Two-Stage, High-Altitude Rocket with Internal Skeleton Design Entered in Advance Category of 7th ESRA IREC

Samuel S. Bowman[1], Kevin J. Byrne[2], Allen Capatina[3], Aliki S. Loper-Leddy[4], and Joshua A. Van Schoyck[5]
California Polytechnic State University, San Luis Obispo, CA, 93407

A high-altitude, two-stage rocket was designed, built, and entered in the advanced category of the 7th Annual Experimental Sounding Rocket Association (ESRA) Intercollegiate Rocketry Engineering Competition (IREC). The rocket, called AJAKS, featured an internal skeleton made of carbon fiber rods, and a combination of plywood, carbon, and aluminum bulkheads. Loads were driven through the internal structure, with an outer skin tube providing an aerodynamic surface. A unique separation device was developed to ensure proper stage separation. The competition required the rocket to carry a 10-lb payload, which was chosen by the team to consist of an IMU and data logging computer for recording the descent profile, a CubeSat test unit, and a digital video recorder. Prior to the competition launch, AJAKS was test launched on May 5th in the Mojave at the Friends of Amateur Rocketry (FAR) launch facility. During the test launch AJAKS suffered a PIRM malfunction and the main parachute did not deploy. Following the test launch, the second stage of the rocket was rebuilt with a stronger payload configuration. The ESRA IREC was held on June 21st to the 24th. AJAKS was launched on the 23rd and during ascent the second stage became unstable and reached an altitude of only 6,000 ft. Both stages suffered damage upon landing.

Nomenclature

A	=	reference area (inches^2)
$C_{N\alpha}$	=	normal force coefficient (unitless)
cp	=	center of pressure location relative to nosecone tip (inches)
E	=	elastic modulus (psi)
I	=	area moment of inertia (inches^2)
L	=	length of the rocket (inches)
P_{cr}	=	critical load for buckling (pounds)

Subscripts

b	=	first stage
s	=	second stage
$total$	=	first and second stage

I. Introduction

THE 2012 Intercollegiate Rocket Engineering Competition (IREC) is the 7th annual competition sponsored by the Experimental Sounding Rocket Association (ESRA). The ESRA was founded in 2003 with the goal of advancing experimental sounding rocketry, doing so mainly through the IREC. There are two categories in the competition: basic and advanced. The advanced category requires building a rocket to carry at least 10-lbs of payload as close to 25,000 feet as possible. The IREC places emphasis on student design and construction of rocket components, as well as a presentation, a report, payload functionality, and launch day organization and operation.

[1-5] Undergraduate, Aerospace Engineering Department, 1 Grand Avenue San Luis Obispo, CA 93407

These criteria are broken up into point values and the highest score with a qualifying rocket wins. Qualification is determined by the altitude the rocket reaches. The qualification range for the advanced category is between 12,500 and 27,500 feet. There are rules and regulations for the competition, which levy requirements on the rocket design. Rocket components and payload must be recoverable, and a radio tracker must be present in each stage used. The IREC is held for three days during the summer in Green River, Utah. For 2012, the competition was held from June 21^{st} to the 24^{th}.

Cal Poly Space Systems (CPSS) is an engineering student club at the California Polytechnic State University in San Luis Obispo, California. The club's primary mission is to have students gain experience in high power rocketry through yearly projects and individual amateur rocket construction. Projects are usually led by senior members of the club, and often can be used as senior projects for fulfilling graduation requirements. First year members are encouraged to build their own rocket and gain certification through the Tripoli Rocketry Association (TRA). This teaches them the design and manufacturing process of a rocket. While traditionally attracting mostly Aerospace Engineering students, CPSS is multidisciplinary and open to anyone who shares a love of or interest in rockets.

Rockets built by CPSS are typically constructed out of composite materials such as fiberglass, carbon fiber, plywood, and phenolic. The structures are fabricated entirely from these raw materials, while the motors, parachutes, and electronics are off-the-shelf components, which are chosen for their safety, reliability, and performance. CPSS receives funding for its projects from student fees, membership dues and donations from industry and amateur rocket enthusiasts.

Starting in the summer of 2011, the authors decided to enter the 7^{th} annual ESRA IREC advanced category. The team name, and the final rocket's name, was AJAKS and comes from the first letters of each member's name. Our goal was to build a successful two-stage rocket that would address many of the issues CPSS experienced with the previous year's IREC flight test, Caution: Mythical.

II. Small Prototype

Many new features were being included in the design for the main competition rocket, so a small prototype was built as a flight test bed and to practice construction and integration. This prototype rocket, called Thing1/Thing2, would incorporate many of the core features of the main rocket such as: an internal skeleton, a new stage separation device, and staging operations. The rocket was designed and built in only four weeks in preparation for a launch at the end of October.

Thing1/Thing2 was not built to any scale with respect to the main competition rocket. As such, the main difference between the test bed and the full scale design is the lack of a payload. It was determined that the prototype rocket would sufficiently test the various ideas being implemented in the full scale design without needing a payload or being built as a scale model of the final design.

The main features being tested were the Separation Pyrotechnically Initiated Release Mechanism (Sep-PIRM), the construction and integration of an internal skeleton, and the programming of flight boards. The Sep-PIRM was designed to function as an inter-stage connection that would both hold the stages together and allow the stages to separate at the correct time. The Sep-PIRM was required to support the entire weight of the rocket while the rocket is picked up horizontally at the stage interface and still be able to separate in flight. This requirement came from a previous launch conducted in May 2011 in the Mojave at the Friends of Amateur Rocketry (FAR) test facility. FAR officials explained that if a two stage rocket could not be picked up at the stage interface then it would probably not withstand flight loads and would not allow it to be launched at their facility.

The Sep-PIRM was inspired by CPSS's Pyrotechnically Initiated Release Mechanism (PIRM), which is a device that is used to handle deployment of drogue and main parachutes from the same parachute bay. The PIRM uses nylon machine screws to hold two aluminum parts together, which have a black powder charge in the middle. The charge is set off by the flight electronics, which shear the bolts and allows the aluminum parts to separate. This releases the parachute being held back by the PIRM. The Sep-PIRM works on the same principal as the PIRM; however, the Sep-PIRM was required to have a hole in the center to allow for parachute ejection on the first stage side and motor firing on the second stage side. This required the use of a ring charge instead of a single point charge. The ring charge was made of quick match instead of loose black powder. #8-32 nylon bolts were used for the Sep-PIRM and PIRM, and aluminum was the metal of choice because it is readily available, light weight, and easy to machine.

Related to the Sep-PIRM is the electronic staging of the rocket. The prototype was used as practice for programming flight boards for staging and air starting motors. Historically, staging has been an issue for CPSS to do successfully in club rockets. The test bed allowed for practice in programming the flight boards as well as harnessing of the electronics and all their associated wiring.

The stability of the rocket was calculated using the Barrowman equations exclusively[1]. The equations were designed for use in amateur rocketry, and when programmed, allow for continuous iteration so different fin shapes can be tested quickly. This allowed for the design of the fins to be pushed back until the actual center of gravity of the rocket was known. Microsoft Excel was used to design the fins. In order to make sure the prototype would be stable for the entire flight, the second stage fins had to be designed first. The first stage fins were then designed taking into account the second stage fins.

The structure and layout of the prototype can be seen in Figure 1 below. The structure used three 0.197" diameter protruded carbon fiber rods as the stringers, and 3/8" plywood bulkheads as ribs. The diameter of both stages was 4.5", and the overall length of the rocket was 96". When prepared for flight, the first stage used an Aerotech K-695 and the second stage used an Aerotech J-540. One G-Wiz LCX was used in the first stage while the second stage required a G-Wiz HCX for the extra pyro port it has compared to an LCX. The Sep-PIRM used a quick match charge with redundant e-matches separated by 180˚ and tied into a loop in the chamber for actuation. Only the second stage PIRM was loaded with redundant e-matches and 0.75 grams of black powder. The first stage came down on a main parachute only, so no PIRM or drogue parachute were used. The first stage had two ejection charges of 1.0 grams of black powder each; similarly, the second stage had two ejection charges of 1.0 grams in the piston, which ejected the drogue parachute. A single 18" parachute was used in the first stage, while a 12" drogue and a 36" main parachute were used in the second stage. The Sep-PIRM, once loaded, was bolted together using 9 #8-32 nylon bolts. The total wet mass on the launch pad was 18.5 lbs.

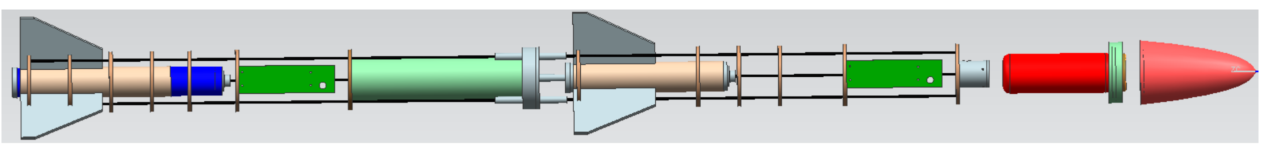

Figure 1. Thing1/Thing2 internal view.

Thing1/Thing2 flew on October 30th and the launch was a success; the stages separated cleanly and the second stage motor ignited. Rocksim calculations predicted the second stage would reach an altitude of 8,000 feet, but the actual altitude recorded by the flight electronics was only 5,500 feet. The authors have seen similar discrepancies between predicted and actual altitude when using Rocksim. Rocksim's predicted altitude is always higher than the actual altitude reached by rockets when flown. The recovery systems in both stages deployed properly, and both stages were recovered. There was only minor damage to the fin tips, and some epoxy bond shearing at a few of the spar and rib connections. The shearing caused concern that a stronger epoxy would be needed to ensure structural soundness under the increased loads of a larger rocket. The concern resulted in research of stronger resins and better bonding methods, as well as tests to investigate epoxy bond strength between carbon rods and plywood bulkheads. The successes of the small prototype gave confidence to move ahead with a larger rocket designed with similar features.

III. Design Methodology

The design methodology for this project began with a review of previous CPSS high-altitude rockets. Through an iterative process of design meetings, Computer Aided Design (CAD) modeling, and stability and performance analysis, decisions were made that eventually led to the final rocket design. Important steps include choosing the motor configuration, creating the structural design and layout, determining stability, and simulating this design in Rocksim.

A. Rocket Motor Configuration

Previous large rockets built by CPSS featured an external skin that carried the majority of flight loads, and used staging of commercial motors as the primary method of reaching high altitudes. This has been true of both of the club project rockets titled Caution: Flammable, built in 2008, and Caution: Mythical, which was built for the 6th IREC in 2011. For this competition, many options for rocket design and configuration were weighed at the beginning of the design process. The options under consideration were: single-stage with clustering of large commercially off the shelf (COTS) motors; single-stage with in-house built solid motor; single-stage with in-house built hybrid motor; single-stage with single COTS motor; and two-stage with two COTS motors.

Clustering of large motors is risky because of the ignition timing inconsistencies with the larger grains. Clustering is more consistent with smaller motors because the grains ignite faster and produce peak thrust in a shorter amount of time. Since Cal Poly does not have the facilities to mix and cure Ammonia Perchlorate or any other type of high power solid motor grains, this option was also ruled out. A custom built CPSS hybrid motor was in the process of being developed at the same time as this competition, but its Technology Readiness Level (TRL) was not high enough to be counted on to carry a rocket with a 10-lb payload to 25,000 ft. Using the most powerful COTS motors available, through Aerotech, this left the two-stage rocket as the best method for meeting the competition goals after a single stage single motor was eliminated with preliminary altitude analysis. It also became a goal of the team to develop a successful staging rocket, since past staging rockets have proven difficult to stage successfully.

B. Structural Design Considerations

Due to experiences from Caution: Mythical, the structural design was considered the most important design aspect of the project. Trades were performed to determine how loads would be carried through the rocket, and how the layout of each stage should be designed for optimal functionality. Flight loads come from axial and transverse forces rising from perturbations such as wind gusts and thrust misalignment, aerodynamic drag forces, and the motors.

1. Internal Skeleton Trade

The rocket structure was the first component to be designed. The trade was between using some kind of internal skeleton and a thickened monocoque structure. The monocoque structure would effectively work the same way Caution: Mythical did, but the load-bearing skin would be significantly thicker than in any previous rocket built by CPSS. The thickness required for the skin, however, would be extremely difficult to calculate with certainty due to CPSS' non-standard composites manufacturing processes; an analytical solution for thickness required to prevent zippering of the skin would require the fibers to be laid up at more precise angles and the epoxy to be cured using higher temperatures than CPSS can affordably do. It is also not possible to analytically determine the thickness required to bear the flight loads because the manufacturing techniques used are not consistent in the pressure or temperature during epoxy curing. Finally, the monocoque structure option was eliminated as it would limit staging options; if the staging was to be carried out using a machined part, this part would need to be bonded permanently to the rocket, and a removable high-value item is more desirable than a permanent one.

The primary disadvantage of an internal skeleton was CPSS' inexperience with that method. The advantages outweighed this disadvantage, so it was determined that the competition rocket would be built around an internal skeleton. To mitigate the disadvantage with this selection, a small scale prototype was built. This is detailed in section II. Because the internal skeleton uses commercially made load bearing rods, structural analysis can be done on the rocket to determine the size and number of rods best suited to this project.

The composition of the internal skeleton needed to be selected. The architecture selected was a set of vertical graphite rods to carry lateral and pitching moment loads. These graphite rods would be epoxied through holes in plywood bulkheads. The other option considered was creating a system of notched vertical plywood stringers mating with notched plywood bulkheads; this option was rejected because analyzing the stress concentrations in these notch joints would be impossible for plywood, a situation not acceptable for the motor mount bulkheads. In contrast, simple tests for shear strength of the rod-epoxy-hole joint could be conducted and analysis of the shear strength of this joint could be used for analysis. Using preliminary experimental results, it was determined that five rods of 0.315" diameter gave a factor of safety through these joints of four, at a cost which was reasonable considering the project budget at the time of the decision. The five rods were to be equally spaced in a circular pattern to carry axial and pitching loads. Five rods was selected over four rods to save money and reduce the cost of the project. Larger rods would be required to maintain a good margin of safety on epoxy if the number of rods were reduced. Four of these larger rods cost significantly more than the five 0.315" rods selected for the rocket.

The selected rods were also analyzed for buckling and compressive failure using the manufacturer's provided material specifications.[2] The equation below was used for buckling analysis:[3,4]

$$P_{cr} = \frac{EI\pi^2}{L^2} \tag{1}$$

P_{cr} is the critical load for buckling failure, E is the elastic modulus of the rods, I is the area moment of inertia of the rod layout, and L is the length of the rocket. It was found that the rocket had a margin of safety of nearly 20 in buckling. Because the epoxy factor of safety was only 4, rod diameter could not be reduced. Tubes could have been used instead but this would have added cost to the project, so the buckling safety factor was left relatively high. This internal skeleton design can be seen in Figure 2.

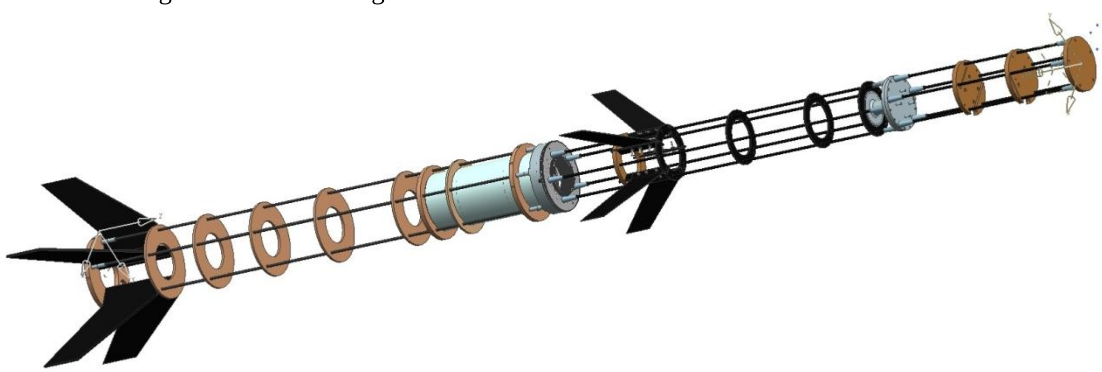

Figure 2. Internal skeleton of AJAKS. Five carbon fiber rods are epoxied to hole in bulkheads.

2. First Iteration Design

With the primary configuration of the rocket selected, layout of the rocket could commence. This was done by creating parts and assembling them in the 3D modeling program NX[5]. Mass properties of materials used were entered into the program, allowing an estimate of total mass and center of gravity (c.g.) location to be determined. These values then could be used in Rocksim to determine rocket performance.

The first stage includes a parachute tube inside the diameter of the internal skeleton. At the time of initial design, CPSS intended to use heritage main parachutes which required a 6” diameter tube. Thus, the skeleton had to surround a 6” diameter tube which meant the outer skin of the first stage needed to be 8”. Initially, the second stage was also made 8”. Since the first stage does not include any payload, it could be designed with a shorter length, thus reducing bending loads.

The second stage was designed similarly to the first. The major differences between the two were the addition of payload bulkheads between the motor mount and recovery system, and the recovery system not requiring its own tube. The payload bulkheads were designed similar to the motor mount; the axial launch loads were transferred to the bulkheads in shear through the epoxy. The parachute in the second stage was contained directly in the body tube. This could be done by terminating the rods at the bulkhead upon which the parachutes rested.

The first iteration of the payload section was laid out with the inertial measurement unit (IMU) computer and PolySat payload mounted to a total of three bulkheads, sharing the middle of the three, and the IMU sharing the top payload bulkhead with the top of the PolySat. This layout was used because the IMU could not be inserted between the rods and had to be installed from the top after removing the parachute bulkhead. Bolt and integration geometry defined the rest of the layout. The PolySat had to be integrated from the side of the rocket, and thus one of the graphite rods was cut short. The computer was also integrated from the side but was able to slide between two of the rods.

The avionics batteries were placed in a void between the top of the motor mount and the bottom of the payload section. The avionics were placed near the computer, as the avionics and the computer happen to be similar in height, and there was not enough room in the module that contained the PolySat.

Following the test launch in Mojave, CA, which will be discussed in section V, the payload was redesigned to prioritize putting the PolySat on the bottom of the payload stack, without cutting any of the rods short. These restrictions meant the bottom plate of the payload section had to be removable. The method for removing the Sep-PIRM was extended to this bulkhead and aluminum sleeves were added to the bottom bulkhead and the top bulkhead of the motor mount. These two bulkheads each had holes drilled into them such that they would be bolted together face-to-face and the payload section was an entirely removable module.

C. Rocksim Analysis

Rocksim 8.0 was used to perform the flight analysis of the rocket. Rocket builders can design a rocket in Rocksim, and then simulate a launch in order to see how the rocket will perform.[6] A geometric model was created in Rocksim, allowing for aerodynamic coefficients and forces to be computed by the program. The dry mass and center of gravity for the rocket as a whole and the sustainer stage alone were entered into the program. All these values are based upon the CAD model of the rocket. The appropriate motors would then be loaded into the rocket, and the parameters for event sequencing of parachutes and staging would be entered in. The rocket flight was then simulated with expected flight condition such as wind, altitude, and launch angle. From these simulations altitude, speed, acceleration, and other parameters could be obtained. Figure 3 shows some of these characteristics. These data points are the result of simulating the model at 800 samples per second.

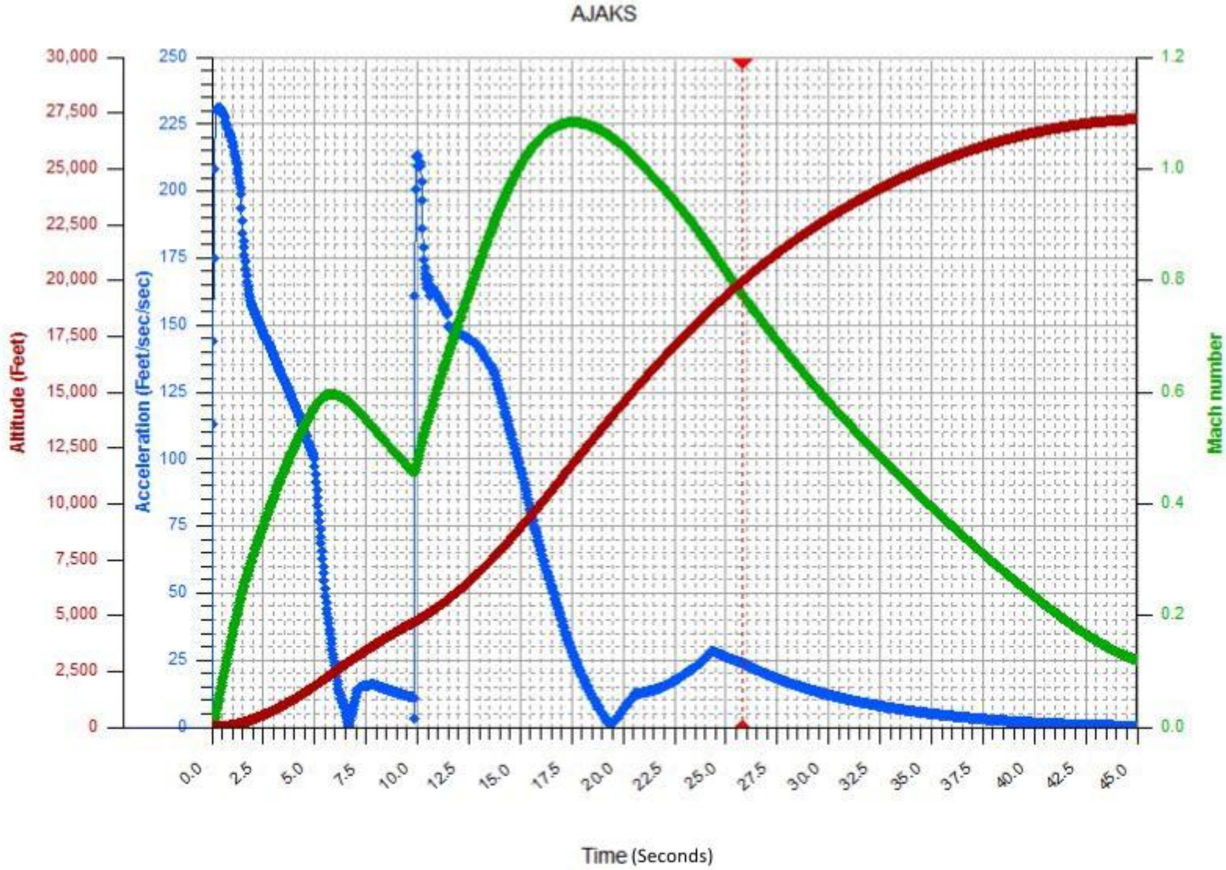

Figure 3. Performance characteristics of AJAKS from Rocksim.

Since the competition requires 10 lbs of payload be delivered between 12,500-27,000 feet with more points earned the closer the rocket is to 25,000 feet, altitude was the most important merit of performance. From the Rocksim analysis, it was determined that a motor combination of an N-2000 in the first stage to and N-1000 in the second stage would offer the best results. The design changed from a 6.3" to 8.7" diameter body tube based upon parachute compartment sizing, but analysis showed that the second stage needed to be 6.3" to reduce drag and weight. Finally, the addition of two J-350 motors in the first stage was necessary for the rocket to reach above 25,000 feet in the simulation. As discussed previously. Rocksim has a tendency to over-predict rocket altitude so a simulation altitude close to the upper limit of the qualification range was desirable.

D. Stability Analysis

Initially, it was desired to use just the Barrowman equations for their simplicity. Unfortunately, the speeds the rocket would achieve were too high according to Rocksim performance analysis. The Barrowman equations are only valid for low, subsonic Mach numbers.[1] The preliminary analysis showed that the rocket would be going transonic. This makes the Barrowman equations inaccurate for the expected flight, so other methods for calculating center of pressure were investigated.

Rocksim[6], Open Rocket[7], Digital Datcom[8], and modified Barrowman equations[9] were ultimately used to determine fin size and shape required such that the rocket would be stable in all stages of flight. Of special importance was the sustainer because the Rocksim analysis determined that the sustainer would reach transonic speeds. Transonic effects shift the position of the center of pressure and motor burn causes the center of gravity to shift. It was important that any methods used to evaluate stability of the rocket took these factors into account.

The programs use the geometry of the rocket to determine center of pressure. Rocksim and Open Rocket are similar interfaces that have a convenient graphical user interface to allow for the dimensions to be entered quickly. Digital DATCOM is not like that. It requires a file to be written with very specific syntax in order to ensure the geometry is correct. This file also controls flight conditions which can affect the center of pressure. For these reasons extra care had to be taken when using Digital DATCOM.

Many programs and methods besides those listed were considered for stability analysis but rejected for a variety of reasons. Many could not take transonic effects into account. Other programs could not handle analysis of rockets with 5 fins. The modified Barrowman equations are only designed for a single set of fins but a method was devised that allowed the modified Barrowman equations to be used for multiple stages. The sustainer was analyzed normally. Then weighted averages were used to determine the impact of the sustainer and first stage fins on the overall center of pressure of the rocket before separation. The equations include the calculation of normal force coefficients. These coefficients and the fin reference area were used to weight the center of pressure impact of each set of fins. The weighting used can be seen below:

$$cp_{total} = \frac{cp_b * A_b * C_{N\alpha,b} + cp_s A_s * C_{N\alpha,s}}{A_b * C_{N\alpha,b} + A_s * C_{N\alpha,s}} \quad (2)$$

In the equation cp is center of pressure. Subscript b denotes with only the booster fins and s is just the sustainer fins. A and $C_{N,\alpha}$ are from the modified Barrowman equations, representing fin reference area and normal force coefficient due to angle of attack. By weighting the center of pressure calculated for each set of fins independent from the other set, an overall center of pressure for the entire rocket can be determined. Over the course of iterating through fins it was found that this method correlated closely with the center of pressure predicted by the different programs that are capable of handling multiple fin sets. Table 1 compares the center of pressure and stability margins calculated by the methods used. Overall numbers are not included for Digital DATCOM because that program was not capable of handling the inputs required to simulate multiple fins.

Table 1. Comparison of Stability Methods Used

	Sustainer Center of Pressure (inches from nosecone)	Sustainer Stability Margin (calibers)	Total Center of Pressure (inches from nosecone)	Total Stability Margin (calibers)
Digital DATCOM	71	1.7	NA	NA
Rocksim	68	1.2	105	1.4
Open Rocket	70	1.6	103	1.3
Modified Barrowman	73	2.0	109	1.9

Five fins were selected for both the sustainer and the booster because this would allow them to be lined up accurately by aligning them with the carbon rods. Unevenly spaced fins can lead to instability. The rods were spaced by a machine, so aligning the fins with the rods spaces them as evenly as possible.

Using an estimate for center of gravity based on a comprehensive solid model of the rocket, fin geometry was altered in the four stability analysis methods until geometry was found that satisfied stability requirements. The stability requirement chosen was a minimum margin of one caliber between the center of gravity and the center of pressure. Furthermore, the stability margin was limited to a maximum of 2 calibers at motor ignition. This range of stability margins has been shown to work well for amateur rocketry.[10] This range of margins has also worked well for CPSS in the past. All geometries used were trapezoidal and a minimum chord of 1 inch was used to prevent the fins from breaking during landing or handling of the rocket. Trapezoidal fins, unlike triangular ones, do not come to a single point that the rocket can land on, having an edge to land on instead. Placing a lower limit on tip chord of the fins lowers the risk of having fin tips break off on landing. Geometries more complex than trapezoidal were not used because that would increase the difficulty in machining the parts as well as require approximations of the fin be made for use in some of the stability methods. Sweep was also used on the fins to delay the onset of transonic effects on the fins. This is similar to transonic aircraft using swept wings to delay and reduce the effect of sonic and transonic airflow.

The sustainer fins had to be designed first for just the sustainer. Once fin geometry had been found that satisfied the stability requirements for the sustainer, first stage fins were then designed that took the shape and placement of the sustainer fins into account. For the second stage alone, a caliber is 6.3 inches. One caliber is 8.7 inches for the rocket as a whole.

IV. Structural and Functional Component Testing

During the design process, tests were completed to help with verification including: an inter-stage moment test, parachute ejection, separation of the PIRM, separation of the Sep-PIRM, ignition time of the first stage motor, and GPS receiving. The moment test involved creating an apparatus with two 8'' plywood bulkheads and five 0.25'' carbon fiber rods equally spaced towards the edges of the bulkheads. One bulkhead was braced to a wall and the other was loaded with increasing weights until yielding. It was concluded that the carbon fiber rod structure could hold the launch moment loading we expected to see of 240 lb in. This test also allowed us to understand the general strength of the rods between two bulkheads and decide that the maximum distance between any given bulkhead section should be no more than 12 inches.

For the parachute ejection test the main parachute was loaded with Kevlar chord into the body tube and the piston was placed on top of it. The piston was loaded with 1.2 grams of black powder charges in each of its copper caps and finally the Aramid-wrapped drogue was placed on top of the piston. The nose cone was put on top of the body tube. The test itself involved using an igniter to set off the pyrotechnic charge inside the piston and verifying that the drogue ejected the nosecone. This test was successful in that the drogue ejected from the rocket and popped the nosecone off properly to allow the parachute to release properly in flight. We also were concerned the piston would become cocked in the tube due to the moment created by the black powder charge, but this test demonstrated the piston actuated easily after drogue deployment.

For the separation of the PIRM test a 1.5 gram pyrotechnic black powder charge wrapped in plastic wrap around an igniter was inserted into the PIRM. The igniter was fired by sending electrical current through the wire and the PIRM then separated due to the pressure build up in the small charge. This proved that the correct amount of black powder charge was being used to separate the seal of the cap without causing damage to the aluminum parts of the PIRM. This is crucial to the flight performance to make sure the main parachute can release from the rocket.

For the separation of the Sep-PIRM a quick match ring charge was loaded into the groove and the aluminum interfaces were bolted together with nylon bolts. Enough quick match was used to go around the entire Sep-PIRM cavity once. The charge was fired from a safe distance using an igniter and a launch box to send electrical current through the wire. The Sep-PIRM instantaneously separated with no damage to the aluminum hardware. This proved that one wrap around of the quick match was enough charge to separate the device. There was a concern that this charge could damage the interface if too much force was being applied. To solve this problem the Sep-PIRM was entered into NX-NASTRAN to analyze its strength under pressure.

The ignition time of the first stage motor became an issue when it was determined two J-350 motors in addition to the main N-2000W would be needed in the first stage. The large N-2000 motor might not have had a short enough ignition time to make sure the smaller clusters did not power the rocket without the N-2000 firing at the same time. To test this, igniters were made and a test stand was set up in the propulsions laboratory on campus. Behind a blast proof window in the control room the motor was fired and timed to have less than a second of delay. For comparison, the expected worst case scenario was a delay in excess of two seconds. We concluded that clustering the motors on the first stage would not cause flight instability upon first stage ignition off the launch rail. As a further precaution against the rocket only being powered by the two smaller motors, they were ignited by the flight electronics after the main motor had ignited.

The GPS trackers were tested both on the ground and in the air before the launch. Ground testing was meant to see that the GPS worked and that coordinates could be received by a ground station. The GPS transmitter was then flown in a different rocket to test its locking and transmitting characteristics in flight. This test showed that the GPS not only lost lock during launch, which was expected, but also could not regain lock during descent. Line of sight was also lost, so no transmissions could be received. The GPS behaved in a similar fashion during the Mojave test launch, but did eventually get lock, which led to recovery of the sustainer. GPS is still a viable option for tracking the sustainer, but only after a long enough period has passed for lock to be acquired, and if line of sight is maintained. A directional transmitter will be flown as the primary tracker, and the GPS will serve as the secondary tracker.

V. Test Launch at FAR Site

For major testing of the design, a full test launch, except for the payload module, was included into the program schedule to occur on May 5th, 2012. This test launch took place in the Mojave Desert, CA at the Friends of Amateur Rocketry (FAR) launch site which has high altitude clearance. The rocket was built, prepared, and programmed to fly exactly as it would be on the competition launch day except the actual payload hardware was replaced with appropriate weights to keep the center of gravity in the proper location and keep the rocket mass unchanged.

The launch was a successful test until the recovery stage of the flight. The first stage ignited successfully, and had good flight performance through motor burn out. Then the separation mechanism fired appropriately after the motor burn out with immediate second stage ignition. The first stage tumbled during its initial separation but the drogue and main parachute both deployed for this stage. Upon recovery it was discovered that the drogue was shredded but the main successfully carried the rocket body to a soft landing. There was minimal damage to the first stage except in the piston and false nosecone which will be manufactured again using stronger bulkhead material. To prevent main shredding again, the flight boards were reprogrammed to deploy the main at barometric apogee instead of inertial apogee. Changing this setting prevents tumbling from setting off the flight electronics.

The second stage ignited properly and continued on its ascent to apogee. It was out of human sight range but was being tracked via radio and GPS tracking. Tracking was lost when the sustainer reached the ground because line of sight was obstructed. Once in line of sight of the transmitters, the search field was narrowed using the directional antenna, and final recovery was made possible by receiving a coordinate from the onboard GPS. Upon investigation of the rocket body, it was determined that the PIRM for the main parachute became jammed in-flight and could not deploy the main parachute, leading to a harder-than-anticipated landing. During launch, the dynamics caused the metal carabineer, used to attach the parachutes, to hit against the PIRM, causing it to jam just enough to cause failure. The large weights in the payload section broke the bulkheads inside of the skin on impact making it so the second stage needed to be completely rebuilt. The lessons learned from this were that the PIRM needs to be separated from the U-bolt connection of the parachute Kevlar chord and that a stronger material needed to be used for the bulkheads that would be seeing the most forces during flight. The final important change that has been addressed is to make the PIRM a higher factor of safety so the aluminum would not fail.

VI. Final Design

Following the FAR site test launch of the rocket, the second stage was redesigned and rebuilt in only six weeks. The following presents the final design of the rocket that flew at the IREC in Utah. The final design can be seen in Figure 4 below.

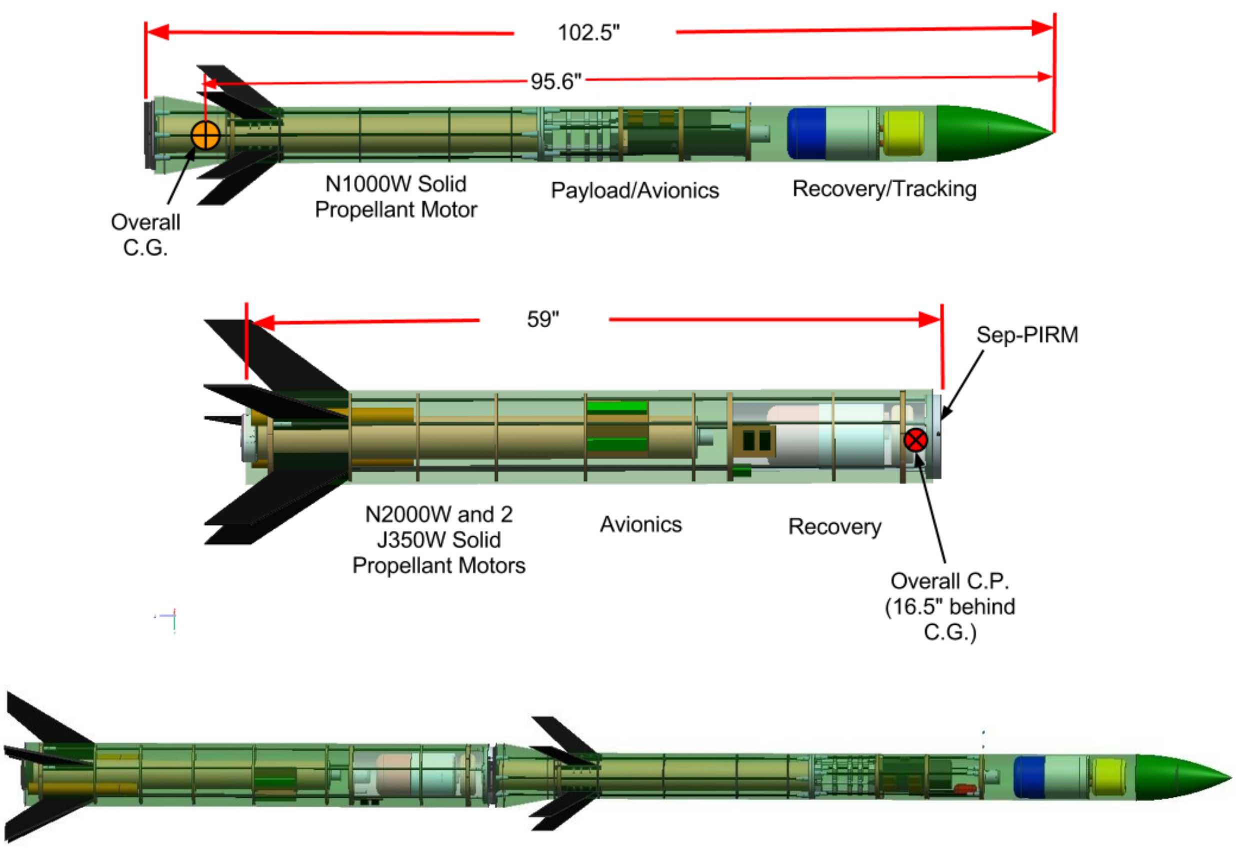

Figure 4. Overall rocket design.

A. Structure

The final design consisted of five 0.315" diameter rods and was found to have a safety factor of 100 for pure compression and 24 for buckling. Carbon fiber and plywood were used as the main bulkhead material in the structure, with aluminum used in the Sep-PIRM and the second stage payload/motor interface plate. These were used for mounting components. The epoxy bond factor of safety was four for the bond between the rods and the bulkheads. The motors fit into phenolic tubes, as seen in Figure 5 below. These are common in amateur rocketry for this purpose, coming in sizes that match the various standard motor diameters. The 8.7" body tube on the first stage gave ample room between the outer skin and the phenolic tube to allow electronics to be mounted between the two.

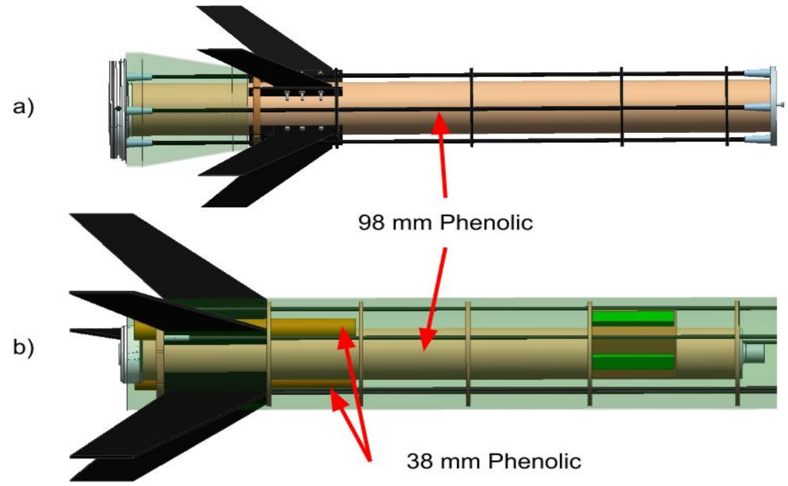

Figure 5. Motor mount structure of a) second stage and b) first stage. ***Note: fins not to scale.***

As discussed in section III, the first stage parachutes are contained within a 6.3" diameter inner body tube that serves as the parachute module. This module contains the PIRM, main and drogue parachutes, and piston with two explosive caps. The module is covered with a false nosecone, which serves two functions; it creates a pressure chamber, allowing the expanding gasses from the charges to eject the drogue chute, and it protects the parachutes from the second stage motor exhaust. Figure 6 shows the parachute module with components highlighted. Unlike the parachute module in Thing1/Thing2, which could slide up and down to accommodate the loading of the PIRM, this module is fixed to a bulkhead. The rods end in aluminum sleeves which bolt into the Sep-PIRM, allowing the Sep-PIRM to be disconnected.

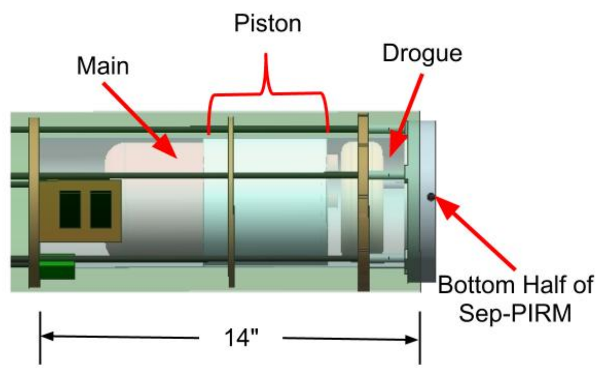

Figure 6. Parachute module

The fins for the first stage were mounted up against the graphite rods. L-brackets were used to hold the fins and constrain them axially, while ZIP-ties attached at a different distance from the root of the fin were used to take lateral loads, and the distance between the two supported the moments about the rocket's long axis.

Aluminum sleeves were epoxied to the end of each rod, and the bottom bulkhead and Sep-PIRM were bolted into the other end of the sleeves. These aluminum sleeves distributed the compressive and tensile loads in the rods over the bulkhead and Sep-PIRM faces. One of these sleeve interfaces is shown in Figure 7.

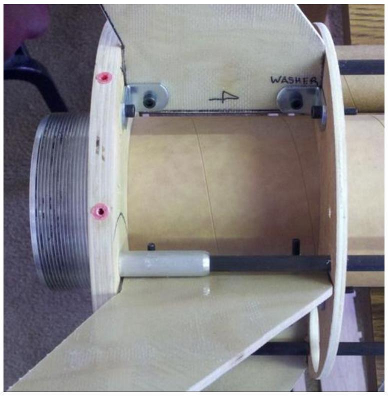

Figure 7. Rod-to-bulkhead sleeves interfaced rods to bulkheads, Sep-PIRM, and module mating bulkheads in both stages.

The re-design of the second stage also provided an opportunity to reimagine the fin mounting method. The fins were bolted in three points to a flat plate installed axially between the bottom two bulkheads of the second stage. This proved much easier for integration as well as a more rigid attachment. This can be seen in Figure 8.

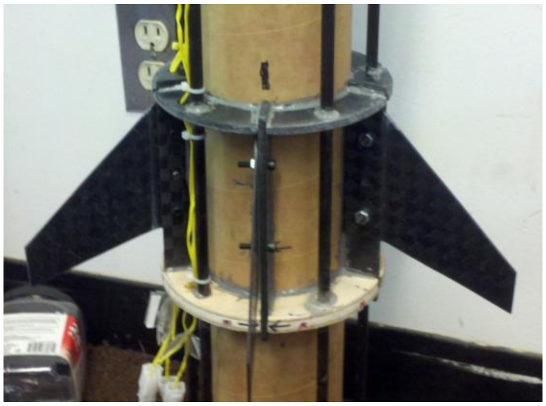

Figure 8. Second stage fin attachment.

The second stage payload and avionics segment attaches to the motor segment via two 0.5” aluminum plates. These aluminum plates are held together by 10 ¼-20 bolts, with counter-sunk bolts holding the rods in. The design of this section has already been discussed in section III above. Figure 9 shows the upper-second stage segment, with payload/avionics bay, parachute bay, and nosecone. The nosecone shape was selected to be ogive, which gives favorable boundary layer conditions.[11]

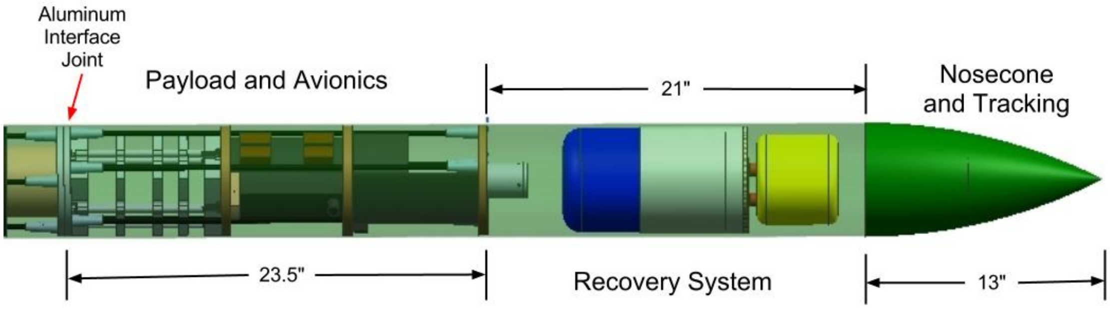

Figure 9. Upper second stage section.

The skin is mounted to the internal skeleton primarily by wood screws threaded into plastic plugs that are inserted into the 0.5" wood bulkheads. An exception is at the aluminum interface joint. Here, bolts are threaded directly into the aluminum. Slots were cut at the bottom of each body tube for the fins. Holes were drilled in the skin to allow access to switches for avionics and payload components while on the launch rail, as well as pressure holes. There was a larger hole cut in the skin for the camera to take video through. This hole was covered with a piece of plastic in order to prevent air and debris from flowing into the rocket.

B. Motors and Motor Retention

Four motors were used in the final design of AJAKS: one N-2000W with two J-350W motors in the first stage, and a single N-1000W motor in the second stage. All motors are solid grain motors manufactured by Aerotech, with Ammonium Perchlorate as the oxidizer, and use the reloadable RMS (Reloadable Motor System) motor casings.[12] Both N motors used 98 mm diameter motor casings, and each produced an impulse greater than 13,300 Ns. The N motors were ignited using a copperhead igniter triple dipped in pyrogen and then coated by a 1 gram layer of copper thermite. This ensured that the large grains ignited quickly, and reduced the chance of a hang fire. The J motors were clustered and set to ignite at two seconds after launch. This was meant to reduce the chance of the J motors igniting before the N-2000 and causing the rocket to leave the rail without enough thrust to maintain steady flight and done using the flight boards on the first stage.

All the motors require some kind of retention to prevent them from falling out of the rocket. The two J motors were held inside the rocket by using a pair of aluminum hooks on each motor. Two hooks are mounted on opposite sides of each J motor, and they were secured to the rocket using a piece of #10-24 all-thread and several nuts. The larger N motors require something stronger and relatively more compact than a set of hooks with all-thread. Thus, to hold the N motors Highly Adaptable Motor Retainers (HAMR's) were made. A HAMR works on the same principal as the hooks, but in a slightly different way. HAMR's consist of two parts: a big nut with a lip that comes in just enough to cover the rim of the motor casing's nozzle cap, and an externally threaded sleeve that screws into the big nut. The sleeve fits snuggly over and is bonded to the phenolic tube that holds the motor. The nut is removed before the motor casing is inserted into the phenolic tube, and then screwed on to the sleeve. The HAMR's and the hooks were both machined out of aluminum. The hooks were made using a manual mill and the HAMR's were made using a CNC lathe.

C. Recovery

Competition rules state that both stages must employ a drogue and main parachute, so the first and second stage each has two parachutes. The parachutes are connected to the rocket by Kevlar cord. The Kevlar cord for the first stage is attached in two places; once at the base of the parachute module and once at the base of the stage due to the high, concentrated weight of the payload. The first stage is lighter so the Kevlar is only attached to the base of the parachute module.

The parachutes were sized based on the expected weight of the stage it would be supporting upon descent as well as the 25 ft/sec rate of descent maximum constraint. On descent, the second stage weighs 49 pounds and the first stage weighs 31 pounds. This means the second stage requires slightly larger parachutes than the first stage in order to assure a safe landing. The parachutes are SkyAngle CERT-3 parachutes, and the expected descent rates are 20 ft/s for the second stage, and 23 ft/s for the first stage.

The parachute module on the second stage is formed by putting the aerodynamic skin over the load bearing skeleton. The skeleton terminates at the base of the parachute module but the skin continues up, creating a space for the parachutes to be stored. When the drogue is deployed, the nose cone pops off, leaving a hole for the parachutes to exit the rocket.

The parachute module on the first stage is a smaller tube surrounded by the structural rods of the first stage. The rods on this stage had to go all the way to the top of the stage to connect with the Sep-PIRM. This inner tube prevents the parachutes from catching on the rods or the Sep-PIRM. This module is capped by a piston attached to the Kevlar cord. The piston helps the black powder charge to create a pressure difference within a contained area and protects the parachutes from separation and second stage ignition. It pops off similar to the nose cone on the second stage. Both the nose cone and this piston remain attached to the Kevlar cord.

The charge that releases the drogue parachute is on a piston that shields the main from the explosion and helps to create a pressure difference to eject the parachute from rocket. Ground testing was done to size the black powder charge for each stage.

The main parachute is released by a Pyrotechnically Initiated Release Mechanism (PIRM), seen in Figure 10. Each PIRM is machined out of aluminum and consists of a chamber and a cap. The cap is held on by nylon screws and the main parachute is attached to the cap by an eyebolt. When the flight board sends the signal to release the main, the charge in the PIRM goes off, shearing the nylon bolts and allowing the main parachute to be pulled out of the rocket by the drogue. Ground testing was done to determine the charge required to shear the nylon bolts and to ensure the PIRM was built strong enough to endure the charge going off inside it.

Figure 10. Pyro Initiated Release Mechanism (PIRM) used for main parachute deployment.

D. Fins

The final dimensions of the first stage fins were a 3” root chord, 1” tip chord, sweepback of 4”, and a span of 4”. This positioned the center of pressure of the whole rocket 9.5” behind the center of gravity. This corresponds with a stability margin of 1.3 calibers. The fin dimensions are shown in Figure 11. Fins were constructed out of 1/8” plywood sandwiched between fiberglass face sheets instead of the carbon fiber, because the original fins were cut before the carbon fiber sheets became available to CPSS, and keeping the old fins saved in manufacturing and integration time.

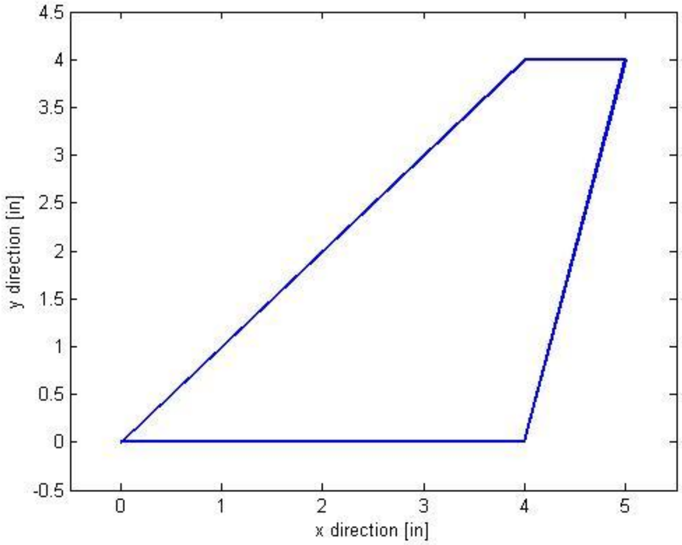

Figure 11 First stage fin dimensions

The second stage fins were designed to have a chord of 3.5” at the root, 1.5” at the tip, a sweepback of 3.5”, and a span of 2.7”. The second stage center of pressure is located 9.8” behind the second stage center of gravity for a margin of 1.2 calibers. The fin dimensions can be seen in Figure 12. These fins were cut from a 0.080” thick carbon fiber sheet.

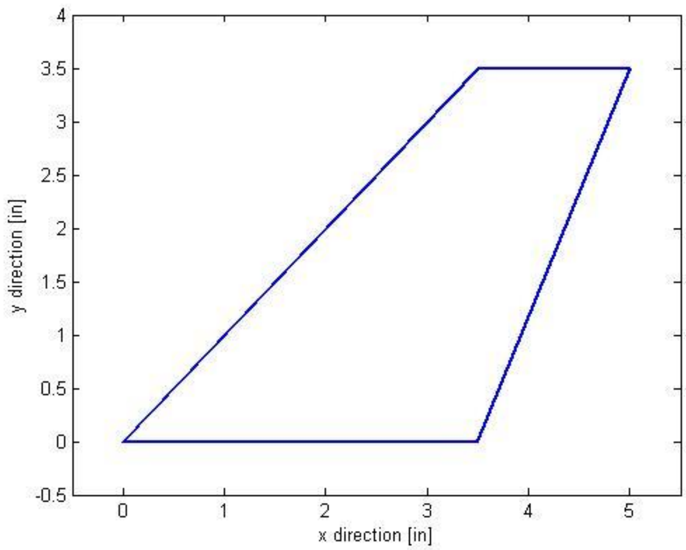

Figure 12 Second stage fin dimensions

E. Electronics

1. Avionics

Commercial amateur rocket avionics were used for the rocket. The electronics selected are produced by G-Wiz Partners. These electronics were selected due to their CPSS heritage. The second stage of the rocket required four events to carry out the conceptual operations (CONOPS), and the first stage required three. G-Wiz produces two types of boards, the HCX and LCX, which are capable of four and three events, respectively. Thus, HCX electronics were used in the second stage and LCX electronics were used in the first stage. As these were the electronics responsible for the recovery system deployment, each stage had fully redundant boards and wiring.

The avionics boards were wired with one battery powering the processor and another battery powering the pyrotechnics. The boards were set up and programmed in accordance with the G-Wiz User Guides. For the Mojave launch, the LCX boards were programmed to fire the J-350 motors at liftoff with a delay of 2 seconds, to fire the drogue charge at inertial apogee, and to fire the main at 1500 feet. This was derived from a similar setup from the Thing1/Thing 2 test launch. It was found that unlike the first stage for Thing1/Thing2, the first stage for the high-altitude rocket was aerodynamically unstable and tumbled after second stage separation, and that inertial apogee was not appropriate. Thus, for the competition, barometric apogee was used to fire the drogue parachute. For the second stage, the ports were programmed to fire the separation charge at first stage burnout, to ignite the N-1000 after 0.5 seconds' delay, and to fire the drogue at inertial apogee and the main at 1500 feet.

2. *Wiring*

The wires for the rocket were re-used E-match wires connected with Tamiya connectors. The wiring diagrams for the second and first stages are shown in Figure 13 and Figure 14 respectively.

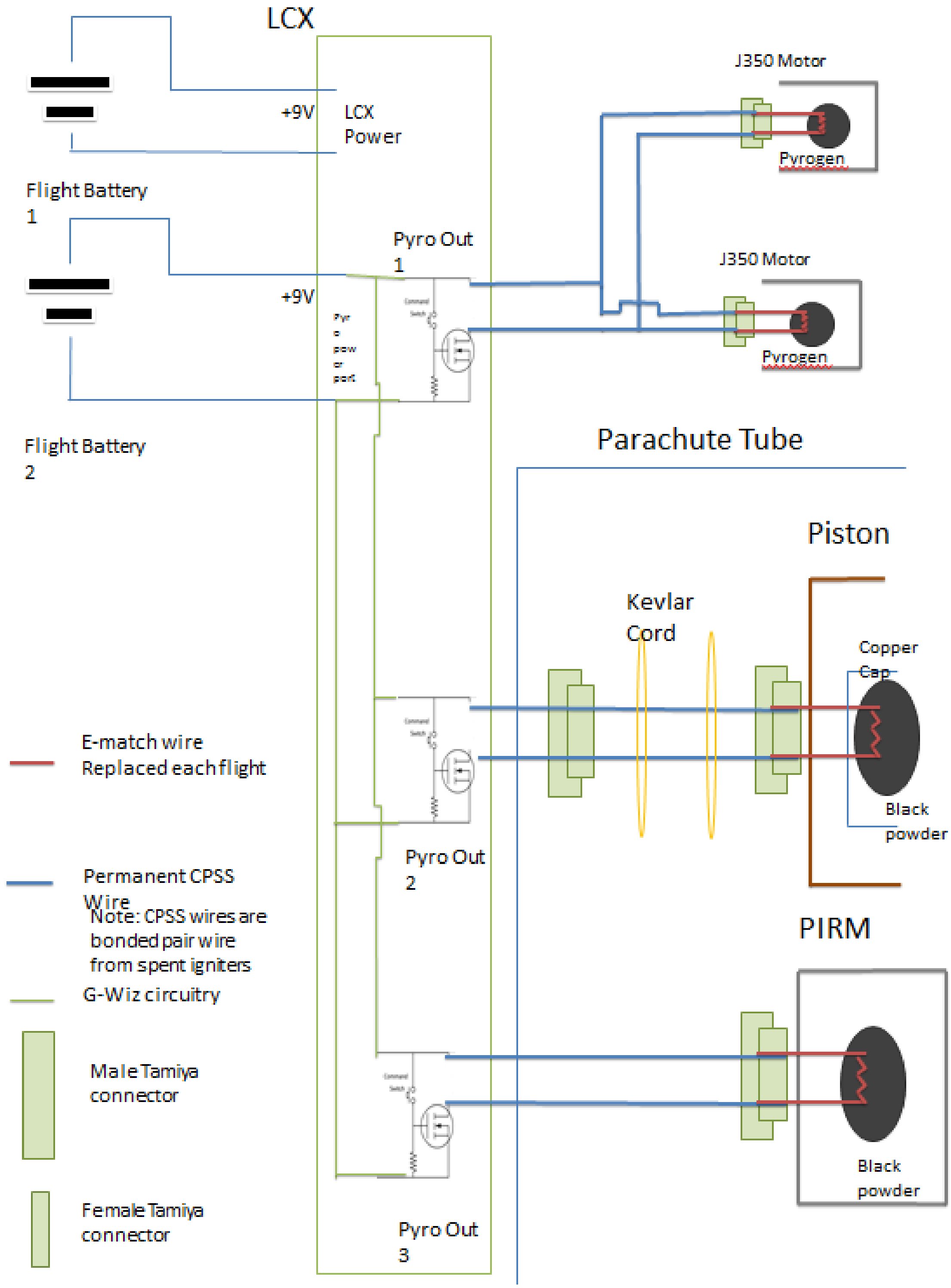

Figure 13. First Stage wiring diagram

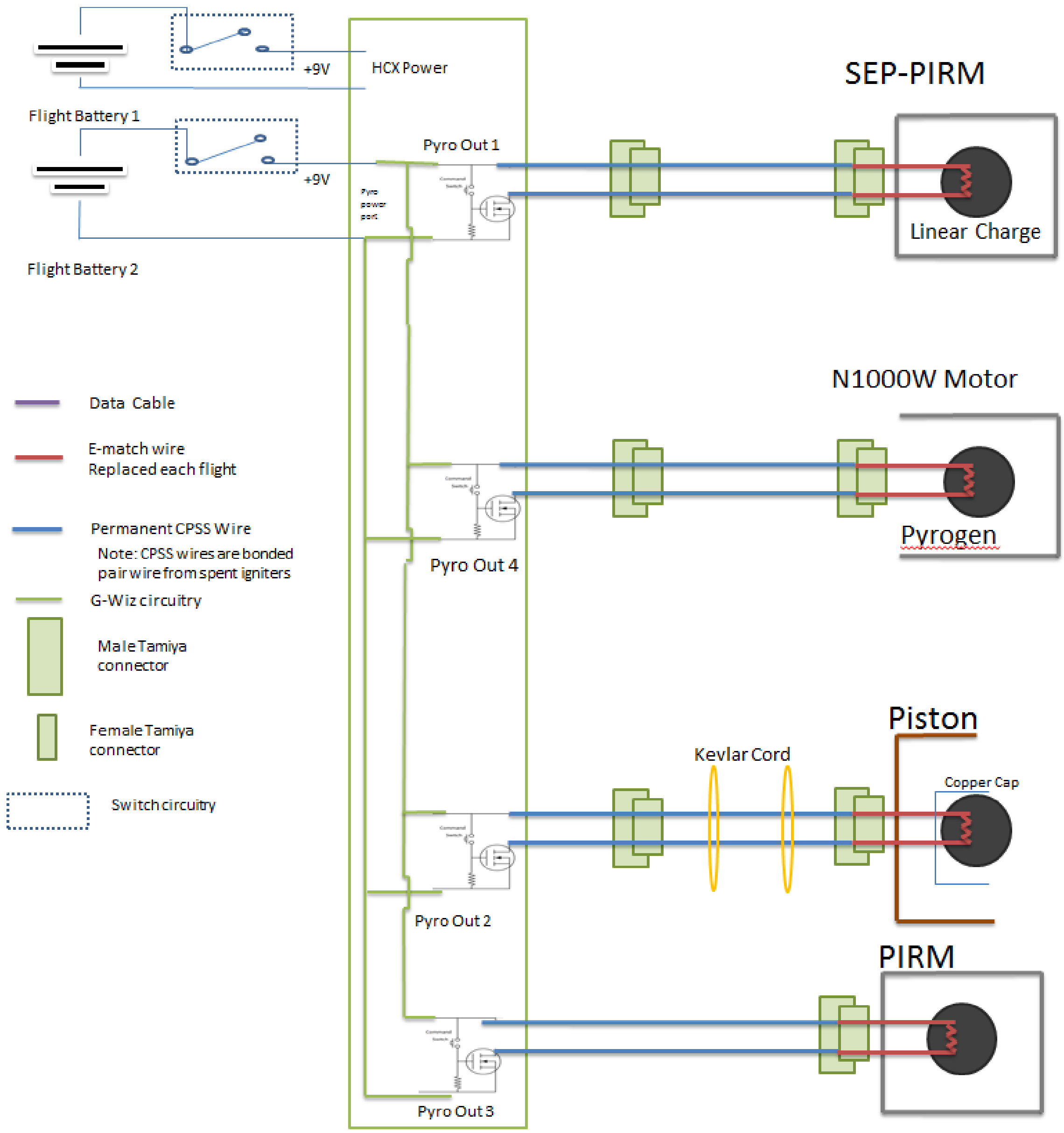

Figure 14. Wiring schematic for the second stage.

3. Tracking

Radio tracking and GPS were the primary methods for tracking the second stage. Competition rules state that both stages must have radio tracking. This is not completely necessary for first stage, since it is within visual range at its apogee, but one was installed to comply with the competition guidelines. This tracker was a BeeLine transmitter provided by the competition. The second stage used two trackers: a 222.250 MHz transmitter by Communication Specialist, and a 70cm BeeLine GPS. The transmitter signals are picked up with a directional receiver, and location pinpointed by triangulation. The GPS transmits to a ground station consisting of a VHF/UHF radio, a laptop, and decoding/mapping software. The GPS gives the coordinates of the second stage, and those coordinates are used with hand-held GPS devices to find the rocket. Two trackers are carried for redundancy.

F. Separation

The two stages are held together by the separation PIRM (Sep-PIRM), seen in Figure 15. The Sep-PIRM is similar to the PIRMs in that it consists of a chamber and cap to contain a charge that shears the nylon bolts that hold it together. It is different in that it needs to have a hole through it to allow the first stage parachutes to deploy as well as to allow the second stage motor to fire. For this reason a tongue and groove system was developed. The tongue and groove are both circular. The groove is 0.25” deeper than the tongue, leaving a rectangular ring where a quick match charge is placed. The Sep-PIRM was analyzed for flight conditions using NASTRAN FEA, and machined by the team. Ground testing was done on the Sep-PIRM to see how many windings of quick match were required to shear the nylon bolts.

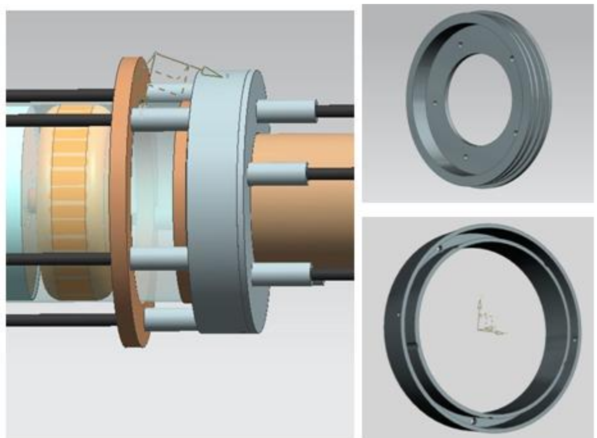

Figure 15 CAD model of Sep-PIRM.

G. Payload

The payload consists of the Cubesat test board and FlatSat housing, the Crossbow IMU with data recording computer and 12V battery, and the Flip MinoHD video camera. All the payload components are contained within the payload module, which can be assembled separately and attached to the second stage motor module during launch preparations. The payload module can be seen in Figure 16.

The FlatSat is made from five rectangular, aluminum plates connected by five steel rods with spacers in between the plates. The total length of the FlatSat is 8.35”, and the length of each side of a plate is 4”. The plates vary in thickness from 1” for the endplates, to 0.5” for the middle plates. The spacers come in two sizes: 0.925” and 1.55”. This allows for the plates and spacers to be arranged to create various compartment sizes. The endplates of the FlatSat were drilled and tapped to fit four ¼-20 bolts, which are used for mounting the FlatSat to the payload module bulkheads. The customer (PolySat) can tap the plates in whatever configuration best suits their component mounting needs. There are no harnessing connections between the FlatSat and the rest of the rocket, and components contained within the FlatSat are self contained for operation and power. The Cubesat test hardware was built by Cal Poly PolySat. The main objective for PolySat is to test their prototype hardware in a sounding rocket. The satellite’s mission is to determine the launch environment and their sensor suite includes vibration accelerometers which can be used to derive testing requirements for CubeSats on further missions. CPSS intends to use the data from this flight to derive a test program for future users of this rocket.

The IMU measures acceleration and rotation rates about three axes during the descent of the payload. The data is logged on an Artigo A1000 single-board computer running Windows XP. The computer is configured so that when turned on, it automatically runs the Gyroview software and begins recording data from the IMU. Using a code developed in Matlab, this data is used to find the position and velocity of the second stage during its descent. A special connector is used to connect the IMU’s RS-232 data port to the one of the computer’s USB ports. A rechargeable battery with 2000mAh of battery charge provides over an hour of power to the computer and IMU. The computer and IMU are connected in parallel to the battery.

The Flip video camera was added very late in the rocket design in order to fill out the 10 lb weight requirement. It is capable of recording up to 1 hour of HD video. The camera was mounted with the lens facing along the horizontal axis of the rocket; because of scheduling restriction there was not enough time to devise a way to have the camera facing downward. From this position however, it is possible to see roll and yaw motions of the rocket.

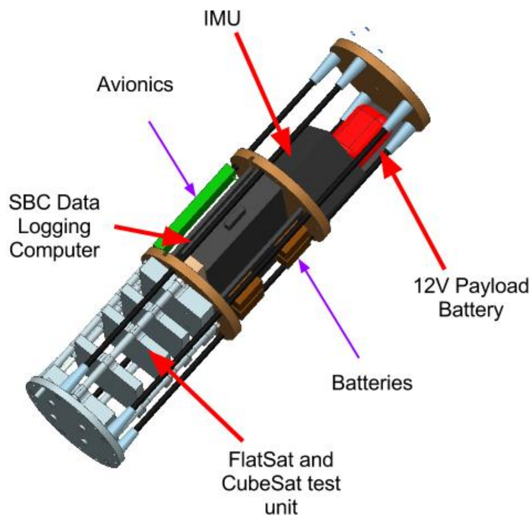

Figure 16. CAD model of payload section.

VII. Machining

After the test launch in the Mojave the second stage of the whole rocket had to be rebuilt because the damage from landing was too great to be repaired. In order to rebuild the second stage it was decided to redesign the configuration of the payload and the overall structure in order to make it stronger and better at handling high impact loading in the event of another recovery system failure. Carbon fiber plates were donated to the club and they were to be used for some of the bulkheads, the remaining bulkheads were to be made of 0.5" aircraft grade plywood. At the same time, two aluminum plates 0.375" thick were used to make a strong connection between the newly designed payload bay and motor compartment. A new male Sep-PIRM half was also machined from an 8" diameter, 3" tall disk. The last change, in terms of machining, was choosing 0.75" diameter aluminum to make the feet connections. All of the aluminum used was 6061 T6, bought from McMaster Carr. As with previous parts, everything was machined using a Haas TM1 NC mill and a TL1 NC lathe.

The carbon fiber plates were the first and most challenging of the new design to machine. The plates are very abrasive and dull the sharp edges of machine bits, making the mill work harder to cut the same shape and causing the surface finish of the cut to be much rougher. In particular, once bits became dull, the carbon would splinter and delaminate more often compared to when the bits were new and sharp. To lessen the abrasive effects of the carbon, full carbide bits are recommended. Further benefits are possible if the bits are diamond coated. Unfortunately diamond coating costs more than other coatings. The carbon plates were all machined using the Haas TM1 NC mill in the Aero Hangar. Flood coolant is also recommended to help evacuate the cut carbon and keep air borne carbon dust to a minimum. The coolant reservoir needs to be cleaned of carbon dust and once wet, the dust sticks to everything, making it hard to clean, and it must be cleaned well so that the bearing surfaces of the ways do not get severely worn. Pumping a shot or two of lithium grease into all grease ports on the mill is recommended after machining a substantial amount of carbon. The grease lubricates and pushes out any carbon that became trapped in the bearings while the mill was running. The remaining bulkheads which are machined out of plywood should be cut using any sharp bits and no coolant, also ensuring that the setup is dry and free of coolant. The plywood is nowhere near as abrasive as carbon and high speed steel bits should work well as long as the cutting edges are sharp.

The new male Sep-PIRM half was first machined on the TL1 and the final holes were drilled using the TM1. The new Sep-PIRM half was made to have a 0.25" plate thickness connecting the outer lip to the threaded section, while the previous model had a 0.1" plate thickness. That was the only change between the two models. All operations were performed using moderate feed rates and high speeds. As always, coolant was used on all operations.

The two aluminum plates used to connect the payload bay and the motor compartment were cut using the TM1. The same feeds and speeds as used for machining the Sep-PIRM were used to machine the aluminum plates. The only difference in machining was the restraint method. The aluminum plates were held onto an acrylic back plate using toe-clamps. The Sep-PIRM was held in a rotary table that was zeroed with the axis of the mill's spindle.

The aluminum feet were all machined using the TL1. A piece long enough to make two feet was chucked, drilled in both ends to hold a carbon rod, chamfered to the proper amount, and then parted in the middle. After parting, the final holes were drilled and tapped for a ¼-20 bolt. The holes were not drilled all the way through in order to keep epoxy from getting into the threaded section. However, when inserting a carbon rod with epoxy into the feet, air becomes trapped and a small hole was drilled perpendicular to the main axis to allow air to escape.

The machining performed to rebuild the new second stage did not take as long as it did for the original second stage. Lessons learned in previous manufacturing proved to be invaluable.

VIII. ESRA IREC Flight and Results

The ESRA IREC took place from June 21st to 24th, with the first day dedicated to registration and presentations, and the final three days being launch operations. The rocket was prepped the night before launch; the flight electronics were installed and wired, the fins were mounted, and payload was checked over. Most of the work that involved making explosive charges or assembling motors was done the following morning. The first launch day was scrubbed due to high winds, and the rocket sat with fully loaded charges and motors until the following morning. The igniters were removed from the first stage motors to keep them from accidently starting the motors. Solid propellants are generally safe to store, and precaution was taken to make sure the rocket was in a safe location away from people.

The results from the ESRA IREC led to lessons learned by CPSS and some successes. The rocket was launched in favorable conditions, separated the stages, but did not reach the altitude expected from the design. The rocket left the launch pad stable in flight but it could be seen from the smoke trail that the rocket was pitching slightly. This could have been caused by the rocket being 14 ft in length with a large heavy 10 lb payload near the top. The rocket would be experiencing bending loads during flight, which would be taken by the carbon fiber rod configuration and the Sep-PIRM. The next event was the separation of the two stages, which did not have nominal conditions and therefore the second stage ignition did not happen properly. The stages might have still been connected when the second stage motor fired, causing it to have improper stability for the second stage flight. The second stage became unstable in flight and spiraled until motor burnout. During this time the parachutes ejected and shredded due to the flight forces. The nosecone was also ripped off the rocket during this stage of flight. The first stage continued in its parabolic trajectory but also had parachutes eject early and shred. Both stages flat spun without deployed parachutes until landing just outside the launch site. From visual inspection, both stages impacted the ground in one piece in their separate locations. The only items that were separated from the rocket were the nosecone and the first stage motor casing, which both fell off in flight. Once the rocket stages were recovered, they were taken apart carefully to analyze what happened during flight.

For the first stage, the main events that happened which were not nominal was that the bottom bulkhead was broken on one side and torque inside of the skin causing two of the fins to be shifted up the skin by about two inches. Another problem was that the casing was missing since the HAMR came off during flight. For the parachute module, the parachutes were shredded and the PIRM and piston black powder charges did not fire. The last part of the first stage which did not perform as planned was the false nosecone which was charred from a pyrotechnic firing onto the ½" plywood bulkhead. There are several theories or explanations to these events, which has led to lessons learned by CPSS. The bottom bulkhead could have broken upon impact with the ground, backed up by photographs, which show that side being the one that had hit the ground first. Another possibility could be that the impulse of the J-350 motor sheared the 40 minute epoxy in one or more of the three bulkheads it was attached to. This would have made it so that J-350 was no longer constrained in the rocket properly and could have shifted up the rocket. Before launch it was noticed that one of the J-350 phenolic tubes had a slight crack in the epoxy which was deemed minimal. This could have been a fracture that was enough to allow the beginning of the shearing process. A few lessons learned for this problem was that CPSS should always use high quality plywood, always check the epoxy bonds in rockets that have been flown before, and always try to stay away from air starting clusters due to the probability of confusing the flight electronics.

The second error in the first stage was the motor casing being missing when the rocket was recovered. The HAMR, which keeps the motor inside of the rocket, was also missing. This could have been due to the bottom bulkhead breaking and torquing to one side. This movement could have sheared the 5-minute epoxy on the HAMR and popped it off during flight. This theory is only true if the J-350 did in fact break the bottom bulkhead in flight and not on impact. The other explanation is that the motor casing weight under the acceleration loading during flight had enough force on the HAMR to cause it to shear off. The lesson learned from this event is that the 5-minute epoxy should not be used for force critical flight hardware anymore since it does not have very good strength characteristics for the flight forces in rockets. In addition, heat resistant adhesives should be used for mounting motor retention. Since the motor casing was never located in the desert there can be no further investigation of other possible causes to this event or any definite answers.

The next event problem in the first stage was the parachute module which did not perform as designed. The drogue and main were both shredded which could have been because they ejected from the rocket early. The flight forces could have been too strong when they pulled out and shredded the fabrics since they are designed to come out of the rocket at apogee and the stable flight point of 1500 ft. What was particularly interesting was that the PIRM and piston charges never fired on this section. This could have been an electronics problem, but reviewing the flight board memory indicated that the proper signals were sent. The next reason would be that the false nosecone pulled the drogue and piston out so quickly that it broke the electrical connection in the Kevlar chord. This would make it so the module could never receive the proper signals from the electronics. The main parachute was able to come out when the nylon bolts holding the PIRM together sheared prematurely under the load of the drogue parachute and piston. The main parachute shredded when it was released while the first stage was traveling at a high speed. The lessons learned from this were that CPSS has had multiple failures due to improper parachute ejection and should look into a project to optimize and redesign a robust parachute system. As for the false nosecone being burned, this was caused by the ignition of the second stage motor while the stages were still trying to separate from each other. This was acceptable because the false nosecone was designed to be a failsafe to protect the parachutes if the ignition happened early.

The successes of the first stage were that it reached an altitude of 4651 ft and the carbon fiber internal structure held up for the flight. This is particularly impressive because this portion of the rocket had already flown in the Mojave Desert on May 5th. The skin proved to be fairly robust since it was able to cut through approximately two inches of the fins when the bottom bulkhead broke. The Sep-PIRM bottom cup was recovered in good condition with evidence that it did fire in an attempt to separate the stages as planned. One big concern for the first stage was the J-350 motors igniting at the same time and working properly with the large N-2000 motor. After recovering the rocket it was found that all three motor did fire as planned which was the biggest success of the first stage since air starting a cluster of this configuration was a difficult task.

For the second stage, the main critical events were: the stage separation, motor ignition, bending of the carbon fiber rods, deformation of the aluminum payload structure, damage to the payload section hardware, and undesired performance of the parachute module. The following paragraphs will discuss these events and their causes.

Based on observation of the rocket during and after its flight, there are a few possible causes for the under performance of the rocket. It is quite obvious that the rocket was not following a straight trajectory prior to separation. The pitching pattern began around 3 seconds into the flight. This is in the middle of the J-350 burn. We also have evidence of one J-350 motor shifting either during flight or upon impact with the ground. If the motor shifted in flight, it could have caused the waving pattern seen in the video. We can also see in the video that the pitching was not totally damped out by the time it separated. Also, we have evidence that the stages did not separate before the second stage motor ignited and the flight electronics say that there was no continuity. It is believed that the second stage motor caused separation. Also, the burn patterns caused by the second stage are not even on the first stage. Based on this evidence, it is possible the stages did not separate evenly. This would have put even higher angular accelerations on the second stage. The reduced stability of the rocket as a whole was not able to dampen this out and the stage began spinning. It is not clear when exactly the nosecone came off, but if it came off near the separation event, it could have made the stage unstable, leading to the trajectory shift. Some steps that could have prevented this from occurring include building rockets with a higher stability margin and using better connectors for electronics. The stability margin in the May test launch was 2.2 versus the stability margin in the competition which was 1.4. A higher stability margin would reject disturbances leading to pitching faster and may have allowed the rocket to stage simply with second stage motor ignition. It was also learned at the IREC that sounding rockets typically have a minimum stability margin of two calibers. The other problem which was related to the separation was the motor ignition which did not happen as programmed. The first stage might have sensed motor burn out at the wrong time making the second stage ignite early. This also could have added to the Sep-PIRM malfunction. Overall, the effect of the rocket performance on the electronics actually firing at the correct times is something that needs to be taken into further design detail for future CPSS members.

The bending of the carbon fiber rods could be due to the possibility of in-flight bending moments on the rocket. The rocket was being subjected to instability in flight, which caused it to pitch back and forth through its flight path, which put bending moment loads on the internal connections of the rocket under the skin. The design involved having the motor module bolted to the payload module on the internal structure, which provided a breaking point in the rocket, which was more susceptible to bending moment problems. The loading caused two carbon fiber rods to come out of the aluminum end cap supports and crack underneath the payload module. The cracking was on the opposite side of the two rods, which came out of their supports, which makes sense and supports the instability in flight. It was known that two of the rods had been cut too short by approximately ¼” but was deemed to not be a fixable problem without completely redoing the motor module. The lessons learned from this is that complete structural analysis in all flight loads would help to make sure the rocket actually will hold up in launch environments, and that careful manufacturing needs to be implemented to reduce building error. The other possible improvement would be to make sure everyone understands where possible sources of error would be to make sure they are critical failure possibilities.

For the deformation in the aluminum part of the payload structure this was caused by the load always taking the stiffer path. The in-flight bending moments went straight in to the aluminum structure and were able to bend it to one side slightly. This could have been the reason why the PolySat electronics appearance to be damaged from the structure moving. As far as the other payload components, the electronics were bent to the point of breaking the boards, the computer box casing was crushed on one side, and the IMU black box container ripped off. All of these things are believed to have happened on landing. From video it was seen that the camera inside was ripped off of its stand when it hit the ground. This suggests the rocket body experienced a lot of shock when it hit the ground without a parachute. The lesson learned is that for the payload module or important pieces, CPSS should be wrapping it with flexible foam to further protect it from moving around in the module even if it breaks off. This could prevent hardware from destroying other hardware on accident. In this case, the structure itself sheared which is what deformed most of the payload components. The shearing of the epoxy connections of the payload module was either from the flight bending or impact; either risk could be mitigated by more analysis and a larger margin of stability.

The parachute section performed similar to the parachute module of the first stage since it shredded both chutes and did not deploy properly. The nosecone fell off during the flight, which was one of the reasons why it went unstable so quickly. When the parachute released it had the opportunity to take the drogue chute out but not the piston. The piston was held in by the PIRM which should not have come out until a charge fired to release its cap. Since the drogue came out of the rocket early during the full power flight it shredded and the nosecone ripped off of the Kevlar chord. The in-flight forces were enough to bend the eyebolt on the PIRM and release the main chute prematurely. The main chute then proceeded to shred and the rocket flat spun to the ground. The cause of this problem was mainly the rocket going unstable and the loss of electronic connection in the rocket electronics. The lessons learned are the same for the second stage as it was for the first, in that CPSS needs to develop a better, more reliable parachute system. This is a common problem in rocketry and needs a better mechanical system.

IX. Conclusion

Five Cal Poly Space Systems students designed, built and flew a rocket in a contest to boost 10 pounds of payload to 25,000 feet. Architecture trades determined the best configuration was a two-stage rocket powered by commercial solid motors. The rocket used techniques novel to CPSS to solve inherent issues with a similar rocket built by the club the previous year. The rocket airframe emphasized strength and ease of integration, and allowed for the use of a novel staging device. A scaled-down version of the rocket was successfully flown in October 2011, and lessons from this small rocket were applied to the contest rocket, first flown in May 2012. The rocket payload was an IMU and associated data recording computer, a video camera, and a test article flown for PolySat.

The May 2012 flight of the rocket was a successful demonstration of the rocket structure, stage separation, second stage air-start, and first-stage recovery. The second-stage recovery system malfunctioned and the second stage needed to be rebuilt. Lessons from this flight were implemented in a re-design of the second stage.

The rocket's contest flight occurred in June 2012. The rocket performed successfully in the first-stage boost phase. A series of anomalies, however, lead to the second stage being unstable upon separation and the second stage tumbling out of control. The violent flight conditions lead to malfunctioning in both stages' recovery systems.
The rocket design and construction experience was valuable, and the team learned a great deal. Specific lessons were learned about rocket and airframe design, and teamwork in the design process. Other lessons were learned about rocket mechanism design, which have been documented for future members of CPSS to integrate into future projects.

While the rocket did not perform as expected at the contest in June, the robustness of the airframe design, fast fabrication and integration, and particularly the successful test flight represent success in CPSS' continuing pursuits in a challenging field. Future designs will integrate experimental propulsion, some form of guidance control, and improved airframe techniques to fly rockets to new heights.

Appendix

A. Competition Rules

Intercollegiate Rocket Engineering Competition Rules

Basic Category:

- Design, build and launch a rocket with a 10-lb (minimum) payload closest to 10,000 feet above ground level (AGL) (14,320 feet above mean sea level).

- Rocket must reach at least 5000 feet AGL and not exceed 12,000 feet AGL to qualify for any of the awards. This altitude will be taken from the approved on-board altimeter (see below) and verified by a judge or designated surrogate during ground recovery. If no altimeter reading is available, judges will have the discretion to estimate whether the rocket was within the qualification altitude band or not.

Advanced Category:

- Design, build and launch a rocket with a 10-lb (minimum) payload closest to 25,000 feet above ground level (AGL) (29,320 feet above mean sea level).

- Rocket must reach at least 12,500 feet AGL and not exceed 27,000 feet AGL to qualify for any of the awards. This altitude will be taken from the approved on-board altimeter (see below) and verified by a judge or designated surrogate during ground recovery. If no altimeter reading is available, judges will have the discretion to estimate whether the rocket was within the qualification altitude band or not.

Rules Common to Both Categories:

Rocket design/flight:

- All rocket and payload components must be recovered. Maximum points are awarded if components are in re-flyable condition after recovery (less consumables such as propellants or battery charge).

- Maximum points are given for student-designed and -built components (including propulsion), though commercial components are acceptable.

- Non-toxic solid, hybrid, or liquid propulsion is acceptable.

- The teams will be evaluated on team organization, clear assignments of personnel, use of checklists, communication discipline, and level of preparation/readiness for launch.

- Payload design is not specified. Rocket must be designed to deliver the payload to the target altitude independent of any payload function (i.e. the payload could be replaced with ballast of the same mass with no change to the trajectory). Bonus points will be awarded based on the judges' assessment of payload functionality and innovation.

- Rockets will be required to deploy their main recovery system at between 700 and 1500 feet above ground level (AFTER descending from apogee!). At least one level of redundancy is required for the initiation electronics (including sensors and batteries).

- Teams will be required to demonstrate the initiation of their recovery system before coming to the Competition. This can either be a ground test (by "fooling" the sensor used to initiate recovery) or a flight test. A video will need to be provided to ESRA or posted on a publicly available site such as YouTube.

- A commercial altimeter must be flown to verify peak altitude. If multiple altimeters are flown, the "official" altimeter must be chosen by the team and marked before flight. A judge or designated surrogate will accompany the ground recovery team to verify the peak altitude reported by the altimeter. The altitude must be verified prior to two hours before the Awards Banquet. Therefore, it is to your advantage to be "first in line" ready to fly.

- Each rocket stage must carry a **transmitter** provided by the Bridgerland Amateur Radio Club (**BARC**) to aid in finding the rockets after launch. This is a free service but will require a $75 deposit as part of the registration fee which will be returned once the transmitter(s) are returned in good condition after the flight. Teams are still responsible for finding their rockets; BARC cannot be held responsible for loss of points, etc., if the stage with the official altimeter cannot be found prior to 2 hours before the Awards Banquet. The transmitter should be placed in an RF-transparent portion of the airframe (e.g. fiberglass; NOT metal or carbon fiber composite), or have the transmitter attached to a parachute strap or other component that will be "visible" (in the RF sense) after recovery system deployment. BARC recommends packing the transmitter and antenna in 1'2" thick foam padding to help protect it. The transmitter includes a 6.25" whip antenna and weighs 30 g (1 oz) total.

Posters, Written Reports and Presentations:

"Basic" Category:

- Provide a 36" x 48" (approx) poster with a technical description of the rocket design. The poster needs to be self-supporting on a 6' long table (provided) since no partitions or other places to hang a poster will be provided.

- Have the team be present with the poster during the poster session to answer questions from the judges. An informal oral summary of the poster is recommended, followed by questions from the judges.

- Provide 10 copies of a summary of the poster (on standard 8 1/2" x 11" paper, 3 pages minimum) for the judges.

- E-mail pdf versions of the poster and summary to experimentalsoundingrocket@gmail.com at or immediately after the IREC for posting on the ESRA web site.

- Teams are welcome to take their posters back to their schools for display.

"Advanced" Category:

- A technical paper, no longer than 6 pages of text (including tables) and 2 (separate) pages of illustrations, describing the rocket design must be submitted to experimentalsoundingrocket@gmail.com by 1 June, 2012, 5:00 PM MDT. Late submissions will be assessed a 10% penalty for each 24-hour period after the due date/time. Click the links (all may not be active yet) for the **paper format** and papers from previous IRECs (note: there was no specified format in previous years).

- A 20-minute oral presentation on the rocket design will be given at the beginning of the competition. All participants are required to attend the presentations for their category (Basic or Advanced). Click the links (all may not be active yet) for the **presentation format** and presentations from previous IRECs (note: there was no specified format in previous years).

- A safety analysis (**example**) identifying potential hazards, risk assessment, and risk mitigating procedures must be submitted to experimentalsoundingrocket@gmail.com by 8 June, 2012, 5:00 PM MDT

Team composition:

- Teams must consist of members who were matriculated undergraduate or graduate students during the previous academic year (e.g. former students who graduated shortly before the IREC are eligible). There is currently no limit on the number of students per team or how many graduate students are allowed.

Budget:

- There is currently no limit on the teams' budgets for their rockets. The more sponsorships/donations you can get, the better!

Judging:

- Recruiter-Judges from industry and academia will evaluate the teams based on criteria in the **judging sheet**. The judges will use grading sheets to help them decide on points to award for the following criteria: **Operations**, **Student Design and Construction**, and **Payload** (more grading sheets may be posted later).

B. Budget

Category	Amt.	Cost Per	Estimated Cost	Source
Rocket Construction				
Fiberglass (50 inch width, 5.8 oz)	35	$ 7.35	$ 257.25	cstsales
Fin Plywood (part # 02-20650)	1	$ 86.00	$ 86.00	aircraft spruce
98mm Phenolic (x36in)	2	$ 23.50	$ 47.00	Public Missiles
Bulkhead Plywood (part # 02-26730)	1	$ 66.50	$ 66.50	Aircraft Spruce
Bulkhead Plywood (1/4")	1	$ 7.5	$ 7.5	Home Depot
Carbon Fiber Rod, 0.315" Dia., 2 m length (T348L2m)	10	$ 33.2	$ 332	cstsales
SkyAngle Cert 3Parachute Large	1	$ 90.35	$ 90.35	B2 rocketry
SkyAngle Cert 3 Parachute X-Large	1	$ 122.85	$ 122.85	B2 rocketry
8 inch PVC pipe sch 40	1	$ 83	$ 83	SLO farm supply
½ in Tubular Kevlar shock chord	50	$ 2.57	$ 128.5	Giant Leap Rocketry
Copper pipe end cap (1 inch dia)	6	$ 2.00	$ 12.00	Home Depot
West Epoxy Resin A105-B	1	$ 96.00	$ 96.00	cstsales
West System Epoxy Hardener A205-C	1	$ 96.00	$ 96.00	cstsales
Quick-Cure 5 minute Epoxy	2	$ 7.00	$ 14.00	El Corral
8” diameter Buna-N O-rings (9452K363)	1	$ 8.54	$ 8.54	Mc Master
Aluminum				
Aluminum 8 inch Stock for Sep-PIRM (1610T65)	1	$ 108.36	$ 108.36	Mc Master
¼ inch aluminum rod	1	$ 16.00	$ 16.00	Mc Master
bolts	1	$ 15.00	$ 15.00	Mc Master
Aluminum Stock for HAMR (1610T44)	1	$ 55.34	$ 55.34	Mc Master
#6 Anchors and Screws	1	$ 8.54	$ 8.54	Mc Master
Payload				
Artigo A1000 Computer	1	$ -	$ -	EBay
IMU	1	$ -	$ -	Donated
Polysat- Flatsat	1	$ -	$ -	Partnership
iFlip	1	$ -	$ -	Donated
Wiring	1	$ 50.00	$ 50.00	
Motors				
N-2000 Aerotech solid motor	1	$ 600.00	$ 600.00	Performance Hobbies
N-1000 Aerotech solid motor	2	$ 600.00	$ 1,200.00	Performance Hobbies
ML-24 Engine Igniters	1	$ 30.00	$ 30.00	What's Up Hobbies
eMatches	1	$ 56.00	$ 56.00	What's Up Hobbies
N-2000 Rousetech Casing	1	$ 550.00	$ 550.00	Rouse tech
N-1000 Rousetech Casing	1	$ 550.00	$ 550.00	Rouse tech
Flight Electronics				

G-Wiz LCX Flight Board	2	$ 108.00	$ 216.00	G-Wiz Partners
G-Wiz HCX Flight Board	2	$ 188.00	$ 376.00	G-Wiz Partners
G-Wiz USB Programmer	1	$ 35.00	$ 35.00	G-Wiz Partners
Red on/off flip electronic switches	4	$ 8.00	$ 32.00	Radio Shack
Baofeng UV-3R Dual Band Radio (UHF/VHF)	1	$ 42.80	$ 42.80	409shop
Testing				
Construction of Thing 1 Thing 2	1	$ 200.00	$ 200.00	Various
Other testing	1	$ 50.00	$ 50.00	Various
Travel and Competition Fees				
Entry Fee (8 students + advisor)	1	$ 400.00	$ 400.00	ESRA-IREC
Additional students	3	$ 50.00	$ 150.00	ESRA-IREC
Guests of students	0	$ 25.00	$ -	ESRA-IREC
Gas (1 car)	2	$ 300.00	$ 600.00	

Subtotal			$ 6,896.89
Tax (7.75%) and Shipping (8%)			$ 7,931.42
Total			$ 7,931.42

AJAKS ROCKET COMPONENTS	Quantity	$/ Quantity	Total	Store
98 mm Phenolic Motor Mount 4 ft	1	$36.25	$36.25	Public Missiles
DDP Carbon Fiber Rods .315 " (T348L2m)	5	$32.00	$160.00	CST Sales
West System - 105 Resin, 0.98 Gallon	1	$98.26	$98.26	CST Sales
West System - 205 Hardener, Fast Cure, 0.94 Gallon	1	$153.17	$153.17	CST Sales
Medium Latex Free Gloves case qt: 20 boxes	1	$95.99	$95.99	Gloves Online
Beeline GPS Antenna	1	$6.00	$6.00	Bee Line
AT-2B Transmitter (222.250 MHz)	2	$99.50	$199.00	Communications Specialists
PR-100 Receiver	1	$299.95	$299.95	Communications Specialists
Kevlar Parachute chord 20 ft	1	$29.99	$29.99	Giant Leap Rocketry
SkyAngle Cert 3 Drogue Parachutes	2	$20.00	$40.00	B2 Rocketry
Aramid Fire retardant sheets	1	$9.50	$9.50	B2 Rocketry
8” diameter by 3” Aluminum disk (1610T65)	1	$108.36	$108.36	McMaster
1/2" Aluminum stock	1	$18.32	$18.32	McMaster
6" Aluminum stock	1	$37.21	$37.21	McMaster
Bolts, Nuts, Screws for skin and mounting	1	$50.00	$50.00	McMaster
Electrical Harnessing: Tamiya connecters, switch	1	$50.00	$50.00	Radio Shack

Subtotal			$1,398.90	
Tax (9%) and Shipping (8%)			$237.81	
TOTAL			$1,636.71	

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