The subscale model will be a half-scale replica to the full-scale launch vehicle.	Analysis: The subscale model shall be built as a 1:2 scale in order to test recovery design decisions and to identify potential design obstacles.	Complete: See Subscale Vehicle November 11th Test Flight section.
2.18.2	The subscale model will carry an altimeter capable of reporting the model's apogee altitude.	Inspection: StratoLogger CF altimeters shall be mounted in the subscale model in order to report the model's apogee altitude.	Complete: See Subscale Vehicle November 11th Test Flight section.
2.18.2.1 TDR	The subscale model will carry two StratoLogger altimeters powered by 9-volt Duracell batteries.	Inspection: The subscale model shall carry two StratoLogger altimeters powered independently by new 9-volt Duracell batteries for redundancy.	Complete: See Subscale Vehicle November 11th Test Flight section.
2.19	All teams will successfully launch and recover their full-scale rocket prior to FRR in its final flight configuration. The rocket flown at FRR must be the same rocket to be flown on launch day. The purpose of the full-scale demonstration flight is to demonstrate the launch vehicle's stability, structural integrity, recovery systems, and the team's ability to prepare the launch vehicle for flight. A successful flight is defined as a launch in which all hardware is functioning properly (i.e. drogue chute at apogee, main chute at a lower altitude, functioning tracking devices, etc.). The following criteria must be met during the full-scale demonstration flight.	Test: The team will conduct a test launch prior to FRR to verify the success of all launch vehicle systems.	Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.

<table>
<tr><td>2.19.1</td><td>The vehicle and recovery system will have functioned as designed.</td><td></td><td>Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.</td></tr>
<tr><td>2.19.2</td><td>The payload does not have to be flown during the full-scale test flight. The following requirements still apply:</td><td>N/A</td><td>N/A</td></tr>
<tr><td>2.19.2.1</td><td>If the payload is not flown, mass simulators will be used to simulate the payload mass.</td><td></td><td>Complete: 2/17/18. See Launch Day Conditions
The first full-scale test flight was conducted in Talladega, Alabama. Simulations of the flight trajectory for the full-scale vehicle were created using the meteorological data gathered before the launch. The launch day conditions on February 17th were gathered by an AcuRite 01604 weather station that collected windspeed, temperature, air pressure, and air density. The launch day conditions of the March 3rd launch were recorded by a La Crosse Technology EA-3010U Anemometer. This data is presented in Error! Reference source not found..
<table>
<tr><th>Property</th><th>February 17th in Talladega, Al</th><th>March 3rd in Elsburry, Mo</th></tr>
<tr><td>Average Wind Speed (mph)</td><td>10</td><td>13</td></tr>
<tr><td>Wind Speed at Launch (mph)</td><td>9</td><td>9</td></tr>
<tr><td>Wind Direction</td><td>North East</td><td>South East</td></tr>
<tr><td>Temperature (F°)</td><td>72</td><td>60</td></tr>
<tr><td>Pressure at Ground Level (inHg)</td><td>29.9</td><td>30.2</td></tr>
</table>
Table 37: Launch day conditions for the full-scale launch vehicle.

February 17th Flight section.</td></tr>
<tr><td>2.19.2.1.1</td><td>The mass simulators will be located in the same approximate location on the rocket as the missing payload mass.</td><td></td><td>Complete: 2/17/18. See Launch Day Conditions
The first full-scale test flight was conducted in Talladega, Alabama. Simulations of the flight trajectory for the full-scale vehicle were created using the meteorological data gathered before the launch. The launch day conditions on February 17th were gathered by an AcuRite 01604 weather station that collected windspeed, temperature, air pressure, and air density. The launch day conditions of the March 3rd launch were recorded by a La Crosse Technology EA-3010U Anemometer. This data is presented in Error! Reference source not found..
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</table>
Table 37: Launch day conditions for the full-scale launch vehicle.

February 17th Flight section.</td></tr>
<tr><td>2.19.3</td><td>If the payload changes the external surfaces of the rocket (such as with camera housings or external probes) or manages the total energy of the vehicle, those systems will be active during the full-scale test flight.</td><td></td><td>Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.</td></tr>
</table>

2.19.4	The full-scale motor does not have to be flown during the full-scale test flight. However, it is recommended that the full-scale motor be used to demonstrate full flight readiness and altitude verification. If the full-scale motor is not flown during the full-scale flight, it is desired that the motor simulates, as closely as possible, the predicted maximum velocity and maximum acceleration of the launch day flight.		Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.
2.19.5	The vehicle must be flown in its fully ballasted configuration during the full-scale test flight. Fully ballasted refers to the same amount of ballast that will be flown during the launch day flight. Additional ballast may not be added without a re-flight of the full-scale launch vehicle.		Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.
2.19.6	After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components will not be modified without the concurrence of the NASA Range Safety Officer (RSO).	Inspection: The full-scale launch vehicle will not be modified after the first successful test flight without the authorization of the NASA RSO.	Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.
2.19.7	Full-scale flights must be completed by the start of FRRs (March 6th, 2018). If the Student Launch office determines that a re-flight is necessary, then an extension to March 28th, 2018 will be granted. This extension is only valid for re-flights; not first-time flights.	Demonstration: The full-scale integration launch will be completed prior to March 6, 2018, or by March 28, 2018 if an extension is granted.	Incomplete: Extension approved. Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.
2.19.8 TDR	The launch vehicle will undergo at least four full-scale test flights prior to competition.	Test: Several full-scale launches will be conducted to identify potential problems and to verify repeatability of successful launch vehicle systems.	Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.
2.20	Any structural protuberance on the rocket will be located aft of the burnout center of gravity.	Demonstration: The VDS will be placed as far aft on the vehicle as possible so that the drag blades will be located aft of the burnout center of gravity.	Incomplete: Retest 3/17/18. The launch verifying this requirement must be completed by 3/27/18.
2.21	The following constraints shall be placed on the launch vehicle:	N/A	N/A
2.21.1	The launch vehicle will not utilize forward canards.	Demonstration: The design of the full-scale launch vehicle shall not implement forward canards.	Complete: See Launch Vehicle Overview section.
2.21.2	The launch vehicle will not utilize forward firing motors.	Demonstration: The design of the full-scale launch vehicle will not incorporate forward firing motors.	Complete: See Launch Vehicle Overview section.
2.21.3	The launch vehicle will not utilize motors that expel titanium sponges (Sparky, Skidmark, MetalStorm, etc.)	Demonstration: The launch vehicle will utilize an AeroTech L2200-G motor, which does not expel titanium sponges.	Completed in October 2017.
2.21.4	The launch vehicle will not utilize hybrid motors.	Demonstration: The launch vehicle will utilize an AeroTech L2200-G motor, which is not a hybrid motor.	Completed in October 2017.

2.21.5	The launch vehicle will not utilize a cluster of motors	Demonstration: The launch vehicle will utilize a single AeroTech L2200-G motor.	Completed in October 2017.
2.21.6	The launch vehicle will not utilize friction fitting for motors.	Demonstration: The launch vehicle will utilize a thrust ring to transmit the thrust to the motor mount.	Completed: See Motor Retainer section.
2.21.7	The launch vehicle will not exceed Mach 1 at any point during flight.	Analysis: OpenRocket simulations of the full-scale launch vehicle will be conducted to verify that the maximum velocity is less than Mach 1.	Complete: See OpenRocket Flight Simulations section.
2.21.8	Vehicle ballast will not exceed 10% of the total weight of the rocket.	Demonstration: The full-scale launch vehicle will not utilize a ballast system.	Complete: See Launch Vehicle Overview section.
2.22 TDR	All structural components of the launch vehicle will undergo Finite Element Analysis to ensure an efficient and structurally sound design.	Analysis: During the design phase of the launch vehicle, each structural component will undergo Finite Element Analysis.	Complete: See CDR
2.24 TDR	Prior to each launch, the launch vehicle shall be fully assembled and undergo black powder separation testing.	Test: The launch vehicle shall undergo separation testing with the calculated amount of black powder needed to separate each section.	Complete: See Subscale Vehicle Separation Test section.

8.2.2 NASA Requirements Verification

Req. ID	Requirement	Verification Method	Status
4.1	Each team will choose one design option from the following list.	Deployable rover has been chosen from the provided list.	Complete
4.2	Additional experiments (limit of 1) are allowed, and may be flown, but will not contribute to scoring.	No additional experiments will be flown.	Complete
4.3	If the team chooses to fly additional experiments, they will provide the appropriate documentation in all design reports, so experiments may be reviewed for flight safety.	N/A	N/A
4.5.1	Teams will design a custom rover that will deploy from the internal structure of the launch vehicle.	Inspection The team will design a custom rover vehicle capable of deploying from the internal structure of the launch vehicle and all necessary subsystems to accomplish this task using the computer aided design (CAD) software SolidWorks.	Complete
4.5.2	At landing, the team will remotely activate a trigger to deploy the rover from the rocket.	Demonstration The rover and the rest of the payload will be integrated into the launch vehicle in full flight configuration. An external transmitter module will be held by a team member. The launch vehicle will be placed on the ground simulating landing. The team member will trigger the deployment signal to be sent to the payload. After the rover is seen to begin deployment only after the deployment signal has been sent, verification will be complete and considered successful.	Tested independently of flight successfully. Incomplete due to unsuccessful flight.
4.5.3	After deployment, the rover will autonomously move at least 5 ft. (in any direction) from the launch vehicle.	Test The rover and the rest of the payload will be integrated into the launch vehicle in full flight configuration. The rover's control system will be running flight ready software. The deployment signal will be sent to the payload by a team member using the transmitter module. Upon receiving the deployment signal, the rover will exit the launch vehicle and continue driving at least 5 ft. with no external intervention. After reaching at least 5 ft., verification will be complete and considered successful. See Rover Performance Test plan.SOWrefRoverPerformanceTest	Tested independently of flight successfully. Incomplete due to unsuccessful flight.

4.5.4	Once the rover has reached its final destination, it will deploy a set of foldable solar cell panels.	Demonstration The rover has been designed with an onboard actuating foldable solar array. The rover will be fully constructed, assembled and configured running software representative of the rover having begun to exit the launch vehicle. The rover will drive at least 5 ft. at which point it will stop and deploy a set of foldable solar cell panels with no external intervention. After visual confirmation of an increase in surface area of exposed solar cells, verification will be complete and considered successful.	Complete

8.2.3 Payload Team Requirements and Verification

Subsystem	**Requirement**	**Verification Method**	**Status**
Payload ROCS-1	The ROCS assembly shall maintain a factor of safety of two at minimum.	Analysis SolidWorks will be used to generated CAD models of each subassembly of the ROCS. Analysis will be performed using SolidWorks FEA tools on each subassembly and the system as a whole under high load conditions representative of those expected during flight. The maximum loads allowable before yielding will then be determined and compared to the results of the analysis done at the expected flight loads to determine factors of safety. After analysis confirms a minimum factor of safety of two for the ROCS assembly and each subassembly, the verification will be complete and considered successful.	Complete See CDR section 5.1.5
Payload ROCS-2	The entire ROCS assembly shall be capable of being integrated and removed from the airframe within five minutes.	Demonstration The ROCS will be manufactured and fully assembled. The payload bay of the launch vehicle will be placed on a table next to the ROCS. A team member will attempt to integrate the ROCS into the payload bay and subsequently remove it. A stopwatch will be started at the moment that the team member touches the ROCS and stopped at the moment that the ROCS is fully removed and the team member need not touch it anymore. If at any point, a design issue is encountered, the trial will be halted and the issue will be assessed at that time. After three consecutive successful trials, the verification will be complete and considered successful.	Complete

Payload ROCS-3	After being rolled, The ROCS shall come to rest in such a way that the bridging sled is nearest to the ground and the rover is oriented within 50° of perfectly upright.	<u>Test</u> The ROCS will be manufactured and fully assembled. The rover will be fully assembled and integrated onto the ROCS bridging sled as intended for its flight configuration. The full assembly will be integrated into the payload bay of the launch vehicle. Two BNO055 gyroscopes will be collecting and logging gyroscopic data onboard the rover. The Feather M0 Bluefruit LE microcontroller and FeatherWing Adalogger will be used to analyze and collect the sensor data. Two RGB LEDs will indicate the status of each gyroscopes readings. If the orientation is within 50° of upright, the LED will be turned green and if the orientation is greater than 50° the LED will be turned red. The payload bay will be placed on an inclined surface and released. After coming to rest, the color of the two LEDs will be noted and the data stored on the Adalogger will be graphed and analyzed. A trial will be considered successful if both LEDs show green after the payload bay has come to rest. After 10 consecutive successful trials, the verification will be complete and considered successful. See ROCS Roll Test.	Incomplete – Postponed due to unsuccessful flight
Payload ROCS-4	The ROCS shall sustain high loads experienced during liftoff, opening of the payload bay main parachute, and landing.	<u>Test</u> The ROCS will be manufactured and fully assembled. The systems will be integrated into the launch vehicle prior to a full-scale test launch. After landing of the payload bay, the ROCS will be removed and thoroughly inspected. After no significant deformation or damage is seen on the ROCS or payload bay, the verification will be complete and considered successful. See Flight Loads Testing Series.	Incomplete – Postponed due to unsuccessful flight
Payload RLM-1	The RLM shall maintain a factor of safety of two at minimum.	<u>Analysis</u> SolidWorks will be used to generated CAD models of each subassembly of the RLM. Analysis will be performed using SolidWorks FEA tools on each subassembly and the system as a whole under high load conditions representative of those expected during flight. The maximum loads allowable before yielding will then be determined and compared to the results of the analysis done at the expected flight loads to determine factors of safety. After analysis confirms a minimum factor of safety of two for the RLM assembly and each subassembly, the verification will be complete and considered successful.	Complete See CDR section 5.1.10

Payload RLM-2	The RLM shall keep the rover fixed to the ROCS and immobile relative to the bridging sled regardless of orientation.	Demonstration The ROCS, RLM, and RBS will be manufactured and fully assembled. The RBS will be integrated into the ROCS via the RLM and the system will be placed in the locked configuration. The entire assembly will then be oriented in all possible ways. If any movement of the RBS is seen, the trial will be halted and note will be made of the movement, the location of the slack that allowed movement, and the orientation of the assembly when the movement was seen. A minimum of three people will observe each demonstration. After five consecutive trials in which no movement was detected, the verification will be complete and considered successful.	Complete
Payload RLM-3	The RLM motor shall fully release the rover after the deployment signal has been sent allowing the rover to move under its own power.	Demonstration The RLM and RBS will be manufactured and fully assembled. The rover will be integrated into the RLM and shown to be locked in place. The RLM motor will be powered using 11.1V such that the motor releases the locking mechanism. If the mechanism does not immediately unlock the rover, the demonstration will be halted and a cause will be determined and attended to. After five consecutive successful releases, the verification will be complete and considered successful.	Complete
Payload RLM-4	The RLM shall retain the rover inside the airframe of the launch vehicle throughout the duration of the flight and recovery.	Test The payload will be manufactured and fully assembled. The payload will then be integrated into the payload bay of the launch vehicle prior to a full-scale test launch. Cameras will be mounted inside of the payload bay. After landing, the payload and footage from the payload bay cameras will be inspected. After confirming that the rover has been retained inside the launch vehicle at all stages of flight, the verification will be complete and considered successful. See Flight Loads Testing Series.	Incomplete – Postponed due to unsuccessful flight
Payload DTS-1	The DTS transmitter and receiver modules shall transmit at a frequency and power level allowable without a license.	Demonstration Two HC-12 Wireless Serial Modules will be obtained and configured for communication at 433.4 MHz and transmission power less than 100 mW. Each module will be connected to a Feather M0 Bluefuit LE microcontroller running software intended to test the communication between he wireless modules. After successful communication is achieved at the specified frequency and power level, the verification will be complete and considered successful.	Complete See CDR section 5.1.14
Payload DTS-2	The DTS slip ring flange shall allow the communication and power wires to pass through the upper payload bay recovery bulkplate without tangling during any rotation of the rover on the ROCS.	Demonstration The DTS will be configured to maintain communication and the received data will be viewed in real-time on a computer terminal window. The communication and power wires from the microcontroller to the receiver module will be connected through the slip ring flange. The receiver microcontroller will be rotated clockwise and counter-clockwise 10 times each. If at any point, communication or power is lost, the trial will be halted and a solution will be determined. After 10 consecutive successful trials, the verification will be complete and considered successful.	Complete
Payload DTS-3	The DTS power and communication lines from the CES will detach by means of the rover driving forward.	Demonstration The RDS and RBS will be manufactured and fully assembled. The Feather M0 Bluefruit LE microcontroller and FeatherWing Motor Shield will be used to control the two main drive motors of the RDS via Bluetooth from a team member's cellphone. This is to represent as accurately as possible the situation of autonomous mission performance	Complete

		while still maintaining full control of the rover. The power and communication wires for the DTS will be connected using breadboard jumper wires. The rover will be driven forward while the receiver module is held in place. At full extension, the wires will disconnect without hindering the forward motion of the rover. After five consecutive disconnect trials, the verification will be complete and considered successful.	
Payload DTS-4	The DTS receiver and transmitter modules shall maintain communication within a distance of 50 linear feet of each other.	Test The DTS will be configured to maintain communication and the received data will be viewed in real-time on a computer terminal window. The receiver module will be connected to a flexible antenna wrapped around the exterior of a section of 6 in. carbon fiber airframe representative of the payload bay. The carbon fiber section will be placed on the ground 50 linear feet from the transmitter module. A team member will carry the transmitter along two perpendicular diameters of a 50 foot radius circle centered on the receiver. After five trials with no downlink in communication, the verification will be complete and considered successful. See DTS 50 Foot Radius Test plan.DTS4refDTSRadiusTest	Complete
Payload DTS-5	The DTS receiver module shall receive the unique deployment signal data packet and relay the information to the CES.	Demonstration An HC-12 Wireless Serial Module will act as the receiver and be connected to a Feather M0 Bluefuit LE microcontroller. A second HC-12 will act as the transmitter and be connected to a second Feather M0 and a yagi antenna designed to operate at 433.4 Mhz transmission frequency. A single RGB LED will be connected to the receiver side Feather M0. Software on the transmitter side will be configured to send multiple different data streams representing outside signals not sent to deploy the rover as well as a unique packet sent to deploy the rover. Software for the receiver side will be configured to look for the unique packet of data. When this packet is received, the LED will be turned green. Otherwise, the LED will be turned red. After five consecutive trials of successful reception and recognition of the unique packet and rejection of all other signals, verification will be complete and considered successful.	Complete
Payload DTS-6	The DTS receiver antenna shall remain functional after flight and landing of the launch vehicle.	Test The DTS will be assembled in full flight configuration and flight ready software will be loaded onto the transmitter and receiver microcontrollers. The DTS will be integrated into the launch vehicle prior to a full-scale test launch. After landing, a team member will walk to within 50 feet of the payload bay and transmit a packet of data to the receiver module. Upon receiving the packet of data, the receiver module microcontroller will turn an RGB LED green indicating reception of the data. After successful acquisition of the signal, the verification will be complete and considered successful. See Full Flight Performance Testing Series.DTS6refFullFlightPerformaceTesting	Complete
Payload RBS-1	The RBS shall maintain a minimum ground clearance of 0.125 in. while driving.	Inspection The RBS and RDS will be manufactured and assembled. The Feather M0 Bluefruit LE microcontroller and FeatherWing Motor Shield will be used to control the two main drive motors of the RDS via Bluetooth from a team member's cellphone. This is to represent as accurately as possible the situation of autonomous mission performance while still maintaining full control of the rover. An object of 0.125 in. in height will be placed in front of the lowest point of the rover, the male T-Slot. The rover will be driven over the object. After clearing the object without touching the rover, the verification will be complete and considered successful.	Complete
Payload RBS-2	The RBS shall house all rover electronics and mechanical systems in a secure and easily accessible manner.	Inspection The RBS will be manufactured and fully assembled with all electronics and rover systems mounted in flight configuration. All parts will be inspected and shown to be accessible without the need to remove or alter in any way, any other component in the RBS. The RBS will then be turned upside-down to ensure that all components are secure. After accessibility and secure mounting are confirmed, the verification will be complete and considered successful.	Complete

Payload RBS-3	The RBS shall sustain high loads experienced during liftoff, opening of the payload bay main parachute, and landing.	Test The RBS, RLM, and ROCS will be manufactured and fully assembled. The systems will be integrated into the launch vehicle prior to a full-scale test launch. After landing of the payload bay, the payload systems will be removed and the RBS will be thoroughly inspected. After no significant deformation or damage is seen on the RBS, the verification will be complete and considered successful. See Flight Loads Testing Series._RBS-3_RBS-3RBS3refFlightLoadsTesting	Incomplete – Postponed due to unsuccessful flight.
Payload RDS-1	The RDS main drive motors shall provide a torque capable of advancing the rover in all directions.	Demonstration The RBS and RDS will be manufactured and assembled using two Actobotics 52 RPM Planetary Gear Motors as the main drive motors. The Feather M0 Bluefruit LE microcontroller and FeatherWing Motor Shield will be used to control the two main drive motors of the RDS via Bluetooth from a team member's cellphone. This is to represent as accurately as possible the situation of autonomous mission performance while still maintaining full control of the rover. Weight will be added to the rover to simulate the full flight configuration weight of the rover. The rover will be driven forward, backward, left, and right. After demonstrating the ability of the drive motors to advance the rover in all directions, the verification will be complete and considered successful.	Complete
Payload RDS-2	The RDS shall allow the rover to surmount a vertical step of minimum height 1 in.	Demonstration The RBS and RDS will be manufactured and assembled. The Feather M0 Bluefruit LE microcontroller and FeatherWing Motor Shield will be used to control the two main drive motors of the RDS via Bluetooth from a team member's cellphone. This is to represent as accurately as possible the situation of autonomous mission performance while still maintaining full control of the rover. An object with a vertical step height of 1 in. will be placed in front of the rover. The rover will be driven over the object. After five consecutive trials of clearing the obstacle, the verification will be complete and considered successful.	Complete
Payload RDS-3	The RDS shall allow the rover to continue forward motion on a sloped terrain of a minimum incline of 20°.	Test The RBS and RDS will be manufactured and assembled. The Feather M0 Bluefruit LE microcontroller and FeatherWing Motor Shield will be used to control the two main drive motors of the RDS via Bluetooth from a team member's cellphone. This is to represent as accurately as possible the situation of autonomous mission performance while still maintaining full control of the rover. The rover will be placed on an adjustable incline ramp set at 20°. The rover will be driven one foot up the incline. After five consecutive trials in which the rover reaches the one foot mark driving up the incline, the verification will be complete and considered successful. The incline will then be incremented and the test repeated to determine the maximum incline possible. See RDS Sloped Driving Test plan.RDS3refRDSSlopedDriveTest	Complete

Payload RDS-4	The RDS drive belts shall maintain traction without misalignment on wet and dry concrete, grass, gravel, loose dirt, compact dirt, and sand.	Demonstration The RBS and RDS will be manufactured and assembled. The Feather M0 Bluefruit LE microcontroller and FeatherWing Motor Shield will be used to control the two main drive motors of the RDS via Bluetooth from a team member's cellphone. This is to represent as accurately as possible the situation of autonomous mission performance while still maintaining full control of the rover. The rover will be placed on dry and wet concrete, grass, gravel, loose dirt, compact dirt, and sand and driven forward, backward, left, and right for two minutes on each. If at any point, the treads loose traction or become misaligned, the demonstration will be halted and a solution determined. After performance has been confirmed on all terrains, the verification will be complete and considered successful.	Complete
Payload OAS-1	The OAS lidar sensor shall detect an object directly in front of the sensor within a distance range of 5 to 45 in.	Demonstration The VL53L0X Time of Flight lidar sensor will be connected to the Feather M0 Bluefuit LE microcontroller. The sensor will be configured to relay the distance of any object in front it to the serial monitor of the Arduino IDE. An object will be placed in front of the sensor 5 in. away from the sensor. The object will be moved within the sensors line-of-sight to 45 in. away from the sensor. If at any time, the sensor fails to recognize the object, the trial will be halted. After five consecutive trials of no loss of recognition of the object within the range, the verification will be complete and considered successful.	Complete
Payload OAS-2	The OAS lidar sensor shall relay the distance between the sensor and an object to the CES with an accuracy of +/- 1 in.	Test The VL53L0X Time of Flight lidar sensor will be connected to the Feather M0 Bluefuit LE microcontroller. The sensor will be configured to relay the distance of any object in front it to the serial monitor of the Arduino IDE. An object will be placed in front of the sensor at various locations within the range of 1.97 to 47.24 in. The object distance will be measured with a ruler and compared to the distance data collected by the sensor. Five readings will be taken at the low end of the range (5 to 15 in.) and five readings will be taken at the high end of the range (30 to 40 in.). After 10 consecutive readings within +/- 1 in. of the ruler distance, the verification will be complete and considered successful. See OAS Accuracy TestOAS2refOASAccuracyTest	Complete
Payload OAS-3	The OAS servo motor shall pan the lidar sensor along a 156° field of view.	Demonstration The VL53L0X Time of Flight lidar sensor and SG92R servo motor will be connected to the Feather M0 Bluefuit LE microcontroller. The sensor will be configured to relay the distance of any object in front it to the serial monitor of the Arduino IDE. Two objects will be placed 156° apart from each other. The servo will pan the lidar sensor starting from one object and ending on the other. The lidar will confirm recognition of the two objects based on the distance data sent to the Arduino IDE. After five consecutive trials of recognition of both objects, the verification will be complete and considered successful.	Complete

Payload SAS-1	The SAS tower assembly shall actuate from the stowed position via the springe hinge and remain upright under its own power.	Inspection The SAS will be manufactured and assembled. The tower will be held by a team member in the stowed configuration. The tower will then be released and allowed to actuate via the spring hinge. Upon reaching full actuation, the tower shall remain upright under its own power. After five consecutive demonstrations of the tower being supported upright under its own power, the verification will be complete and considered successful.	Complete
Payload SAS-2	The SAS shall unfold the solar panels such that the exposed solar panel surface area increases to four times that of the folded configuration.	Demonstration The SAS tower and solar panel support arms will be manufactured and fully assembled. The deployment motor will be controlled by the Feather M0 Bluefruit LE and FeatherWing Motor Controller Via Bluetooth from a team member's cellphone. This is done to avoid possibility of damage to the support arms and solar panels during testing by maintaining full control of the deployment motor. The solar panels will be in their folded configuration where only one panel is exposed to light. The deployment motor will be activated unfolding all of the solar panels. After all four solar panels are exposed, the motor will be stopped. A team member will visually confirm that all four solar panels are fully exposed. After five consecutive demonstrations, the verification will be complete and considered successful.	Complete
Payload SAS-3	The SAS solar panels shall harvest energy from the sun and pass a continuous minimum power of 4 mW to the CES.	Demonstration The SAS will be manufactured and assembled. The SAS will be put in its fully deployed configuration. The solar panels will be connected in parallel to the Feather M0 Bluefruit LE microcontroller. An RGB LED will be illuminated red when the power level is below 4 mW and green when the power is above 4 mW. Once the LED is green, a stop watch will begin counting up. If at any point the light turns red, the trial will be halted and restarted. After the LED is shown to remain stable green for more than 30 seconds representing continuous power being delivered, the verification will be complete and considered successful.	Complete
Payload SAS-4	The SAS shall raise the solar panel support arms from a stowed flight configuration to achieve a minimum clearance of 0.5 vertical inches from any other rover component.	Demonstration The rover will be manufactured and fully assembled. The SAS locking motor and deployment motor will be connected to the Feather M0 Bluefruit LE microcontroller and FeatherWing Motor Shield. The locking motor will be commanded to release the tower assembly. Once the tower assembly is fully upright, the deployment motor will be activated. Once the panels are fully deployed, the vertical distance from each solar panel support arm and the next closest component to it will be measured. After confirming the smallest distance is greater than 0.5 in., the verification will be complete and considered successful.	Complete
Payload SAS-5	The SAS shall support the four solar panels throughout the duration of the launch vehicle's flight and the payload's mission.	Test The payload will be manufactured and fully assembled. The payload will then be integrated into the payload bay of the launch vehicle prior to a full-scale test launch. After landing, a team member will walk out to the payload bay and deploy the rover. A team member will carefully inspect the SAS support arms and solar panels while and after the payload performs its mission. If at any point, a solar panel is damaged or dislodged from its support arm, note will be taken to determine a solution. After all four solar panels are deployed and undamaged, the verification will be complete and considered successful. See Flight Loads Testing Series._SAS-5SAS5refFlightLoadsTesting	Incomplete – Postponed due to unsuccessful flight.

Payload SIS-1	The SIS camera module shall take images and store them on the CES SD card at a minimum rate of six images per minute.	Demonstration The SIS ArduCAM OV5642 camera module will be connected to the Feather M0 Bluefruit LE. The software will be configured to loop taking images at a rate of six images per minute. This will represent mission configuration. Images will be stored on the FeatherWing Adalogger's microSD card. Images will be inspected after allowing the camera to take pictures for a total of five minutes. If less than 30 images had been taken, the software will be changed accordingly trial will be restarted. After a minimum of 30 images is taken, the verification will be complete and considered successful.	Complete
Payload SIS-2	The OAS servo motor shall pan the SIS camera module to achieve a minimum field of view of 156°.	Demonstration The SIS ArduCAM OV5642 camera module and SG92R servo motor will be connected to the Feather M0 Bluefuit LE microcontroller. The camera and microcontroller software will be configured to store images taken at the starting angle and at the final angle on the FeatherWing Adalogger's MicroSD card. Two objects will be placed 156° apart from each other. The servo will pan the camera starting from one object and ending on the other. The images will be inspected to ensure that both objects were photographed. After confirmation of capturing both objects, the verification will be complete and considered successful.	Complete
Payload SIS-3	The SIS shall be triggered to begin taking images by the amount of energy produced by three of the four SAS solar panels being exposed to full and direct sunlight.	Demonstration The SIS ArduCAM OV5642 camera module and four SAS solar panels will be connecetd to the Feather M0 Bluefruit LE microcontroller. Software will be configured to begin taking images with the camera once the power level of the input from the solar panels exceeds 4 mW which is experimentally the case when three of the four panels are fully exposed in direct light. The Solar panels will begin covered and one by one will be fully uncovered in a well-lit place. After the third panel is fully revealed the camera will be commanded to begin taking pictures by the microcontroller. If this does not occur, the trigger power level will be adjusted and the trial restarted. After five consecutive trials without need for adjustment, the verification will be complete and considered successful.	Complete
Payload CES-1	The CES shall obtain the 3-axis orientation of the rover with an minimum accuracy of +/- 0.1°.	Test Two BNO055 9DOF IMUs with documented accuracy of +/- 0.05° will be connected to the Feather M0 Bluefruit LE microcontroller. Software will be configured to receive 3-axis gyroscope data from the two IMUs. An RGB LED will be illuminated green if the sensor data reflects less than 50° of inclination in the pitch and roll directions with a base point of the sensor being flat on the surface. The LED will be turned red if the inclination exceeds 50°. The electronics will be fixed inside a tube and rolled in all possible pitch and roll angles. After 10 consecutive trials of the LED correctly indicating the angle of inclination within 0.1° error and with a drift of less than 1° over the testing period, the verification will be complete and considered successful. See CES Orientation Accuracy Test plan.CES1refCESOrientationAccuracyTest	Complete
Payload CES-2	The CES shall autonomously control motor of the RLM to both lock and release the rover to the ROCS.	Test The payload will be manufactured and fully assembled. The rover will be integrated with the RLM and ROCS. Software will be configured to release and lock the RLM after trigger commands have been sent from a team member's cellphone via Bluetooth representing the deployment signal being received. The state of the RLM will be	Complete

		inspected after each command is sent. If the RLM is not either fully locked or fully released, the trial will be halted and a solution determined. After 10 consecutive commands have been given, the verification will be complete and considered successful. See CES Autonomous Control Testing Series.CES2refCESAutonomousControlTests	
Payload CES-3	The CES shall autonomously control the SAS locking motor to both release and lock the tower assembly.	Test The rover will be manufactured and fully assembled. Software will be configured to release and lock the SAS locking motor after trigger commands have been sent from a team member's cellphone via Bluetooth representing the SAS deployment stage of the mission being reached. The state of the SAS locking motor will be inspected after each command is sent. If the SAS is not either fully locked or fully released, the trial will be halted and a solution determined. After 10 consecutive commands have been given, the verification will be complete and considered successful. See CES Autonomous Control Testing Series.CES3refCESAutonomousControlTests	Complete
Payload CES-4	The CES shall autonomously control the SAS deployment motor to both fold and unfold the solar array.	Test The rover will be manufactured and fully assembled. Software will be configured to fold and unfold SAS solar panel support arms after trigger commands have been sent from a team member's cellphone via Bluetooth representing the SAS deployment stage of the mission being reached. The state of the SAS solar panel support arms will be inspected after each command is sent. If the SAS is not either fully folded or fully deployed, the trial will be halted and a solution determined. After 10 consecutive commands have been given, the verification will be complete and considered successful. See CES Autonomous Control Testing Series.CES4refCESAutonomousControlTests	Complete
Payload CES-5	The CES shall autonomously analyze the data collected by the OAS lidar sensor in real-time to determine the optimal travel path for mission success.	Test The rover will be manufactured and fully assembled. Objects of greater than 4 in. tall will be placed in front of and around the rover. The CES will command the rover to drive in a straight line until an object is detected within 10 in. of the OAS sensor. The rover will be halted, the OAS servo motor will pan the lidar sensor 175°, and data points will be collected at each degree of the sweep. The data will be stored on the CES microSD card. The CES will analyze the data and turn the rover to avoid the object. If the rover touches an object at any point, the trial will be halted and a solution determined. After no objects are within five feet of the rover, the trial will be completed. After five consecutive trials have been completed, the verification will be complete and considered successful. See CES Autonomous Control Testing Series.CES5refCESAutonomousControlTests	Complete
Payload CES-6	The CES shall autonomously control the two main drive motors of the RDS and all forward motion and maneuvering of the rover via the drive motors.	Test The rover will be manufactured and fully assembled. The Feather M0 Bluefruit LE microcontroller and FeatherWing Motor Shield will be connected to the main drive motors. Software will be configured to autonomously drive the rover along a path consisting of four forward, one reverse, one left turn, and one right turn commands. Markers will indicate the intended location of each setpoint. If at any point, the intended setpoint location is not reached, the trial will be halted and a solution determined. After the rover reaches and stops on the end marker five times consecutively, the verification will be complete and considered successful. See CES Autonomous Control Testing Series.CES6refCESAutonomousControlTests	Complete

Payload CES-7	The CES shall log all deployment signal, gyroscope, lidar, drive controls, solar power harvesting, and images acquired throughout the mission on a microSD card.	Test The payload will be manufactured and assembled. The payload will be integrated into the launch vehicle prior to a full-scale test launch. Flight ready software will be loaded onto the CES prior to launch. After the full mission is completed, data collected on the microSD of the CES FeatherWing Adalogger will be analyzed. After confirmation of data collected from the DTS deployment, two gyroscopes, OAS lidar sensor, autonomous drive commands, solar power harvest levels, and SIS images is achieved, the verification will be complete and considered successful. See Full Flight Performance Testing Series._CES-7CES7refFullFlightPerformaceTesting	Incomplete – Postponed due to unsuccessful flight
Payload CES-8	The CES controller battery lifetime shall exceed a minimum of three hours running flight ready software.	Test The rover will be manufactured, assembled, and integrated with the DTS. The 500 mAh controller battery will be recharged fully prior to beginning the test. The rover will be switched to internal power and left to run flight ready software for three hours. Controller battery levels will be monitored at 10 minute increments. If at any point the battery level reduces below the required level of 3.7V to power the rover's electronics, the trial will be halted and a larger capacity battery obtained. After three hours of continuous runtime has been reached, the verification will be complete and considered successful. See Battery Life Testing Series._CES-8CES8refBatteryLifeTesting	Incomplete – Postponed due to unsuccessful flight
Payload CES-9	The CES motor battery lifetime shall exceed a minimum of 5 minutes of motor runtime on a single full charge.	Test The rover will be manufactured and assembled. The 400 mAh motor battery will be fully recharged prior to beginning the test. Software will be running on the CES Feather M0 Bluefruit LE microcontroller to run the main drive motors at full power for 30 seconds at a time with 15 seconds of rest between each interval. Battery levels will be monitored every 15 seconds. If at any point the battery voltage drops below 6V, the trial will be halted and a battery of larger capacity will be obtained. After five minutes worth of motor runtime has been achieved, the verification will be complete and considered successful. See Battery Life Testing Series._CES-9CES9refBatteryLifeTesting	Incomplete – Postponed due to unsuccessful flight

8.3 Budget

For the 2017-2018 season River City Rocketry had an operating budget of $45,000.00 the income sources for to allow for this operating budget is shown in Table 73 below.

Source	Amount
Remaining Balance	$ 12,300.00
Alumni Donations	$ 20,000.00
NASA Prize Money	$ 5,000.00
Speed School Money	$ 5,000.00
Raytheon	$ 1,000.00
Misc. Donations	$ 1,700.00
Total	**$ 45,000.00**

Table 73: Team Income

From the projected budgets above we see that River City Roc1ketry has a projected budget of $45000 coming from a variety of sources. These sources include companies, the university and its sponsors along with miscellaneous donations through our website and remaining money from last year's sustainable budget.

From there the projected budget based on a worst-case scenario was created based on expense reports from previous years along with a general understanding of the scope of this year's project and what costs should be expected from it. The summary of that budget can be seen in Table 74.

Budget Results			
Category	Budgeted Cost	Real Cost	Percent Difference
General Team	$ (17,803.41)	$ (5,167.79)	244.51%
Payload	$ (4,406.80)	$ (2,907.95)	51.54%
Recovery	$ (1,453.00)	$ (1,634.53)	-11.11%
VDS	$ (2,268.56)	$ (1,694.33)	33.89%
Vehicle	$ (6,542.18)	$ (5,310.51)	23.19%
Total	$ (32,473.95)	$ (16,715.11)	94.28%

Table 74: Team Budget Overview

As seen from the table above the team is significantly below its projected costs for the year in nearly every category, this budget was projected to be a worst-case scenario to account for any CATOs or other factors that may plague the team. Additionally, the team gained access to additional manufacturing resources this year allowing us to purchase raw materials allowing us to save money on buying finished goods and allowing us to buy in bulk which gave us the ability to save significantly on shipping especially in unexpected situations like a motor CATO.

To better understand how funds were being spent during this season we decided to break down our expenses by both project and category. The total expenses can be seen in Figure 242 along with a breakdown of expenses seen in Table 75 where category sums are shown in bold and their projects are shown below it.

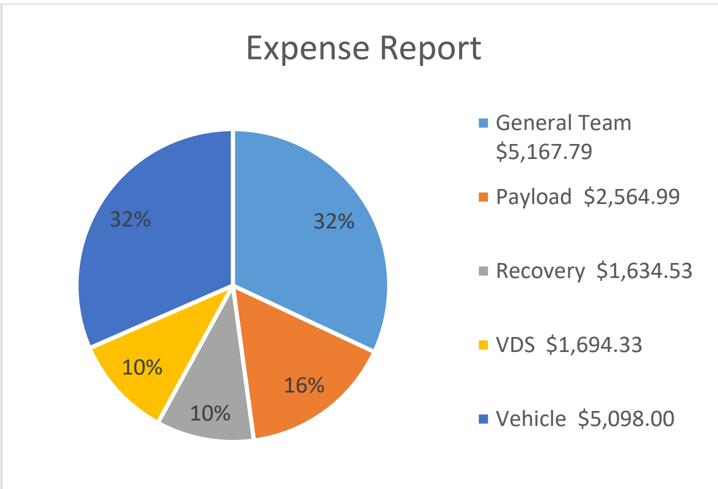

Figure 242: Team Budget Overview

Expenses		
General Team	$	5,167.79
Outreach	$	120.86
Team Improvement	$	545.26
Safety	$	117.04
General Team Cost	$	993.19
Travel	$	3,391.44
Payload	$	2,564.99
CES	$	431.00
ROCS	$	590.98

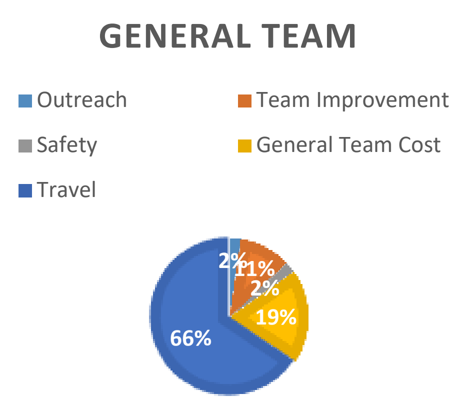

Figure 243: General Team Expenses Overview

RDS	$	1,247.72
OAS/SIS	$	5.95
SAS	$	122.00
Rover	$	2.61
DTS	$	125.72
RBS	$	26.96
RES	$	12.05
Recovery	$	1,634.53
Full Scale	$	1,365.23
Subscale Vehicle	$	122.80
Testing	$	146.50
VDS	$	1,694.33
Level 2	$	28.88
VDS 3.0	$	923.45
Full Scale	$	100.00
Telemetry	$	200.09
VDS PCBs	$	116.06
VDS 3.0 Remake	$	325.85
Vehicle	$	5,098.00
Level 2	$	29.95
Vehicle	$	2,419.63
Subscale Vehicle	$	176.83
Full Scale	$	1,970.46
Vehicle Tracking	$	149.99
Testing	$	27.49
Full Scale Rebuild	$	323.65

Table 75: Team Expenses Overview

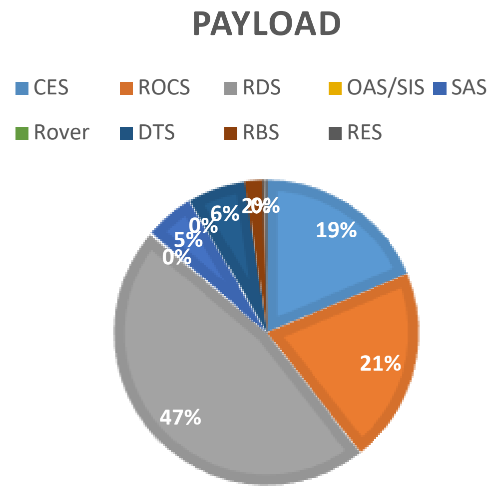

Figure 244: Payload Expenses Overview

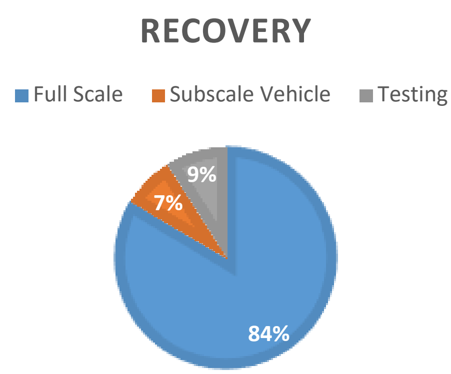

Figure 245: Recovery Expenses Overview

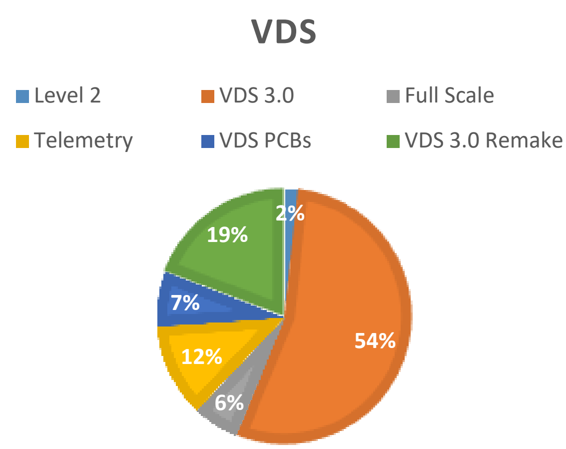

Figure 246: VDS Expense Overview

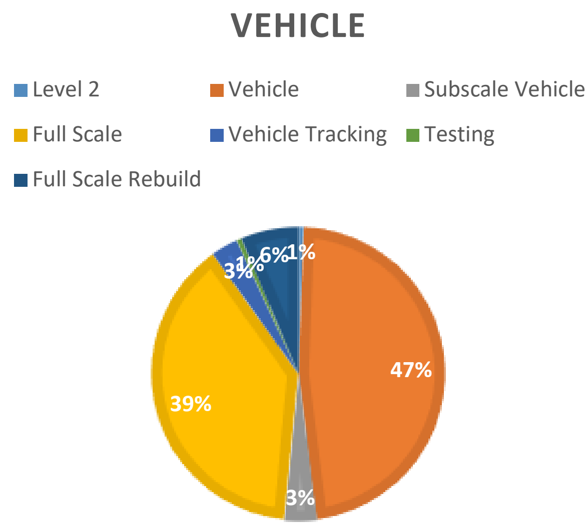

Figure 247: Vehicle Expense Overview

A full list of expenses is shown below based on the team defined catergories discussed above.

Date	Project	Item	Company	Quantity	Unit Cost	Shipping	Total Cost
9/7	Outreach	PVC Cement	Amazon	1	$ 9.10	$ -	$ 9.10
9/7	Outreach	plasticweld	Amazon	1	$ 7.86	$ -	$ 7.86
9/7	Outreach	Standard Tire Valve	Amazon	1	$ 4.82	$ -	$ 4.82
9/7	Outreach	sprinkler system valve	Amazon	1	$ 15.27	$ -	$ 15.27
9/7	Outreach	push button switch	Amazon	1	$ 11.99	$ -	$ 11.99
9/7	Outreach	battery lead 9v	Amazon	1	$ 5.39	$ -	$ 5.39
9/7	Team Improvement	2-way radios (3 pack)	Amazon	1	$ 43.00	$ -	$ 43.00
9/7	Safety	Gloves	Amazon	3	$ 9.46	$ -	$ 28.38
9/7	Safety	Silverware	Amazon	1	$ 9.75	$ -	$ 9.75
9/7	General Team Cost	Gorilla tape	Amazon	3	$ 8.49	$ -	$ 25.47
9/7	General Team Cost	Packaging tape	Amazon	1	$ 11.63	$ -	$ 11.63
9/7	Team Improvement	Power Cord	Amazon	1	$ 4.80	$ -	$ 4.80
9/7	General Team Cost	USB to VGA adapter	Amazon	1	$ 14.88	$ -	$ 14.88
9/7	Outreach	High Performance Inflator	Amazon	1	$ 28.49	$ -	$ 28.49
9/7	Team Improvement	gun turret pad	Apogee rockets	0	$ 486.75	$ -	$ -
9/7	General Team Cost	Extension and 3 joiner plates	Giant Leap Rocketry	1	$ 62.99	$ -	$ 62.99
9/7	General Team Cost	Rail Stops	Giant Leap Rocketry	1	$ 11.54	$ -	$ 11.54
9/7	Team Improvement	Scale charger	Global Industry	1	$ 8.95	$ -	$ 8.95
9/7	Outreach	2" to 1" reducer bushing	home depot	1	$ 1.52	$ -	$ 1.52
9/7	Outreach	1" to .5" reducer bushing	home depot	1	$ 1.09	$ -	$ 1.09
9/7	Outreach	.5 in threaded male adapter	home depot	2	$ 0.44	$ -	$ 0.88
9/7	Outreach	.5" x2' pvc pipe	home depot	1	$ 1.47	$ -	$ 1.47
9/7	Outreach	Pipe wrench	Lowes	1	$ 14.98	$ -	$ 14.98
9/7	Outreach	10' 6" PVC	Lowes	2	$ 6.74	$ -	$ 13.48
9/7	Outreach	2" slip fit t joint	Lowes	1	$ 2.84	$ -	$ 2.84
9/7	Outreach	2" end cap	Lowes	2	$ 0.84	$ -	$ 1.68
9/25	General Team Cost	White Board Marker Kit	Amazon	2	$ 6.78	$ -	$ 13.56
9/25	General Team Cost	Sharpie Special Edition	Amazon	1	$ 16.46	$ -	$ 16.46
10/25	Team Improvement	Tank launch pad	Knight Mfg	1	$ 359.99	24	$ 383.99
11/14	General Team Cost	ABS 3D print material	Amazon	1	$ 21.99	$ -	$ 21.99
11/14	General Team Cost	ABS 3D print material Red	Amazon	1	$ 21.99	$ -	$ 21.99
11/30	General Team Cost	Calipers	Amazon	5	$ 9.97		$ 49.85
11/30	General Team Cost	PLA Filament	Amazon	2	$ 16.99		$ 33.98
11/30	Team Improvement	Dremel	Amazon	1	$ 99.00		$ 99.00
1/3	Safety	Over the Door Shoe Organizer	Amazon	1	$ 6.97		$ 6.97
1/3	General Team Cost	Pad Lock	Amazon	1	$ 8.99		$ 8.99
1/3	Travel	Hotel rooms	Comfort Inn	30	$ 98.00	$ -	$ 2,940.00
1/3	Safety	Sanding Respirator	Lowes	2	$ 24.97		$ 49.94
1/16	Team Improvement	4-40 tap	Amazon	2	$ 2.76	$ -	$ 5.52

1/16	General Team Cost	Camera eq. rental	Murphy's	125	$ 1.00	$ -	$ 125.00
1/25	Safety	Dust Mask Box of 50	Amazon	1	$ 8.00		$ 8.00
1/25	General Team Cost	5-minute Epoxy Loctite	Amazon	3	$ 3.59		$ 10.77
1/25	General Team Cost	1-minute Epoxy Loctite	Amazon	3	$ 3.44		$ 10.32
1/25	General Team Cost	5pack 4gb MicroSD card	Newegg	1	$ 30.01		$ 30.01
2/5	General Team Cost	WM02-EJECTION LIGHTER × 15	Wildman Rocketry	15	$ 15.79	$ 105.00	$ 341.85
2/7	General Team Cost	9v battery	Amazon	1	$ 29.90	$ -	$ 29.90
2/7	General Team Cost	Dremel cutting bits	Lowes	1	$ 21.89	$ -	$ 21.89
2/7	General Team Cost	Diamond Bit Cutting Wheel	Lowes	0	$ 24.89	$ -	$ -
2/7	General Team Cost	Bins	Lowes	6	$ 11.98	$ -	$ 71.88
2/7	General Team Cost	Terminal Blocks	Mouser	25	$ 1.09	$ 7.99	$ 35.24
2/7	General Team Cost	Terminal Block Connectors 796637-2	Mouser	50	$ 0.46		$ 23.00
2/16	Travel	First Launch Hotels	Hilton	4	$ 112.86	0	$ 451.44
2/19	Safety	Gloves	Amazon	200	$ 0.07	$ -	$ 14.00

Table 76 General Team Expenses:

Date	Project	Item	Company	Quantity	Unit Cost	Shipping	Total Cost
9/7	CES	HC-12 433 transmitter and receiver	Amazon	2	15.99	$ -	$ 31.98
9/25	CES	Feather M0 Bluefruit	Adafruit	1	29.95	$ -	$ 29.95
9/25	CES	FeatherWing Motor Shield	Adafruit	1	19.95	$ -	$ 19.95
9/25	CES	VL53L0X Distance Sensor	Adafruit	1	14.95	$ -	$ 14.95
9/25	CES	FeatherWing Adalogger	Adafruit	1	8.95	$ -	$ 8.95
9/25	CES	Stacking Headers	Adafruit	4	1.25	$ -	$ 5.00
9/25	CES	Small Push-Pull Solenoid	Adafruit	1	9.95	$ -	$ 9.95
9/25	ROCS	4mm Carbon Steel Ball Bearings	BC Precision	1	6.25	$ -	$ 6.25
9/25	ROCS	145mm Retaining Ring	Grainger	1	22.8	$ -	$ 22.80
9/25	CES	11.1V 400mAh LiPo battery	Helipal	2	14.9	$ -	$ 29.80
9/25	RDS	Micro Metal Gear Motor	Pololu	1	24.95	$ -	$ 24.95
9/25	CES	ArduCAM Mini Camera Module	RobotShop	1	39.99	$ 9.00	$ 48.99
11/14	CES	Adafruit Feather m0 Bluefruit LE	Adafruit	1	29.95	$ 7.17	$ 37.12
11/14	OAS/SIS	SG92R Micro Servo Motor	Adafruit	1	5.95	$ -	$ 5.95
11/14	CES	Adafruit FeatherWing Motor Shield	Adafruit	2	19.95	$ -	$ 39.90
11/14	CES	Lipo Voltage Indicator	Amazon	1	6.34	$ -	$ 6.34
11/14	SAS	6mm x 100mm D shaft extension	AndyMark	1	7	$ -	$ 7.00
11/14	RDS	16 T5 DL/865 V Timing belt	Brecoflex	2	34	$ -	$ 68.00
11/14	SAS	316 Stainless Steel Retractable Spring Plunger	McMaster-Carr	4	18.38	$ -	$ 73.52
11/14	RDS	White Delrin® Acetal Resin Oversized Bar 1" Thick, 2" Wide, 2 feet long	McMaster-Carr	1	41.16	$ -	$ 41.16
11/14	RDS	Light Duty Two-Bolt Flange-Mounted Ball Bearing	McMaster-Carr	10	9.16	$ -	$ 91.60
11/14	RDS	Brass Nylon-Insert Locknut 8-32 Thread Size	McMaster-Carr	2	5.14	$ -	$ 10.28
11/14	RDS	T5 Series Timing Belt Pulley for 16mm Maximum Belt Width, 25.4mm OD	McMaster-Carr	2	12.44	$ -	$ 24.88

11/14	ROCS	Highly Machinable MIC6 Aluminum Sheet 3/8" Thick, 6" x 6"	McMaster-Carr	1	16.91	$ -	$ 16.91
11/14	RDS	Black-Oxide Alloy Steel Socket Head Screw M2 x 0.4 mm Thread, 16 mm Long	McMaster-Carr	1	9.85	$ -	$ 9.85
11/14	RDS	Black-Oxide Alloy Steel Socket Head Screw 4-40 Thread Size, 3/4" Long	McMaster-Carr	1	8.42	$ -	$ 8.42
11/14	Rover	18-8 Stainless Steel Hex Nut 4-40 Thread Size	McMaster-Carr	1	2.61	$ -	$ 2.61
11/14	RDS	Washer for Blind Rivets 8-8 Stainless Steel, for 1/8" Rivet Diameter, 0.134" ID, 0.375" OD	McMaster-Carr	1	8.75	$ -	$ 8.75
11/14	RDS	Black-Oxide Alloy Steel Socket Head Screw 0-80 Thread Size, 1/2" Long	McMaster-Carr	1	6.29	$ -	$ 6.29
11/14	SAS	External Retaining Ring	McMaster-Carr	1	8.5	$ -	$ 8.50
11/14	RDS	1/8" Stainless Steel Precision Shafting 3" long	servocity	3	0.59	$ -	$ 1.77
11/14	RDS	4mm Stainless Steel Precision Shafting 150mm long	servocity	1	0.99	$ -	$ 0.99
11/14	RDS	4mm Bore Shaft Mount Bevel Gears 24T	servocity	4	5.99	$ -	$ 23.96
11/14	RDS	52 RPM Premium Planetary Gear Motor	servocity	2	27.99	$ -	$ 55.98
11/14	SAS	Set Screw Shaft Couplers, choose 3mm to 6mm bore	ServoCity	3	4.99	$ 6.99	$ 21.96
11/30	DTS	SMA female to F male adapter	Amazon	2	5	$ -	$ 10.00
11/30	DTS	SMA male to F male	Amazon	2	5.5	$ -	$ 11.00
11/30	DTS	SMA male to F female	Amazon	2	4.8	$ -	$ 9.60
11/30	DTS	SMA to F cable 6 inch	Amazon	1	6.5	$ -	$ 6.50
11/30	DTS	RF type F cable 3 pack	Amazon	1	8.95	$ -	$ 8.95
11/30	DTS	SMA right angle cable	Amazon	2	5.5	$ -	$ 11.00
11/30	DTS	SMA cable	Amazon	1	8.99	$ -	$ 8.99
11/30	DTS	SMA pigtails	Amazon	1	12.73	$ -	$ 12.73
11/30	DTS	Slip Ring with Flange	Adafruit	1	14.95	$ -	$ 14.95
12/12	RDS	Delrin Stock 13/8"	Grainger	1	34.3	$ -	$ 34.30
12/12	RDS	Press Fit Shafts a8-28	PIC designer	12	10	$ -	$ 120.00
12/12	RDS	MicroMetal Gear Motor	Pololu	1	24.95	$ -	$ 24.95
12/12	RDS	Aluminum Stock 12x4x1	Metal Warehouse	1	35	$ -	$ 35.00
12/12	RDS	Aluminum Stock 1-1/8" Thick, 2" x 48"	McMaster-Carr	1	72.98	$ -	$ 72.98
1/3	CES	BNO055 9DOF IMU	Adafruit	2	34.95	$ -	$ 69.90
1/3	RDS	9273K1, Multipurpose Hook and Loop with Adhesive Backing	McMaster-Carr	1	4.97	$ -	$ 4.97
1/3	RBS	.1" Thick Sheet of Aluminum 12"x24"	McMaster-Carr	1	26.96	$ -	$ 26.96
1/3	SAS	Steel Torsion Spring	McMaster-Carr	1	6.2	$ -	$ 6.20
1/3	SAS	Steel Torsion Spring	McMaster-Carr	1	4.82	$ -	$ 4.82
1/16	DTS	Magnetic Connector	Alibaba	4	8	$ -	$ 32.00
1/16	ROCS	4mm Si3N4 Ball Bearings	BC Precision	1	20.15	$ -	$ 20.15
1/16	ROCS	1/16" Chrome Steel Ball Bearings	BC Precision	1	10.95	$ -	$ 10.95
1/16	ROCS	1/2" button head screws	McMaster-Carr	1	9.54	$ -	$ 9.54
1/16	RDS	1/8" dia x 3" 303 stainless shaft	McMaster-Carr	12	3.26	$ -	$ 39.12
1/25	ROCS	Water Heater	Amazon	0	39.99	$ -	$ -
1/25	ROCS	Sulfuric Acid	Amazon	1	30	$ -	$ 30.00
1/25	ROCS	Aluminum Wires	Amazon	1	6.59	$ -	$ 6.59
1/25	ROCS	DI Water	Amazon	0	48.99	$ -	$ -
1/25	ROCS	Anodizing Dye	Amazon	1	57.99	$ 12.00	$ 69.99

1/25	ROCS	Degreaser	Amazon	1	8.99	$ -	$ 8.99
1/25	ROCS	NaOH	Amazon	1	14.97	$ -	$ 14.97
1/25	ROCS	Measuring Spoons	Amazon	1	6.49	$ -	$ 6.49
1/25	ROCS	Rubber Gloves	Amazon	1	17.18	$ -	$ 17.18
1/25	ROCS	Masks	Amazon	1	9.99	$ -	$ 9.99
1/25	ROCS	Baking Soda	Amazon	1	10.49	$ -	$ 10.49
1/25	ROCS	Chemical Hazard Labels	Amazon	1	8.49	$ -	$ 8.49
1/25	CES	32GB Class 10 MicroSD	Amazon	2	15.15	$ -	$ 30.30
1/25	ROCS	HDPE Plastic Bucket	Lowes	3	3.25	$ -	$ 9.75
1/25	ROCS	Aluminum Sheet	McMaster-Carr	1	38.13	$ -	$ 38.13
1/26	ROCS	26 RPM Premium Planetary Gear Motor	Servo City	1	27.99	$ -	$ 27.99
1/26	ROCS	22mm Bore Clamp Mount	Servo City	2	5.99	$ -	$ 11.98
1/26	ROCS	Clamping Shaft Coupler	Servo City	1	4.99	$ -	$ 4.99
1/26	ROCS	634060	Servo City	1	1.09	$ -	$ 1.09
1/26	ROCS	Bottom Tapped Pillow Block	Servo City	2	5.99	$ -	$ 11.98
1/25	ROCS	BNO055	Adafruit	2	34.95	$ -	$ 69.90
2/7	ROCS	The Lube	Amazon	1	9.99	$ -	$ 9.99
2/7	CES	Rocker Switches	Amazon	1	5.99	$ -	$ 5.99
2/7	CES	RED! LED Rocker Switch	Amazon	1	7.98	$ -	$ 7.98
2/8	CES	BLUE! LED Rocker Switch	Amazon	1	7.97	$ -	$ 7.97
2/7	CES	32GB microSD cards	Amazon	2	12.99	$ -	$ 25.98
2/6	RDS	8-32 x 0.25in flat head phillips	McMaster-Carr	1	6.58	$ -	$ 6.58
2/6	RDS	shielded bearing	McMaster-Carr	6	9.46	$ -	$ 56.76
2/1	ROCS	4mm Si3N4 Ball Bearings	BC Precision	1	20.15	$ -	$ 20.15
2/1	ROCS	1/16" Chrome Steel Ball Bearings	BC Precision	1	10.95	$ -	$ 10.95
1/29	ROCS	Oversized 1.5x6x6	McMaster-Carr	1	59.46	$ 6.71	$ 66.17
1/22	RDS	Custom Treads	F.N. Sheppard	2	114.155	$ -	$ 228.31
2/22	RDS	Custom Treads	F.N. Sheppard	2	114.155	$ -	$ 228.31
2/19	RES	Jumper Wire	Amazon	1	6.99	$ -	$ 6.99
2/19	RES	Female- Male wire jumpers	Amazon	1	5.06	$ -	$ 5.06
2/19	RDS	Drive Shafts	McMaster-Carr	6	3.26	$ -	$ 19.56
2/19	ROCS	Aluminum sheet .19x6x24	McMaster-Carr	1	38.13	$ -	$ 38.13
2/27	OAS/SAS	SG92R Servo Motor	Adafruit	1	5.95	$ -	5.95
2/27	CES	Feather M0 Bluefruit LE microcontroller	Adafruit	1	29.95	7.95	37.9
2/27	CES	FeatherWing Adalogger	Adafruit	1	8.95	$ -	8.95
2/27	OAS	VL53L0X Lidar Sensor	Adafruit	1	14.95	$ -	14.95
2/27	CES	Magnetic Connectors Little Bits	Little Bits	1	15.95	40	55.95
2/27	RBS	5052 12" x 24" Aluminum	McMaster-Carr	1	26.96	$ -	26.96
2/27	SAS	32 RPM Micro Metal Gearmotor	Pololu	1	24.95	$ -	24.95
2/27	DTS	HC-12 Tranceiver Module	SeeedStudio	2	12.9	22.6	48.4
2/27	RLM	26 RPM Planetary Gearmotor	Servo City	1	27.99	6.99	34.98

2/27	RDS	52 RPM Planetary Gearmotor	Servo City	1	27.99	$ -	27.99
2/27	RDS	520 RPM Planetary Gearmotor	Servo City	2	27.99	$ -	55.98

Table 77: Payload Expenses

Date	Project	Item	Company	Quantity	Unit Cost	Shipping	Total Cost
9/25	Full Scale	Sewing Machine	Amazon	1	118	$ -	$ 118.00
9/25	Full Scale	Spectra Line	Ebay	2	84	$ -	$ 168.00
9/25	Full Scale	Shockcord (4,000 lb)	Madcow Rocketry	210	0.55	$ -	$ 115.50
9/25	Full Scale	Sewing Thread	The Thread Exchange	4	30	$ -	$ 120.00
9/25	Full Scale	Silver Sharpies	Wikibuy	1	30.14	$ -	$ 30.14
11/14	Subscale Vehicle	3/16" zinc plated quick link	E-Rigging	6	0.25	$ -	$ 1.50
11/14	Full Scale	Medium-Strength Steel Hex Nut	McMaster-Carr	1	6.4	$ -	$ 6.40
11/14	Subscale Vehicle	Shroud line	Milwaukee Rigging	20	3.3	$ 2.10	$ 68.10
11/14	Subscale Vehicle	Hemmer foot	sewing parts online	2	24.95	$ 3.30	$ 53.20
11/14	Testing	CO2 ejection system	Tinder Rocketry	1	140	$ 6.50	$ 146.50
11/30	Full Scale	RAPTOR	Tinder Rocketry	2	140	$ 6.50	$ 286.50
1/16	Full Scale	Ripstop Nylon	Paragear	30	14	$ 10.00	$ 430.00
1/16	Full Scale	Nomex	Pegasus Racing	3	19.99	$ 6.00	$ 65.97
1/16	Full Scale	Hemmer Foot	walmart	2	8.73	$ -	$ 17.46
2/6	Full Scale	Quick Link	McMaster-Carr	6	1.21	$ -	$ 7.26

Table 78: Recovery Expenses

Date	Project	Item	Company	Quantity	Unit Cost	Shipping	Total Cost
9/7	Level 2	bmp280	Adafruit	1	9.95	$ -	$ 9.95
9/7	Level 2	Perf board	Amazon	1	12.54	$ -	$ 12.54
9/7	Level 2	Terminals	DigiKey	50	0.1278	$ -	$ 6.39
9/25	VDS 3.0	Terminal Blocks	Amazon	1	7.99	$ -	$ 7.99
9/25	VDS 3.0	SD card reader	Amazon	1	8.44	$ -	$ 8.44
9/25	VDS 3.0	VN 100 IMU	Vectornav	1	530	$ -	$ 530.00
11/14	VDS 3.0	Andymark NeveRest DC 40 Motor	Andymark	2	28	$ -	$ 56.00
11/14	VDS 3.0	Limit Switches SS-3GLPT	Digikey	10	1.24	$ -	$ 12.40
11/14	VDS 3.0	Limit Switch	Digikey	2	1.11	$ -	$ 2.22
11/14	VDS 3.0	1/8 diameter x 3/8 inch length Dowel Pin	McMaster-Carr	12	1.2	$ -	$ 14.40
11/14	VDS 3.0	0.125-inch 6061-T6 Aluminum Sheet	Metal Supermarkets	2	75.35	$ -	$ 150.70
11/30	VDS 3.0	Lipo indicator	Hobby King	2	2.85	$ -	$ 5.70
1/3	Full Scale	Beaglebone Green	Mouser	2	50	$ -	$ 100.00
1/16	Telemetry	A09-Y11NF (yagi directional ground station antenna)	Digi International Inc.	1	70	$ -	$ 70.00
1/16	Telemetry	A09-HBMM-P5I (straight half-wave dipole antenna)	Digi International Inc.	1	31.62	$ -	$ 31.62
1/16	VDS PCBs	10 A fuse	Digikey	4	1.53	$ -	$ 6.12
1/16	VDS PCBs	Amber LED	Digikey	4	0.15	$ -	$ 0.60
1/16	VDS PCBs	500 Ohm resistor	Digikey	4	0.72	$ -	$ 2.88
1/16	VDS PCBs	power switch	Digikey	4	2.11	$ -	$ 8.44

1/16	VDS PCBs	Fuse holder	Digikey	4	1.79	$ -	$ 7.16
1/16	VDS PCBs	.33 uF cap	Digikey	4	0.44	$ -	$ 1.76
1/16	VDS PCBs	Motor Controller	Digikey	6	6.46	$ -	$ 38.76
1/16	VDS PCBs	470 ohm resistor	Digikey	5	0.1	$ -	$ 0.50
1/16	VDS PCBs	Zener diode	Digikey	3	0.54	$ -	$ 1.62
1/16	Telemetry	U.FL to N Female Bulkhead	Eightwood	1	8.09	$ -	$ 8.09
1/16	Telemetry	MMCX Male to U.FL IPX	Eightwood	1	6.99	$ -	$ 6.99
1/16	VDS 3.0	1/8" 4130 Alloy Steel	McMaster-Carr	1	25.65	$ -	$ 25.65
1/16	VDS PCBs	surface mount LED	Mouser	2	0.56	$ -	$ 1.12
1/16	VDS PCBs	GPS	Navspark	2	12.5	$ -	$ 25.00
1/16	VDS PCBs	header pins	polou electroics	10	2.02	$ -	$ 20.20
1/16	VDS PCBs	5V reg	sparkfun	2	0.95	$ -	$ 1.90
1/25	Telemetry	U.FL to N Female Bulkhead	Eightwood	1	8.09	$ -	$ 8.09
1/25	Telemetry	MMCX Male to U.FL IPX	Eightwood	1	6.99	$ -	$ 6.99
1/25	VDS 3.0	DSUB Connect (mal3)	Digikey	5	0.8	$ -	$ 4.00
1/25	VDS 3.0	DSuB connecture female	Digikey	5	0.87	$ -	$ 4.35
2/7	VDS 3.0	32GB uSD card	Amazon	2	18.81	$ -	$ 37.62
2/7	VDS 3.0	64GB uSD card	Amazon	2	31.99	$ -	$ 63.98
2/7	Telemetry	N-male to N-male adapter	Amazon	1	25.34	$ -	$ 25.34
2/7	Telemetry	RP-SMA Cable	Amazon	1		$ -	$ -
2/9	Telemetry	StyleZ 3M 10FT Black RP-SMA Coaxial Extension Cable for WiFi LAN WAN Router Antenna	Amazon	1	7.99	$ -	$ 7.99
2/7	Telemetry	IPX /u.fl to N type male pigtail cable 15cm for PCI Wifi Card wireless	Amazon	1	6.99	$ 18.00	$ 24.99
2/10	Telemetry	IPX U.FL female 1.13mm 8inch RF pigtail MMCX female jack pin	Amazon	1	9.99	$ -	$ 9.99
2/19	VDS 3.0 Remake	bmp280	Adafruit	2	9.95	$ 22.47	$ 42.37
2/19	VDS 3.0 Remake	Delrin .25x12x24	Alro Plastics	1	97.99	$ -	$ 97.99
2/19	VDS 3.0 Remake	7.4 lipo battery	Amazon	2	9.5	$ -	$ 19.00
2/19	VDS 3.0 Remake	11.1 li-po battery	Amazon	2	13.49	$ -	$ 26.98
2/19	VDS 3.0 Remake	wire kit (unstranded)	Amazon	1	20.95	$ -	$ 20.95
2/19	VDS 3.0 Remake	Limit switches	Digikey	4	1.11	$ -	$ 4.44
2/19	VDS 3.0 Remake	bno055	Digikey	1	34.9	$ -	$ 34.90
2/19	VDS 3.0 Remake	Teensy 3.6	Sparkfun	2	29.25	$ 20.72	$ 79.22

Table 79: VDS Expenses

Date	Project	Item	Company	Quantity	Unit Cost	Shipping	Total Cost
9/7	Full Scale	low drag delrin rail buttons (x2)	Giant Leap Rocketry	3	3.49	$ -	$ 10.47
9/7	Level 2	X-winder resin bath	X-Winder	1	29.95	$ -	$ 29.95
9/25	Vehicle	Dust Mask	Homedepot	0	39.1	$ -	$ -
11/14	Subscale Vehicle	75MM BLUE TUBE	Apogee Rockets	2	29.95	$ -	$ 59.90

11/14	Subscale Vehicle	AEROTECH 38MM PROPELLANT KIT - I300T-M	Apogee Rockets	2	53.49	$ -	$ 106.98
11/14	Subscale Vehicle	75MM BLUE TUBE COUPLER	Apogee Rockets	1	9.95	$ -	$ 9.95
11/30	Vehicle	Aerotech L2200 Mojave Green Rocket Motor	Chris' Rocket Supplies	6	259.99	$ 75.00	$ 1,634.94
11/30	Vehicle	Aerotech 75/5120 Complete Motor Hardware	Chris' Rocket Supplies	1	550	$ -	$ 550.00
12/12	Full Scale	U-bolt	McMaster-Carr	6	0.68	$ -	$ 4.08
12/12	Vehicle	10-32 Shoulder bolts	McMaster-Carr	9	2.49	$ -	$ 22.41
12/12	Vehicle	10-24 Shoulder bolts	McMaster-Carr	9	2.25	$ -	$ 20.25
12/12	Vehicle	Connecting rod	McMaster-Carr	1	8.25	$ -	$ 8.25
12/12	Vehicle	Double Anchor Connector	McMaster-Carr	3	6.36	$ -	$ 19.08
12/12	Vehicle	Rectangular flat plate	80/20 inc.	2	6.85	$ -	$ 13.70
12/12	Vehicle	6" Carbon fiber coupler 12" length	Madcow rocketry	1	116	$ -	$ 116.00
12/12	Full Scale	U-bolt	McMaster-Carr	2	4.36	$ -	$ 8.72
1/3	Full Scale	60" Nylon Bag Tube 1 yard	ACP Composites	15	6.75	$ -	$ 101.25
1/3	Full Scale	PR2032/PH3660 Gallon Kit	Aircraft Spruce	1	141.95	$ -	$ 141.95
1/3	Full Scale	Sand Paper	Amazon	2	9.97	$ -	$ 19.94
1/3	Full Scale	Syringe	Amazon	5	6.09	$ -	$ 30.45
1/3	Full Scale	XL Gloves	Amazon	3	11.99	$ -	$ 35.97
1/3	Full Scale	Sand Paper 80 grit	Amazon	8	7.59	$ -	$ 60.72
1/3	Full Scale	Gorilla Tape (x6)	Amazon	1	26.16	$ -	$ 26.16
1/3	Full Scale	Painters Tape	Amazon	1	31.83	$ -	$ 31.83
1/3	Full Scale	1/4-20 Tap	Amazon	3	5.25	$ -	$ 15.75
1/3	Full Scale	Couplers	Carolina Couplers	6	110	$ 87.20	$ 747.20
1/3	Vehicle Tracking	Trackimo GPS	Crutchfield	1	149.99	$ -	$ 149.99
1/3	Full Scale	684-A 1" flash tape	FibreGlast	1	29.95	$ -	$ 29.95
1/3	Full Scale	9-B Gallon Acetone	FibreGlast	1	19.95	$ -	$ 19.95
1/3	Full Scale	160-A Acetone Dispenser	FibreGlast	1	10.95	$ -	$ 10.95

1/3	Full Scale	Motor mount tube	MadCow rocketry	1	116.5	$ -	$ 116.50
1/3	Full Scale	1/4 20 threaded rod	McMaster-Carr	2	3.71	$ -	$ 7.42
1/3	Full Scale	10-24 threaded rod	McMaster-Carr	1	3.67	$ -	$ 3.67
1/3	Full Scale	Heavy Duty Paper Wipes	McMaster-Carr	1	18.36	$ -	$ 18.36
1/3	Full Scale	U-bolt mounting plate	McMaster-Carr	2	0.65	$ -	$ 1.30
1/3	Full Scale	ALUMINUM (.25 in thick, 8in. Wide, 3 ft long)	McMaster-Carr	1	56.42	$ -	$ 56.42
1/3	Full Scale	U-bolt mounting plate	McMaster-Carr	2	0.36	$ -	$ 0.72
1/16	Full Scale	Camera	Amazon	2	34.99	$ -	$ 69.98
1/25	Full Scale	Screw Switches	Chris' Rocket Supplies	5	2.95	$ -	$ 14.75
1/25	Full Scale	Carbon fiber sheet	DragonPlate	1	386	$ -	$ 386.00
2/7	Testing	MPU 6050 Accelerometer/Gyroscope	Amazon	2	4.52	$ -	$ 9.04
2/7	Testing	LED Display	Amazon	1	6.59	$ -	$ 6.59
2/7	Testing	Arduino Nano	Amazon	1	11.86	$ -	$ 11.86
2/7	Vehicle	Screw switches	Featherweight	5	5	$ 10.00	$ 35.00
2/19	Full Scale Rebuild	Laminating Epoxy Gallon kit	Aircraft Spruce	1	141.95	$ 18.05	$ 160.00
2/19	Full Scale Rebuild	Rocket Epoxy	Apogee Rockets	2	38.25	$ 16.59	$ 93.09
2/19	Full Scale Rebuild	.25 in aluminum 8x48	Metal Supermarket	1	70.56	$ -	$ 70.56
2/27	Full Scale Vehicle	SuperLube	Amazon	1	18.36	$ -	18.36
2/27	Full Scale Vehicle	AIM BASE ONLY	Entacore	1	125	10	135
2/27	Full Scale Vehicle	Black Powder	Grafs.com	0	18.59	27.95	27.95
2/27	Full Scale Vehicle	Shoulder Bolt 10-32	McMaster-Carr	10	2.1	$ -	21
2/27	Full Scale Vehicle	Shoulder Bolt 10-24	McMaster-Carr	10	1.02	$ -	10.2

Table 80: Vehicle Expenses

9 Appendix

9.1 Payload Equipment Hazard Risk Assessment

Hazard	Cause	Effect	RBM	Mitigation	Verifications	RWM
Pinched, cut, or disconnected wire.	The DTS receiver wires could be twisted as the ROCS spins during the vehicle flight and recovery.	Damaged wire could short an electrical system, the payload would not be able to receive the signal to exit the payload bay, resulting in a failed payload mission.	2A	The receiver wires will pass through a slip ring flange that will be mounted through the bulk plate.	The payload launch checklist will require confirmation that the slip ring flange rotates freely and prevents wire twisting.slipring	2D
Payload bay does not self-orient correctly.	Unexpected contact between ROCS component(s) and airframe prevents the free rotation of the ROCS	The rover would be unable to exit the airframe due to unacceptable gyroscopic orientation readings, causing the payload to fail the mission.	2B	The SAS locking motor will hold the SAS tower assembly in the stowed position until the rover reaches its final destination, preventing it from contacting the airframe. The rover has been designed so that all other components are housed within the RBS.	The free rotation of the ROCS will be tested in requirement ROCS-3 and the integrity of the ROCS and RBS will be tested in requirement ROCS-4 and requirement RBS-3 to withstand all loads experienced during launch.ROCS3reqROCS4reqRBS3reqROCS3reqROCS4reqRBS3req	2D
Black powder residue on light sensitive rover components.	The rover is housed in the bay where the booster separation charge will detonate, expelling black powder residue on exposed surfaces.	The lidar sensor or solar panels may not get adequate light to function properly.	4A	The black powder charge capsule will be covered by a piece of fire retardant cloth that will retain some of the residue.	The current design is a Nomex blast cone that will be tested in a full-scale launch.	4C
Component falls out of payload bay during recovery.	A component could be loosened or broken due to large launch or parachute opening forces, concussive black powder charge explosions, or vibration.	A lost component is a risk to team members or spectators. The payload may not perform as intended, possibly causing a failed payload mission.	1C	All components will be properly attached to the rover body with a sufficient number of mechanical fasteners and Loctite.	Electronic and mechanical systems will be verified secure through requirement RBS-2. Requirement RBS-3 will verify that the rover can withstand high loads during flight. Launch procedures will require confirmation of Loctite on all payload fasteners prior to final assembly.RBS2RBS3reqloctiteOASAccuracyTestRBS3req	1E
Premature deployment.	Extraneous signal not transmitted by the team releases the RLM prior to the bay landing safely or mechanical failure of the RLM due to unexpected recovery loads.	The rover would no longer be axially fixed to the ROCS and it would fall out of the open end of the payload bay, becoming a risk to team members or spectators. The payload may sustain extensive damage upon landing, preventing it from performing as intended,	1C	A unique deployment signal will be sent by a team member after gaining RSO permission. After the unique signal is received and confirmed, the gyroscope will check that the payload bay is appropriately oriented with respect to vertical, the RLM will unlock. The	Team derived requirement DTS-5 will demonstrate the unique deployment signal reception and requirement CES-1 will test the accuracy of the gyroscope measurement. Requirement RLM-2 will demonstrate the RLM ability to keep the rover fixed in a as integrated locked state.DTS5CES1reqRLM2DTS5CES1reqRLM2	1D

		causing a failed payload mission.		RLM is in the locked configuration by default.		
ROCS socket head cap screws shear.	1. Bearing misalignment causes uneven load sharing across socket head cap screws 2. Unexpected take off loads 3. Unexpected main parachute opening force	ROCS is unable to properly orient the rover for deployment, causing gyroscopic measurements to prevent the release of the RLM. The rover would not be able to exit the airframe, leading to a failed payload mission.	2C	20 socket head cap screws will be used to properly align and secure the ROCS to the payload bay. The screws will share the loads that are experienced during flight.	The strength of the socket head cap screws will be tested by a successful full-scale launch per requirement ROCS-4.ROCS4reqROCS4req	2E
Obstructed rover path.	Field debris, launch vehicle, or rough terrain prevent the rover from being able to drive in a straight line.	The rover will not be able to drive 5 feet away from the vehicle resulting in a failed payload mission.	2B	The OAS will select the least obstructed path within the 156° field of view and the RDS will be designed to transverse different terrains and inclines of at least 20 degrees from horizontal.	Team derived OAS requirements, requirement CES-5, and requirement CES-6 will respectively test and demonstrate the selection of the least obstructed path.oas1CES5reqCES6reqgenOASCES5reqCES6req	2D
SAS panel support arms are not able to fully deploy.	Panel support arm(s) or tower assembly are damaged by contacting the airframe during flight or contacting launch field debris following rover deployment.	Rover is unable to deploy solar panels, leading to a failed payload mission.	2C	The panel support arms will be locked in a stowed position until the rover reaches its final destination. The deployed panel support arms were designed to fit inside the footprint of the RDS to avoid contact with debris at any point during panel deployment.	Requirement SAS-1 and requirement SAS-4 will verify complete SAS tower actuation from the stowed configuration through inspection and demonstration. Actuation will also be checked in the payload launch procedure checklist.SAS4	2E
Rover drive belt becomes misaligned.	The passive pulley bearings were inaccurately manufactured with a sloped surface or the pulley bearings were improperly mounted. Large amounts of friction from terrain may pull the drive belt away from the RBS.	Drive belt begins to walk off or even fall off the RDS. They payload may not be able to drive 5 feet if one or both drive belts are lost, leading to a failed payload mission.	2B	The passive pulleys were designed to maintain tread alignment with the addition of lips along each edge. The rear drive pulleys have taller lips that extend past the top of the tread.	Team derived requirement RDS-4 will demonstrate the proper alignment and traction required to transverse over various terrains.RDS4RDS4	2D

Batteries are not fully charged.	Batteries were installed prior to full charge, lose charge during assembly or launch setup, or are impacted and damaged during flight.	Insufficient power to motor driver and control board, leaving the rover locked to the RBS unable to deploy.	2B	Voltage indicators will be used to ensure full charge before installation and final assembly. The batteries will be contained in a mount inside the rover body to avoid damage.	Launch procedures will require the batteries to be checked prior to integration. The Payload batteries will be verified secure through team derived requirement RBS-2. Requirement CES-8 will test controller battery and requirement CES-9 will test motor battery.RBS2CES8reqCES9reqRBS2CES8reqCES9req	2E
Electrostatic discharge to sensor or control electronics.	Electrostatic build up on team member.	Shorts and potential component failure.	2D	Grounding mats and wrist straps must be used when testing electronics.	Test procedures, like that required for team derived requirement OAS-2, all team derived CES requirements, and SOW 4.5.3 verification, require the use of grounding mats and wrist bands. Payload electronics test procedures will require the use of grounding mats and wrist bands.OAS2reqCES1reqSOWreq_CES_Autonomous_ControlOAS2reqCES1reqSOWreq	2E

Table 81: Payload Equipment Hazard Risk Assessment.

9.2 Vehicle Equipment Hazard Risk Assessment

Hazard	Cause	Effect	RBM	Mitigation	Verifications	RWM
Rocket drop (INERT).	Mishandling of the rocket during transportation or rocket supports were not used to hold the rocket horizontally.	Damage to fins and electrical components if installed. There may be minimal damage and scratches to vehicle airframe.	2C	The rocket has been designed to be durable to survive loads encountered during flight and upon landing. Careful handling will be practiced while transporting the rocket and storing the rocket with custom made PVC rocket supports.	Vehicle Safety Checklist requires airframe bays to be placed on rocket supports during vehicle inspection and assembly. RocketStandRocketStand	2E
Rocket drop (LIVE).	Mishandling of the rocket during transportation or rocket supports were not used to hold the rocket horizontally.	If charges do not detonate, damage to fins and electrical components if installed. There may be minimal damage and scratches to vehicle airframe. If charges go off, there would be a serious safety threat to personnel in the area and possibly significant damage to the rocket.	1C	The rocket has been designed to endure all loads encountered during flight and upon landing. Careful handling should be practiced while transporting the rocket.	Vehicle Safety Checklist requires bays to be placed on rocket supports during vehicle assembly. The vehicle launch procedures require 3 identified team members to transport the live rocket to the launch pad.RocketStandthreecarriersRocketStandthreecarriers	1E
Black powder charges go off prematurely.	The altimeters send a false reading or an open flame sets off	A serious safety threat to personnel in the area and possibly	1C	All electronics will be kept in their OFF state until the latest time	Vehicle Safety Checklist requires altimeters remain OFF until the vehicle is upright on the launch pad and that avionics are properly shielded. Vehicle Safety Checklist also restrict black powder	1E

	the charge or avionics are not properly shielded.	significant damage to the rocket could result..		they can be enabled. Altimeters are not to be armed until the rocket is in the launch pad. Open flames and other heat sources are prohibited in the area.	charges or charge preparation less than 25 feet of an open flame.altimeteraccessavionicshieldingbp25_feetscrewswitchesoffavionicshieldingbp25_feet	
Seized nut or bolt due to galling or cross threading.	Repetitive uninstalling and reinstalling of parts made of materials prone to galling or excessive friction caused by poor alignment	Component becomes unusable, potentially ruining expensive, custom machined parts. Rework may be required and would depend on the location of the affected component.	2D	If there is resistance to proper alignment, the sections will not be forced together to fit. The cause for the poor fit will be evaluated and corrected.	Vehicle Safety Checklist require all threads to be checked and evaluated for damage prior to launch. Threads will also be evaluated following launch according to the Post Flight Inspection Safety Checklist. Vehicle launch procedures require easy fit and alignment of screws and bolts without excess force or friction.threadDamagethreadDamageeasyalignthreadDamagegallingeasyalign	2E
Screw switches to arm electronics are inaccessible.	Avionics sleds are not properly aligned with access holes.	The electronics will not be able to be armed on the pad or will require additional access holes to be cut.	1D	Proper altimeter orientation will be identified on the airframe.	Vehicle Safety Checklist will require all altimeter access holes to be properly aligned before the vehicle is cleared to leave for the launch pad.altimeteraccessaltimeteraccess	1E
Bays are improperly aligned.	Bay symmetry makes it difficult to identify how sections align.	Shear pins may not fit or thread into holes easily, causing them to experience more loading than intended, possibly failing during flight	1C	Witness triangles of varying sizes and shapes will be used to allow for the rocket to align in one orientation.	Vehicle Safety Checklist require easy fit and alignment of screws and bolts without excess force or friction. easyaligneasyalign	1E
Lost GPS signal.	GPS unit damage or power loss.	Potential to lose location of the rocket temporarily or permanently.	2D	GPS units shall be charged prior to the day of launch and will be securely mounted inside the vehicle.	Vehicle Safety Checklist require GPS units to be fully charged prior to packing and secure mounting.ChargeGPSsturdygpsChargeGPSsturdygps	2E
Unstable flight.	Shifted center of gravity due to changes in component design and weight.	Rocket does not fly in anticipated path, possibly causing it to follow a ballistic path endangering all team members and launch spectators.	1B	Ballast will be added if components like the payload are missing from the rocket to maintain calculated center of gravity and stability.	OpenRocket Flight Simulations have been run to identify the centers of pressure and gravity. Vehicle launch procedures will require ballast to be added to maintain the locations in accordance with SOW 2.19.2.1 and 2.12.2.1.1.CPCGCPCG	1E
Fin flutter.	Inadequate material strength or damage caused by previous flight.	Fins detach from vehicle causing the rocket to become unstable and fly in an unanticipated path. The rocket could CATO, follow a	1B	Fin flutter calculations and simulations will be conducted with fins made of carbon fiber.	Fin flutter calculations and AeroFinSim analysis shows that the carbon fiber fins will not be impacted by fin flutter. The Vehicle Safety Checklist requires inspection of fins prior to launch and Post Flight Inspection Safety Checklist requires inspection of fins following launch._AeroFinSim_Software_AnalysisLVInspBLLVInspPL	1E

		ballistic path, and endanger all team members and launch spectators.				
Important component left at build site.	Packing list omitted an item.	Temporarily delayed launch, possible risking full-scale launch completion	1C	Packing lists will be thorough and will include all components needed to assemble the vehicle as well as those needed to make small repairs. All sub-team leads will agree to packing lists and add items as necessary. Additional fasteners are brought to the launch site for backup.	Vehicle Safety Checklist detail general equipment and supplies that are needed for each sub-team. Launch checklists must be signed by two members as being completed prior to departing for launch.GenEquipGenSignaturesGenEquipGenSignatures	1E
Zippering.	Recover lines catch and tear through airframe.	Damage to edges of airframe, reducing the flight and/or airframe stability.	2C	The airframe will be made of wound carbon fiber, a strong material. The airframe will be inspected after each recovery to identify any signs of zippering.	Post Flight Inspection Safety Checklist requires thorough inspection of the vehicle following each recovery.LVInspPLLVInspPL	2D
Carbon fiber delamination.	Excessive heat or fire.	Substantial weakening of the airframe.	1D	The launch vehicle will be stored away from all heating elements. In the event of fire, the entire vehicle will be inspected for damages.	Post Flight Inspection Safety Checklist requires all carbon fiber components to be inspected for damage after recovery.carboncheckcarboncheck	1E
Damage to airframe structure.	Flawed recovery or impact with field debris during recovery.	Substantial weakening of the airframe, possibly leading to buckling or shearing of airframe during next flight.	1C	The vehicle will be made of strong carbon fiber and it will be inspected following each flight.	Post Flight Inspection Safety Checklist requires thorough inspection after each launch and recovery.LVInspPLLVInspPL	1E
Unexpected friction between vehicle and launch rail.	Misalignment or ill-fitting launch buttons.	Unstable flight or CATO.	1D	The airframe must slide onto the launch rail without any resistance. If section of airframe does not slide freely up and down the entire length of the launch rail, the vehicle	Launch Pad Safety Checklist requires the airframe to slide freely up and down the entire length of the launch rail prior to launch.freerail	1E

				will not be allowed to launch.		

Table 82: Vehicle Equipment Hazard Risk Assessment

9.3 Propulsion Equipment Hazard Risk Assessment

Hazard	Cause	Effect	RBM	Mitigation	Verifications	RWM
Catastrophe at take-off (CATO).	Defective or improperly packed motor, defect in the motor casing, or improper cleaning of motor casing following launch.	Extensive damage or delamination of carbon fiber airframe, bulk plates may fail, recovery may not deploy or may not fully deploy to be effective.	1C	2 new motor casings were purchased for the season, eliminating possible damage from previous launches. The motor will only be packed by certified members and all motors will be purchased from Chris' Rocket Supplies, a certified provider.	Vehicle Safety Checklist requires the Level 2 certified vehicle lead to pack the motor in strict accordance with the manufacturer's instructions.l2cert	1D
Propellant does not ignite.	Incorrect motor packing or igniter installation.	Launch must be delayed or postponed. The vehicle must be removed from the launch pad and a new motor would have to be assembled and installed.	2D	The motor will only be packed by certified members and the igniter has specific installation steps.	Vehicle Safety Checklist requires the Level 2 certified vehicle lead to pack the motor, igniter installation steps, and the Troubleshooting Safety Checklist details troubleshooting for a motor that does not ignite.l2certigniterinstallnoignite	2E
Premature propellant burnout.	Incorrect motor packing or faulty motor grain.	The vehicle may not reach the intended altitude.	2D	The motor will only be packed by certified members and all motors will be purchased from Chris' Rocket Supplies, a certified provider. Because the vehicle will overshoot the intended apogee and will be slowed down with the VDS, a slightly premature burnout may still allow the vehicle to reach the intended altitude.	Vehicle Safety Checklist requires the Level 2 certified vehicle lead to pack the motor. The VDS simulation has shown the system's ability to reduce the vehicle's apogee.l2cert_VDS_Simulation	2E
Improper assembly of motor.	Incorrect order of motor grain installation, casing threads or O-rings were not greased as instructed by the motor manufacturer.	The motor may misfire or hang fire or could result in a CATO.	1D	The motor will only be packed by certified members with strict adherence to the manufacturer's instructions.	Vehicle Safety Checklist requires the Level 2 certified vehicle lead to pack the motor.l2cert	1E
Motor retainer fails.	Excessive opening forces experienced during recovery.	The motor is no longer held in the vehicle and could fall near team members or launch spectators.	1C	Analysis shows the motor retainer has a factor of safety of 3.65.	Motor retainer FEA was conducted to show the integrity of the design. Vehicle Safety Checklist requires inspection of motor casing following post launch cleaning.motorclean	1E
Centering ring epoxy failure.	Excessive opening forces or insufficient epoxy levels.	Could result in excessive loads on the remaining centering rings. If all centering reals fail, the motor would shoot up the center of the vehicle.	1D	There are 3 centering rings in the vehicle design for redundancy. Each ring is rated to carry the loads with a factor of safety greater than 2.0.	FEA was conducted on the Centering Rings. Vehicle Safety Checklist requires epoxy joint inspection following every launch.epoxyjoint	1E
Propellant burns through casing.	Incorrect motor packing, motor casing threads or O-rings were not greased as instructed by the motor manufacturer, or motor casing defects.	The propellant could catch the airframe epoxy on fire, causing structural carbon fiber to delaminate, severely weakening the strength of the vehicle and causing a CATO. The path of the vehicle could also be significantly affected due to abnormal thrust.	1D	2 new motor casings were purchased for the season, eliminating possible damage from previous launches. The motor will only be packed by certified members with strict adherence to the manufacturer's instructions. The casing will also be inspected following launch to identify any damage.	Vehicle Safety Checklist requires the Level 2 certified vehicle lead to pack the motor in strict accordance with the manufacturer's instructions. Post Flight Inspection Safety Checklist requires inspection of motor casing following post launch cleaning.l2certmotorclean	1E

Motor is misaligned.	Centering rings were epoxied to the motor mount tube at an angle or too close together to eliminate angled alignment.	Forces transferred to the centering rings will not be shared as expected, possibly causing a ring to yield, allowing the motor to shoot up the center of the rocket.	1D	3 centering rings will be epoxied to the motor mount tube with the use of a laser cut jig to ensure proper alignment, eliminating the possibility for all rings to fail. Each ring is designed to carry the takeoff loads individually with a minimum factor of safety of 2.0. The 3 centering rings are also spaced evenly along the tube to further ensure proper alignment.	Post Flight Inspection Safety Checklist requires inspection of motor casing following post launch cleaning.motorclean	1E
Motor igniter fails.	Incorrect igniter installation.	Launch must be delayed and the vehicle must be removed from the launch pad.	4C	The motor will only be packed by certified members and the igniter has specific installation steps.	Vehicle Safety Checklist requires the the Level 2 certified vehicle lead to pack the motor, igniter installation steps. Troubleshooting Safety Checklist details troubleshooting for a motor that does not ignite.l2certigniterinstallnoignite	4E

Table 83: Propulsion Equipment Hazard Risk Assessment

9.4 Recovery Equipment Hazard Risk Assessment

Hazard	Cause	Effect	RBM	Mitigation	Verifications	RWM
The vehicle does not separate between the booster and payload bays or between the payload bay and the nosecone.	There was insufficient pressure generated by the black powder charge to shear the pins or the fit between the couplers was too tight.	Recovery sequence will be unsuccessful, causing the rocket to follow a ballistic path, endangering all team members and launch spectators.	1C	The required pressure will be achieved by using rocket epoxy to seal bulk plates and by using accurate dimensions to calculate black powder amounts. Couplers will be sanded down to give an acceptable seal.	Vehicle separation tests will be conducted as described in Launch Vehicle Test Campaign to verify all sections separate successfully.	1D
Altimeter or e-match failure.	The altimeter or e-match may have damaged component.	If altimeter or e-match fails, the rocket will not separate causing recovery to not deploy. The rocket would follow a ballistic path and endanger all team members and launch spectators.	1C	Multiple and e-matches are included in systems for redundancy. Altimeters will be securely installed to prevent damage.	Vehicle Safety Checklist requires avionics to be securely mounted.altimeterdamage	1E
Recovery does not exit airframe.	Parachutes, shock cord, or shroud lines get caught on a component on the inside of the airframe.	Parachutes or lines may be torn. Recovery sequence will be unsuccessful, causing the rocket to follow a ballistic path, endangering all team members and launch spectators.	1B	internal airframe components will be well shielded to keep recovery materials from being caught on them.	Recovery Safety Checklist requires recovery bays to be inspected for exposed carbon fiber shards and corners.carbonshards	1D
Parachute gets stuck in the deployment bag.	The shock cord or shroud lines could tangle during recovery preparations or they could be wrapped around the parachute prior to packing the deployment bag.	Parachutes or lines may be torn. Recovery sequence will be unsuccessful, causing the rocket to follow a ballistic path, endangering all team members and launch spectators.	1C	Deployment bags are specially made for each parachute and all recovery team members will be taught how to properly pack them.	Recovery Safety Checklist requires the parachute to be easily pulled from the deployment bag and explicitly state to not wrap the cords around the parachute prior to packing it into the deployment bag.loosebagtightlines	1D

Rocket descends too quickly.	Parachute is improperly sized.	The rocket will fall with a greater kinetic energy than designed for, possibly causing damage to the vehicle or onboard systems and causing the rocket to follow a ballistic path, endangering all team members and launch spectators.	2B	The main and drogue parachute designs were each carefully selected and sized to safely recover their sections of the rocket while meeting the kinetic energy limit.	The parachute selection will be tested during Full Scale Flight Tests_Control_Vehicle_Flight	2D
Rocket descends too slowly.	Parachute is improperly sized.	The rocket will drift farther than calculated, potentially exiting the launch field and the allowed range for rover deployment. The vehicle may also face unexpected environmental obstacles like busy roads or water.	2B	The main and drogue parachute designs were each carefully selected and sized to safely recover their sections of the rocket without exiting the allowed drift radius.	The parachute selection will be tested during Full Scale Flight Tests._Control_Vehicle_Flight	2D
Parachute has a tear or ripped seam.	Parachute is less effective or completely ineffective depending on the severity of the damage.	The rocket falls with a greater kinetic energy than designed for, causing components of the rocket to be damaged.	2C	The parachutes will be made of rip stop nylon to prevent tears from propagating easily if they form. In the incident that a small tear occurs during flight, the parachute will not completely fail.	Post Flight Inspection Safety Checklist requires thorough inspection of parachute canopies by 2 recovery team members after each launch. RecoverPostFlight	2D
Parachute or rigging burns.	Parachute is less effective or completely ineffective depending on the severity of the damage.	The rocket falls with a greater kinetic energy than designed for, causing components of the rocket to be damaged.	2B	Parachutes will all be packed in custom-made fire retardant Nomex deployment bags. All lines will be treated with fire retardant spray.	Recovery Safety Checklist requires careful packing of parachutes in deployment bags and treatment of exposed lines with fire retardant spray. NoBurn	2E
Entire recovery system separates from the rocket.	The bulkhead breaks out of the rocket, the U-bolt parachute connection breaks, or the U-bolt itself breaks.	The vehicle will fall without parachute and will follow a ballistic path and endanger all team members and launch spectators.	1B	The bulk plate factors of safety will be evaluated through FEA and only forged U-bolts will be used to connect parachutes to bulk plates. Parachute lines will be thoroughly inspected before and after flight.	FEA was conducted on the Bulkplates verify the strength of the bulk plates as well as the bulk plate test procedure. Recovery Safety Checklist requires inspection of parachute connection points and all lines prior to packing. No structural failure will be caused by opening forces as dictated by Launch Vehicle Requirements.beforechute	1E
Lines in parachutes parachute become tangled during deployment.	Incorrect packing or asymmetry in parachute construction may cause rotation of nosecone or deployment bags that could wrap and choke parachutes.	The drogue parachute could be choked by the tangle, reducing drag force which would prevent the main parachute from opening. The main parachute may tangle due to incorrect packing. In both cases, the rocket would then fall with a greater kinetic energy than designed for, possibly causing damage to the vehicle or onboard systems and causing the rocket to follow a ballistic path, endangering all team members and launch spectators.	1B	Parachute panels will be laser cut to ensure size, accuracy, and symmetry. Main parachutes will have shock cord daisy chained so the cord stays organized until it is pulled by the opening force. Custom deployment bags will be used to further prevent tangling.	Launch Vehicle Requirements will demonstrate drogue symmetry will be tested in drop tests as listed in recovery testing. Recovery Safety Checklist describes the packing process. The deployment bags will be tested as outlined in separation testing.	1D

Premature main parachute deployment.	The altimeters misfires or the ARRD fails due to damage or incorrect assembly.	The rocket will drift farther than calculated, potentially exiting the launch field and the allowed range for rover deployment. The vehicle may also face unexpected environmental obstacles like busy roads or water.	2C	The altimeter and ARRD will be prepared by experienced members that are familiar with the setup processed for the components.	Recovery launch procedures as well as Launch Vehicle Requirements require ARRD load testing and inspection of ARRD and altimeters in post flight inspections to ensure proper use and maintenance of components. Full scale flight tests will verify correct timing of recovery events.	2E

Table 84: Recovery Equipment Hazard Risk Assessment

9.5 VDS Equipment Hazard Risk Assessment

Hazard	Cause	Effect	RBM	Mitigation	Verifications	RWM
7.4 v battery death.	Improper charging.	If the battery dies prior to launch, the drag blades would not potentially actuate during flight. If the battery dies during ascent the rocket will not reach the intended height	2A	The battery will be charged throughout integration up until the rocket leaves for the launch rail	Variable Drag System (VDS) Safety Checklist requires that the installation of all batteries be checked to ensure they are fully charged. All batteries will go through proper testing to ensure they can last the anticipated time on the pad with a factor of safety of 2. **Error! Reference source not found.**0 .	2D
Time variable overflow.	Extended run time.	VDS drag blazes could potentially actuate on rail, leading to increased rail friction, rail button shear and lower than expected exit velocity	1C	If time on rail is excessive, VDS can be restarted removing the issue of the variable overflow	Software testing will be done to ensure that the VDS runs error free and can operate for extended period of times without issues **Error! Reference source not found.**	1D
VDS VN-100 or other sensors are affected by transmitting antenna.	Sensor is not properly shielded from transmitting antenna.	VDS drag blazes could potentially actuate on rail, leading to increased rail friction, rail button shear and lower than expected exit velocity	1C	The VN-100 is no longer being used in the launch vehicle.	N/A	N/A
11.1v battery death.	Improper charging.	If the battery dies prior to launch, the drag blades would not potentially actuate during flight. If the battery dies during ascent the rocket will not reach the intended height	2A	The battery will be charged throughout integration up until the rocket leaves for the launch rail. VDS was designed to have battery plugs accessible after installation into vehicle	Variable Drag System (VDS) Safety Checklist requires all batteries have power level checked prior to installation to ensure they are fully charged. All batteries will go through proper testing to ensure they can last the anticipated time on the pad with a factor of safety of 2.	2D
Broken gearbox.	VDS blades remained actuated during recovery.	Permanent damage to VDS assembly and hazard to crowd if recovery is unsuccessful .	3B	VDS is programmed to retract blades after apogee. The team is currently investigating recovery force reduction.	Through flight testing and opening force calculations the VDS will be testing to ensure the gearbox can handle the induced loads **Error! Reference source not found.**	3E
Sensor error due to DC motor feedback.	improperly isolated circuits.	VDS actuates too early, launch vehicle undershoots altitude resulting in mission failure.	3B	New sensors have a built-in sensor filter to eliminate noise and signal line noise from motor encoder reduced.	Built in Kalman filter will be tested to ensure that all signal noise is properly filtered **Error! Reference source not found.**	3D
Pressure phenomenon from open-ended propulsion bay causes altitude error.	Vacuum formed under propulsion bay.	VDS actuates too early, launch vehicle undershoots altitude resulting in mission failure.	3C	Electronics bay will be airtight from the actuation bay to prevent possible interference.	Both research and data analysis have found this to be a pressure anomaly with a single sensor. Proper sensor inspection before and after flight will prevent damaged sensors from providing faulty data **Error! Reference source not found.**	3D

slow speed SD card causes delay in data reading.	Installed the wrong SD card.	VDS fails to respond to accurate real-time data resulting in imprecise system function and higher altitude than anticipated.	2B	This will be mitigated through pre-flight check lists.	All SD cards purchased will have a read/write speed greater than 300mb/s to ensure that slow SD card problems don't arise **Error! Reference source not found.**	2E
Sharp blade edges.	Burs may result from blade manufacturing.	minor injuries to personnel.	3A	Edges will be deburred prior to VDS assembly.	All blades will be properly sanded to ensure that burs are removed and the likelihood of injury is mitigated. **Error! Reference source not found.**	3D

Table 85: VDS Equipment Hazard Risk Assessment

9.6 Personnel Safety Hazard Risk Assessment

Hazard	Cause	Effect	RBM	Mitigation	Verification	RWM
B						
Prolonged exposure to the sun or intense cold.	Lack of awareness or preparation by team members.	Possibly severe sun burns, frost bite, or hypothermia.	3C	Team members will be informed of the launch location as early as possible to prepare for the location's weather conditions. The pre-launch safety briefing will cover the weather conditions to ensure that the winds and skies will be acceptable for launching. Launch checklists will require water and sunscreen to be packed.	The required safety briefing prior to launch covers the weather conditions expected at the launch site. Sunscreen is listed on the General Safety checklist. 7.2.1	3D
Dangerous driving to test site.	Lack of sleep due to last minute preparation.	Possibly serious trauma to team members in the vehicle or extensive damage to equipment in the vehicle.	2B	Team members must get a minimum of 7 hours of sleep, as suggested by the CDC, before driving to a launch.	The required safety briefing prior to launch requires that drivers are designated in advance to eliminate sleep deprivation and exhaustion. 7.2.1	2D
Black powder explosion or premature ignition while handling.	Incorrect charge assembly or storage that allows the charge to be exposed to open flames or sparks.	Mild to severe cuts and burns or extreme trauma if a team member is holding the charge.	1C	Black powder charges will only be made outdoors with two team members present and they will be properly stored in the team's clearly labeled explosive's box.	The Black Powder Charge Preparation section of the Vehicle launch procedures require careful preparation and storage of all charges. 7.2.2	1E
Rotating parts and tools that move automatically.	Long hair/jewelry or loose clothing were not tied back or removed prior to working with tools/machines.	Team member could be caught or pulled into the machine, causing serious injury or death.	1B	The Engineering Garage rules require all hair and loose clothing to be tied back and jewelry to be removed prior to operation of machines.	All team members signed the Safety Manual and agreed to follow all rules of the Engineering Garage. They also acknowledged and agreed to the penalty of losing access to the Engineering Garage and team membership. 6.2safetyagreementform	1D
Contact with flying debris from machining operations.	Lack of PPE used while machining or incorrect use of machines like closing not closing CNC doors or forgetting to remove the lathe jaw chuck.	Mild to severe cuts, or broken bones, or blunt trauma or death.	1C	Members are not certified on machines until they run machines with careful safety precautions. Two members are required to be in the machining cage at all times to ensure that safety precautions are followed.	All team members signed the Safety Manual and agreed to not use tools or equipment they were not trained on. They also agreed to the penalty of losing access to the Engineering Garage and team membership. 6.2trainedtool	1D
Cuts from handheld power tools like saws, drills, or Dremel.	Improper training on power tools or lack of attention given to work.	Mild to severe cuts or burns to personnel.	2B	Individuals must be trained on the tool being used. Those not trained should not attempt to learn on their own and should find a trained individual to instruct them.	All team members signed the Safety Manual and agreed to not use tools or equipment they were not trained on. They also agreed to the penalty of losing access to the	2C

					Engineering Garage and team membership. 6.2trainedtool	
Cuts from heavy/automatic machining equipment like lathes, electric saws, or CNCs.	Lack of formal training or attention to work.	Severe cuts to personnel, damage to vehicle component or equipment.	2B	Individuals must be trained on the tool being used. Those not trained should not attempt to learn on their own and should find a trained individual to instruct them.	All team members signed the Safety Manual and agreed to not use tools or equipment they were not trained on. They also agreed to the penalty of losing access to the Engineering Garage and team membership. 6.2trainedtool	2D
Electric shock.	Untrained use of welding equipment.	Minor burns to severe nervous system damage or death.	1C	Individuals must be trained on the tool being used. Those not trained should not attempt to learn on their own and should find a trained individual to instruct them.	All team members signed the Safety Manual and agreed to not use tools or equipment they were not trained on. They also agreed to the penalty of losing access to the Engineering Garage and team membership. 6.2trainedtool	1D
Explosive black powder residue or spill.	Leak in black powder charge or dropped powder bottle during charge making.	Contamination of delicate parts that could be damaged if the residue or spill were to ignite, causing mild to severe burns.	1C	All team members will make black powder charges in accordance with launch procedures. Only non-sparking and non-static producing tools should be used to clean black powder spills or residue and the charges will all be made outside.	Launch testing procedures detail charge preparation and required caution with cleanup. 7.2.2bpspill	1E
Inhalation of carbon fibers or particulate matter	Improper use of PPE when sanding or grinding or improper cleanup of work surfaces covered with particulate matter, causing them to become airborne.	Mild to severe pain or asthma from prolonged exposure.	3B	The Engineering Garage requires work tables to be covered with cardboard for protection, making it easy to clean up shavings completely. Safety glasses and respirators will be used by the team when carbon fiber or fiber glass are cut.	All team members received a Safety Briefing prior to PDR and signing the Team Safety Agreement. This agreement was required to participate on the team and detailed the PPE required when cutting and sanding carbon fiber. 6.2safetyagreementform	3D
Exposure to chemicals.	Lack of PPE, chemical splash or fumes when from chemical components.	Mild to severe burns on skin or eyes, lung damage or asthma aggravation.	2B	MSDS documents will be readily available at all times and will be thoroughly reviewed prior to working with any chemical. All chemical containers will be marked to identify appropriate precautions that need to be taken, including required safety glasses, nitrile gloves, and working in well-ventilated areas, when working with hazardous materials.	All team members received a Safety Briefing prior to FRR and signing the Team Safety Agreement. This agreement was required to participate on the team and detailed the emergency equipment, like eyewash stations, and permanent location of all team MSDS that list the hazards of each chemical used by the team. 6.2safetyagreementform	2D
High decibel levels from machinery.	Use of heavy machinery or power tools for extended periods of time.	Prolonged exposure could lead to permanent ringing in the ear, or deafness.	2C	Ear plugs are readily available throughout the Engineering Garage and should be used when operating tools or machines for longer than 30 minutes.	All team members received an official Safety Briefing that covered the importance of ear protection prior to PDR and signing the signed the team Safety Agreement Form that they understood all included topics. 6.2safetyagreementform	2D
Physical contact with hot surfaces.	Team member isn't attentive or a component like a hot glue gun or heat gun is left plugged in.	Mild to severe burns on skin.	3C	All heated elements will be used on a designated table, so members know where to expect heated elements.	The labeled sign identified above in the Safety Manual contents section is required to be used by the Safety Manual. 6.2	3D

Shavings or particles imbedded in skin or eyes.	Improper use of PPE when sanding or grinding or improper clean-up of work surfaces.	Mild to severe rash and pain.	3B	Long sleeves should be worn at all times when sanding or grinding materials and safety glasses are required when working with any power tools. Proper cleanup of all debris that results from sanding and cutting.	All team members received an official Safety Briefing that covered the importance of PPE requirement documentation included in MSDS prior to PDR. All team members signed the Safety Agreement Form confirming that they understood all included topics. 6.2safetyagreementform	3D
Dangerous fumes produced while soldering.	The use of leaded solder or resting of soldering iron on plastic.	Team members become sick due to inhalation of toxic fumes, with prolonged exposure possibly leading to asthma.	2C	The team will use well ventilated areas while soldering and automatic ceiling fans will remain on while soldering. Team members must be trained and certified to use the Engineering Garage soldering equipment that includes iron coils/stands.	The certification required by the Engineering Garage and the Safety Manual teaches members about the fumes generated by soldering and how to properly clean and store the soldering iron. 6.2soldering	2D
Potential burns while soldering.	Lack of attention or untrained use of soldering iron.	Minor burns on hands or fingers.	2C	Team members must be trained and certified to use the Engineering Garage soldering equipment that includes iron coils/stands.	The required certification teaches members about the fumes generated by soldering and how to properly clean and store the soldering iron. soldering	2D
Failed black powder test.	Too much black powder was used, causing the structure to fail or damage to the tube was not noticed prior to the charge test.	The tube being testing could be ruptured or thrown by the charge, causing debris to possibly fly toward team members, causing damage to the vehicle or onboard systems and causing the rocket to follow a ballistic path, endangering all team members and launch spectators.	1C	All team members must wear safety glasses and stand 15 feet away from the charge during all testing procedures that require black powder. All charges will be made outside with two members present immediately prior to black powder testing. PPE will be required for all preparations incolving black poweder.	The Safety Officer or sub-team lead will be present at each black powder space to make sure that all safety precautions are followed.6.2	1D
Intense light from welding.	Improper use of PPE while welding.	Injury to eyesight may occur. May result in loss of eyesight at an early age if welding without proper PPE over long periods of time.	2A	A welding helmet, fitted with a filter shade must be worn at all times while welding.	Safety cards are placed at all equipment that indicate the PPE required for safe operation. 6.2	2E
Radiation and burns from welding.	Improper use of PPE while welding.	Mild to severe burns to skin.	2C	A welding helmet, heat resistant jacket and gloves, and close toed shoes must be worn at all times while welding.	Safety cards are placed at all equipment that indicate the PPE required for safe operation. 6.2	2E
Carbon fiber tow splinters.	Carbon fiber strands splinter when cut or stretched, becoming loose.	Splinters can imbed in the skin or eyes.	3B	Team members are required to wear cut resistant gloves, long sleeves, and safety glasses when handling carbon fiber.	All team members received an official Safety Briefing that covered the importance of ear protection prior to PDR and signing the signed the team Safety Agreement Form that they understood all included topics. 6.2safetyagreementform	3D
Overcurrent from power source while testing.	Failure to correctly regulate power to circuits during testing or failure to identify a short.	Team members could suffer electrical shocks which could cause burns to heart arrhythmia.	2D	The circuits will be analyzed before they are powered to ensure they don't pull too much power. The circuits will be checked for shorts prior to being powered. Power supplies will also be set to the correct levels.	All circuits will be checked for continuity to identify the presence of shorts.7.2.4	2E
Cutting fluid contacts skin or eyes.	Use cutting fluid when machining metals.	The fluid contains known carcinogens that could lead to serious health hazards later in life.	2C	Face shields and long sleeves must be worn when using cutting fluid to prevent the fluid from splashing onto skin.	All team members received an official Safety Briefing that covered the importance of chemical risks and PPE requirement documentation included in MSDS prior to	2E

					PDR. All team members signed the Safety Agreement Form confirming that they understood all included topics. 6.2safetyagreementform	
Use of white lithium grease.	Use in installing motor into casing on threads and O-ring seals.	Irritation to skin, eyes, and lungs from contact or specific inhalation of fumes.	3C	Nitrile gloves and safety glasses are to be worn when applying grease. When applying grease, it should be done in a well-ventilated area to avoid inhaling fumes.	All team members received an official Safety Briefing that covered the importance of chemical risks and PPE requirement documentation included in MSDS prior to PDR. All team members signed the Safety Agreement Form confirming that they understood all included topics. 6.2safetyagreementform	3D

Table 86: Personnel Safety Hazard Risk Assessment

9.7 Environmental Hazards to Rocket Risk Assessment

Hazard	Cause	Effect	RBM	Mitigation	Verifications	RWM
Unlevel launch pad.	Failing to properly level the launch pad or sinking of the launch due to excessively soft ground.	Unanticipated vehicle trajectory.	2B	Launch pad will be leveled directly prior to the launch vehicle being installed on it	Both the vehicle leads and either the co-captain or safety officer will sign off on the leveling of the launch pad section of launch procedures prior to the ignition of the launch vehicle motor 7.2.6	2D
Difficulty assembling vehicle components in field.	Excessive changes in humidity and or temperature causing unequal swelling or shrinking of components.	Hole misalignments and new stresses are induced due to preloading of materials resulting in increased separation friction and possibility of failed separations.	1C	All fits will be verified prior to leaving for the field, separations will be tested in similar weather conditions and sand paper will be brought to the field to make finite adjustments to ensure proper fits.	Vehicle Safety Checklist requires a signature of both the vehicle lead and either a co-captain or the safety officer on the launch procedures to ensure all steps are properly done and risks have been mitigated.	2E
Rover mission halted due to large unanticipated debris.	Large debris in front of the rover’s path.	The rover's path is blocked halting the mission and resulting in a failure in the payload mission.	1C	An onboard lidar sensor scans for debris in front of the rover and will scan for a clear path that the rover can take.	Lidar Requirement Verifications testing has ensured that the onboard system properly identifies obstacles and avoids them.	1D
Rover becomes stuck due to loose dirt mounds or mud.	Recent rain or tilling of the field results in pockets of mud or mounts of dirt that are difficult to gain traction on.	Difficult terrain will result in the wheels failing to gain traction and the rover getting stuck and ultimately failing to complete its mission of driving 5 ft.	1B	Substantial rover drive system testing will be done to simulate different terrains that the rover may encounter to ensure the rover can complete its mission on all terrains the rover may encounter.	9.7.1.1 *Rover drive system testing will ensure that the rover can surmount terrains you intend to encounter. Rover Performance Test*	1D
VDS, Recovery, or rover electronics damaged by environmental conditions.	High winds, rain and cold and hot temperatures	Electronics fail to function properly resulting in mission critical electronics failing..	1A	All electronics will be shielded from light precipitation and will be verified to operate under all anticipated operating temperatures. It will be ensured the rocket and payload do not operate under high winds and under amounts of heavy precipitation	All Avionics are covered with 3d printed sleds protecting them from light precipitation. Flight weather conditions will be verified prior to launch to prevent testing during high winds or heavy precipitation.	1E

Rocket Structure failure or launch pad fire.	Direct sunlight and high outside temperatures can result in high temperatures inside the rocket	Increased temperatures due to extended sunlight exposure and high temperatures results in overheating of batteries and leads to battery fire.	1B	Ensuring that the rocket is covered under a tent during assembly and that all batteries are stored inside insulated bags until needed.	Tents will be listed on the travel check list to ensure they are taken with and set up and all batteries will travel in insulated battery bags and remain there until needed in the assembly process. 7.2.1	1D
Parachute and rocket body damage.	Excessive winds and nearby trees and obstacles.	Recovery equipment being damaged and the rover unable to deploy due to not having ground to deploy onto.	3B	To mitigate these issues the team will not launch with winds exceeding 15mph and will ensure that each launch field adheres to proper launching distances stipulated in the NAR handbook.	A wind speed data logger will be brought to every launch and both the wind speed data logger speed and the local weather station's report of wind speeds will be recorded on the flight procedures by both captains before launch to ensure wind speeds are at an appropriate level along with a discussion with the range safety officer to ensure the rocket pad is at the appropriate distance away 7.2.1	3D
Ice buildup on launch vehicle resulting in sealing of vent holes.	Ice buildup results in pressure sensor holes being fully or partially closed off.	The change in the vent hole size results in failure to proper read altitudes resulting recovery failing to deploy at the proper altitude and the vehicle lands at higher than nominal speed.	1D	To mitigate a visual check of the vehicle will be done to ensure no ice buildup has occurred and that all vent holes are open and free of obstruction.	A visual inspection of the vehicle will be done by both the vehicle and the recovery lead to ensure ice has not accumulated and all vent holes are unobstructed. 7.2.2	1E

Table 87: Environmental Hazards to Rocket Risk Assessment

9.8 Rocket Hazards to Environment Risk Assessment

Hazard	Cause	Effect	RBM	Mitigation	Verifications	RWM
Trash from launch preparations left at launch field.	Lack of garbage receptacles at launch field.	Pollution to the environment and harm to crops grown on launch field.	2B	Garbage bags are included in the launch procedure checklists and	Launch procedures require the team to collect all trash and component scraps in the garbage bags required in General Preparations prior to leaving the field.	2D
Unsuccessful deployment of recovery systems.	Deployment charges failing to ignite, insufficient deployment charges or improper pressure readings.	Launch vehicle plummets to the earth at higher than nominal speed resulting in the launch vehicle getting damaged and debris is scattered around launch area	1B	Both separation charge calculations and separation tests will be done to ensure all sections separate properly	All black powder charges will be calculated then tested according to the Black Powder Charge Preparation section of the Vehicle Safety Checklist.	1D
Launch Pad Fire.	Launch pad fire caused by brush and dry grass catch fire following motor ignition.	Brush and dry grass around the launch pad igniting results in a wild fire in the local area surrounding the launch area, destroying local wildlife and habitats and creating extra pollution.	1B	to mitigate this no launch will happen within 100ft of any dry grass or brush and a fire extinguisher will be brought to every launch as a precautionary measure	Listed in launch procedures and in compliance with NAR regulations we will not launch within 100ft of brush or dry grass and according to General Materials and Safety Checklist a fire extinguisher will be checked and brought to every launch.	1E
Motor CATO.	Improper packing of a motor or motor defect.	Launch motor fires through launch vehicle, destroying it and scattering parts throughout launch field	1C	All motors will be packed by two certified team members including the vehicle lead	Following the packing of motors both packing members must sign the launch procedures under motor packing to verify the motor was packed properly as required in the Vehicle Safety Checklist	1D

Rocket part debris.	Rocket parts loosely secured or free floating inside the rocket body.	Failing to properly secure all rocket parts results in debris scattered throughout the launch field resulting in a potential hazard for local animals	2B	All rocket parts must be fully tethered to a recovered part of the vehicle while all tethering must be able to withstand opening forces	FEA has been completed and documented in sections Centering Rings, Bulkplates, Mechanical Hardware.Testing will be done to ensure all mounts are capable of withstanding launch and opening forces.	2E
Chemical contamination of local water sources.	Leaking batteries and other hazardous materials leaks into body of water the rocket lands in.	Leaking batteries contaminating local drinking water and making it hazardous to local animals	1B	All batteries will be inspected prior to installation into launch vehicle	Launch procedures requires visual inspection of all batteries and a sign off box to confirm this step has been complete 7.2.4	1D

Table 88: Rocket Hazards to Environment Risk Assessment.