The Invisible Man

University of Minnesota,

Twin Cities

Wisconsin Space Grant Regional Rocketry Competition

April 26-28, 2013

Toni Carlstom, Andi Meyer, Luci Baker, Alec Decker, and Charles Schafer

With counsel from Dr. James Flaten

Table of Contents

Executive Summary

Things we cannot see are extremely difficult to understand. The Invisible Man Rocketry team from Minneapolis, Minnesota set out to understand the air which we all breathe but cannot see. Through the years we have gained a general understanding of how it works, shifting the leaves in the fall and feeling hot and heavy in the summer. However, in engineering air is more intricate and interesting than we had known. In building a rocket to reach 3000 feet in any weather conditions, within design restrictions, we decided to create a rocket with variable mass and drag coefficients to change the apogee altitude of the rocket in various wind speeds. Other restrictions to the rocket design included a maximum mass without the motor of 7.5 lbs, a maximum body tube diameter of 4 inches, a maximum length of 72 inches, and the use of the Cessaroni I540 rocket motor.

To change the coefficient of drag of the rocket, it was determined that surface finish and rocket shape were the two main factors that could affect the drag of the rocket. We decided to make custom fin sets that could be interchanged through bolting them to the rocket to vary our drag. Ultimately, a design decision to use clear polycarbonate tubing as the airframe of our rocket resulted in a rocket that was too heavy and had too much drag to reach the target altitude in all wind speeds. The tubing we chose was thicker than typical airframes used for rockets and polycarbonate is dense, so the rocket has a lot of mass due to the airframe.

It is better to have a rocket that would overshoot in all wind speeds than not make the altitude, because we could always add mass to the nosecone in the form of either putty or lead sheeting. It was decided that the brackets to which the interchangeable fins bolt to and the bolts themselves were causing too much drag. Also, the airframe was unnecessarily long resulting in excess mass, so it was decided that we could make interchangeable bottom halves to our rocket as well. The New bottom half was designed to allow easy access to an ejection charge mounted near the end of the motor, reduce drag, and reduce weight. The fins were downsized slightly, and designed to be inserted in slots through the airframe and epoxied to the motor mount tube. The new bottom half was cut three inches shorter than the old bottom half, and a permanent coupler was installed in the top half of the rocket to attach to both bottom halves.

To better understand the forces at work on the rocket, wind tunnel testing was performed on the rocket with both the old and new bottom halves. In addition to this, the rocket was tilted downwards in an attempt to determine the experimental center of pressure. We plan on using these gathered values, in addition to the center of mass of our rocket, to determine the apogee height of our rocket using the computer program Rocsim. These wind tunnel tests, in addition to test launches, will allow us to accurately predict the apogee altitude of our rocket.

Invisible Man CAD Design

The final Design of the Invisible Man consists of two separate bottom halves which can be interchanged based on the amount of drag we need to reach our target attitude on the day of the launch. Originally, the rocket was designed with interchangeable fins and a single airframe. Figure 1 shows this design in an exploded view. Note the dog collar GPS unit that mounts in the nosecone so that the location of the rocket can be determined.

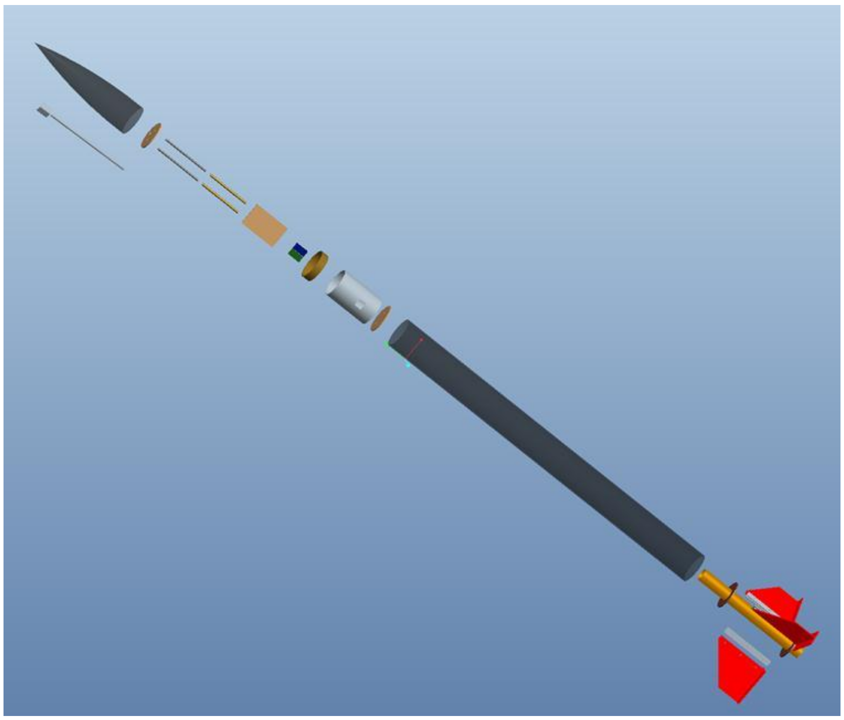

Figure 1 Invisible Man Original Design

However, the original rocket design had too much drag to reach a 3000 foot apogee in all wind conditions, so it was cut in half and a new bottom with decreased drag was created. Figure 2 shows the rocket with the original, or old, bottom half. Note that the fins are held on by brackets and can be interchanged. During parachute ejection, the rocket splits at the nosecone, with the avionics bay acting as a coupler between the body tube and the nosecone. It is riveted to the nosecone. The coupler connecting the bottom and top halves of the airframes is epoxied in place on top and riveted to the bottom. To ensure that the parachute is ejected outwards, instead of compressed into the rocket by the ejection charge, the charge is mounted on a centering ring which can also be changed between rockets. Figure 3 show the two sets of fins that were actually manufactured to change the drag of the old bottom half. One of the sets has 1 inch wide plates epoxied to the bottom of the fins to act as a permanent airbrakes.

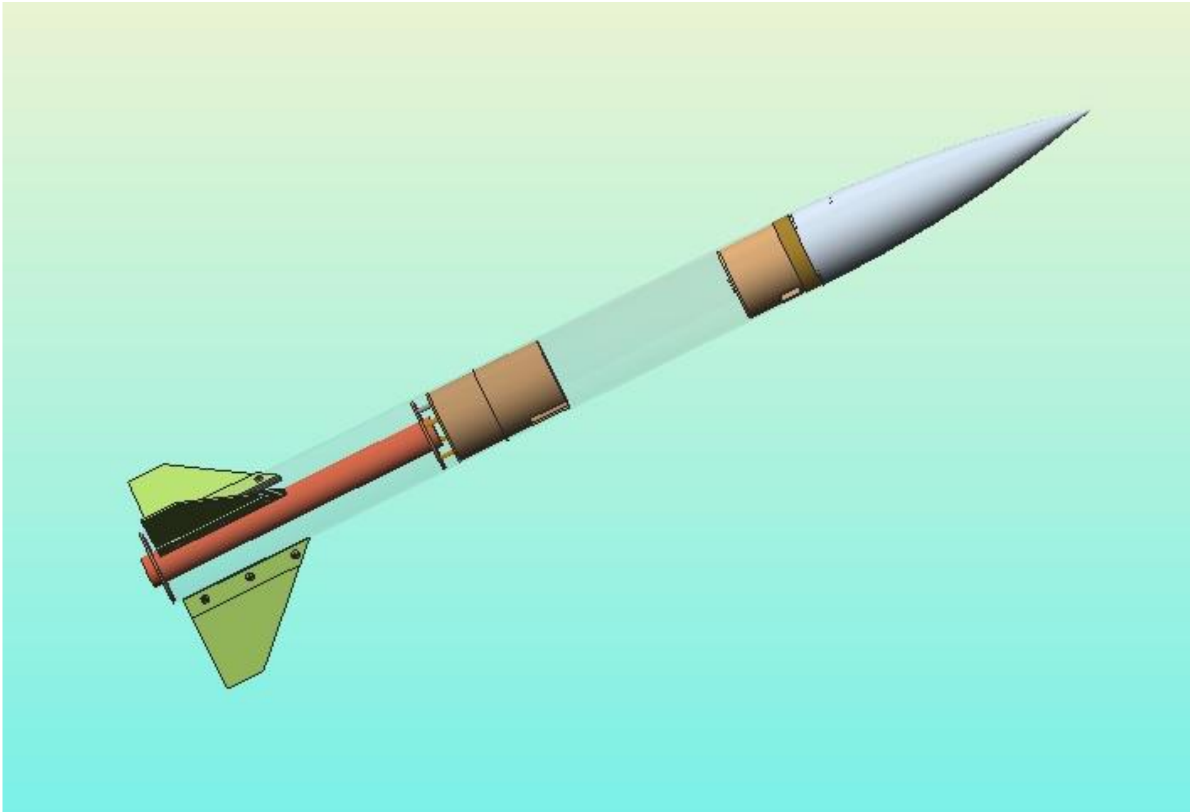

Figure 2 Invisible Man with old bottom half

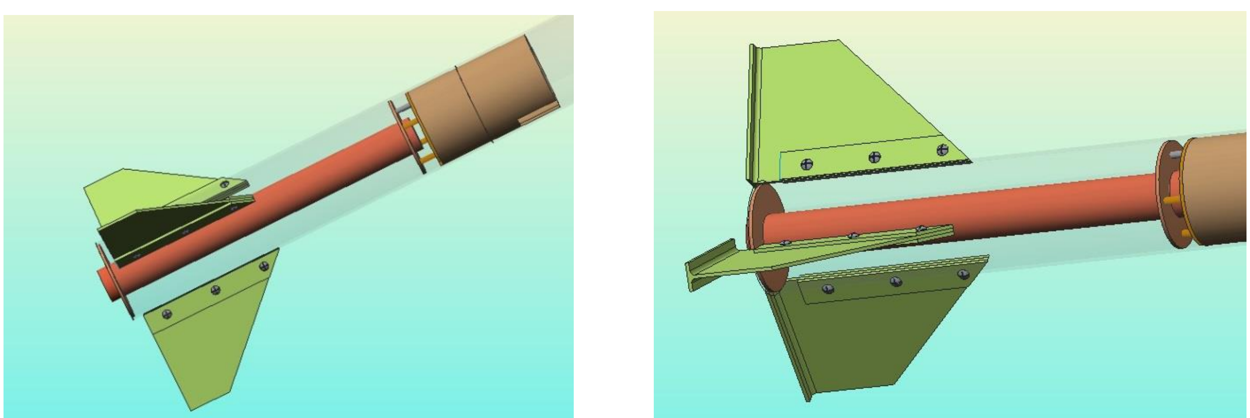

Figure 3 Invisible Man with low and high drag interchangeable fins

The new bottom half is shorter and has permanent fins to create a rocket with less drag and mass to reach a higher apogee altitude in all weather conditions. Figure 4 shows the rocket with the new bottom half. Note that the new fins go all the way to the motor mount tube and that the upper half of the rocket is the same as with the old bottom half. The total length of the airframe was reduced to reduce mass.

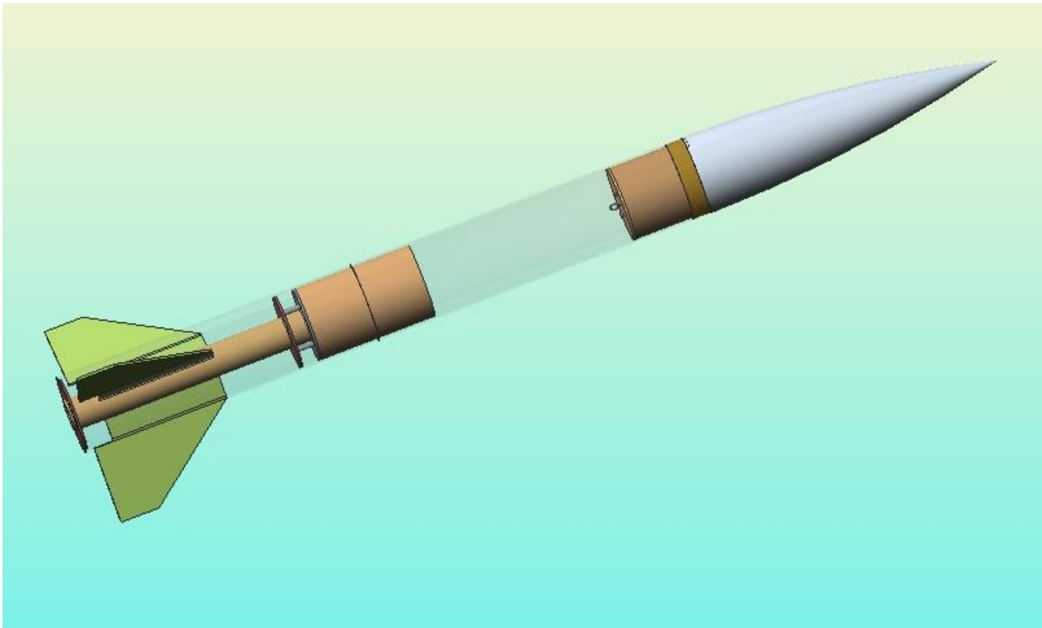

Figure 4 Invisible Man with new bottom half

Rocket Build andTechniques

The Invisible Man rocketry team was part of a freshman seminar on rocketry offered at the University of Minnesota, Twin Cities. As a result, the rocket was initially designed and constructed in November of 2012. The team had plenty time to test and modify the design. The original plan was to have a clear body tube, removable fins, and multiple nose cones with different surface finishes. The removable fins and different nose cones would allow us to change the drag of the rocket and therefore change its apogee altitude. Space in the avionics bay and nosecone of the rocket would also allow us to add mass in different places to change the center of gravity, tweaking the static margin, to change the apogee altitude based on the amount of thrust the Cessaroni I540 provides and the degree to which the rocket windcocks.

Since the rocket was originally built as a part of a class, it had outside goals associated with its construction. One of these goals was to make it a good educational model. To do this the team opted for a clear body tube. The clear tubing would allow people to easily see the inside components of the rocket. Different materials were researched to find a clear tubing that would be strong enough to act as the airframe, and ultimately polycarbonate was chosen. Based on mass considerations, the rocket would theoretically be able to reach 3000 feet in all conditions even with additional airframe weight.

This design choice had many important consequences. The first was that although the tubing had a 4-inch outer diameter, its interior diameter was 3.75 inches. Most rocket construction items such as centering rings do not come standard in this size, so many modifications were made to ordered parts. The mass of the polycarbonate also limited the length of our rocket due to its mass. A standard motor tube epoxied into the airframe using centering rings sanded to the correct outer diameter. Knowing that they would be visible from the outside, the team opted to add color to the centering rings with drawn designs. The shock cord was attached to the motor tube and all of this was held in place with DP 420 No-sag epoxy. Customized slots and fins were cut out of G-10 fiberglass sheet. The slots and fins all had three holes in them for where the bolts would go through. Figure 5 shows an image of the fin slots on the original rocket and the custom-cut fins with channels bolted to them. Note that the slots are surface mounted to the polycarbonate tubing. When cutting slots in the polycarbonate tubing from the edge of the tube up, the tubing bent in on itself. Slots from the bottom were one possible design for removable fins. However, after seeing the pre-stressed tubing cave in, this design was never realized, and as a result the slots were designed to be and were surface-mounted.

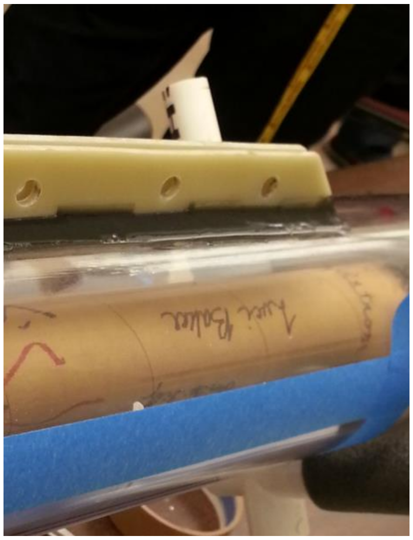 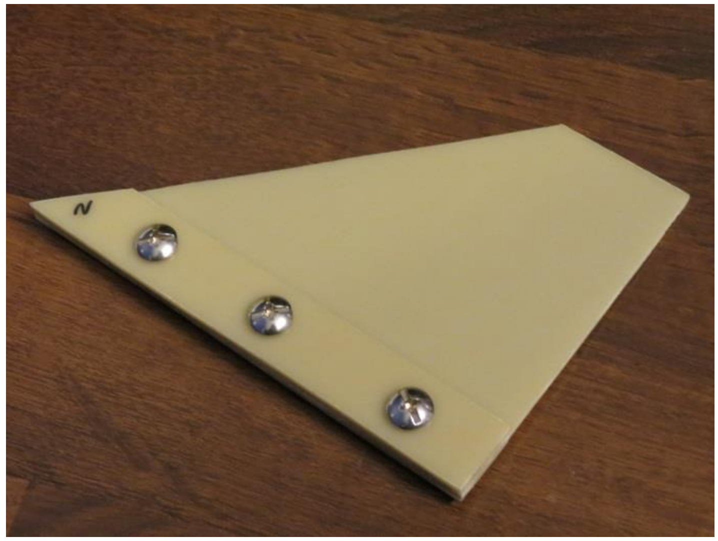

Figure 5 Invisible Man surface-mounted fin slots with holes for bolts and Fin bolted in slots

The slots were tacked on with fins bolted in place. A sheet of wax paper protected the fins from epoxy. The slots were then fileted using DP 420 No-sag epoxy. Before the HAMR retention system was JB welded to the end of the motor mount tube, a small piece of wood was inserted and a rail button was screwed into it. Rail buttons were chosen because they offer more stability during launch than surface-mounted launch lugs. We included the pieces of wood to give the screws extra material hold to, ensuring that they would not come loose during take-off. The rail buttons were also secured with a dab of epoxy. The second rail button was put near the center of gravity (without the motor). This is in the area that houses the parachute so we made sure that epoxy covered the sharp tip so no damage would be done to the parachute. With the rail buttons securely in place the bottom centering ring was epoxied in flush with the bottom of the airframe and the motor retention was JB welded on.

To prepare the 16” ojive nosecone to be coupled to the airframe with the avionics bay, it was cut off below the shoulder. The shoulder would not fit into the polycarbonate tubing, so we customized an avionics bay to double as a coupler. The avionics bay came as a standard size, close to what was needed, so some material was peeled off and then it was reinforced with strapping tape. A customized centering ring was epoxied inside the upper part of the nosecone so that a dog collar GPS unit could be bolted in place. This will aid in the recovery of the rocket. The nosecone was then attached to the avionics bay with six rivets. Figure 6 shows the avionics bay riveted to the nosecone.

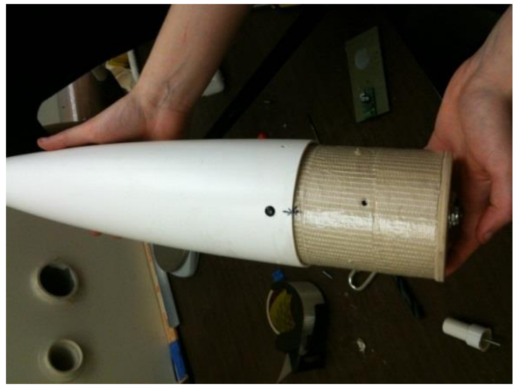

Figure 6 Avionics bay riveted to nosecone

Holes were drilled near the top for the rivets and holes were also drilled near the bottom for shear pins. The Avionics bay is held inside the polycarbonate tubing with three sheer pins to prevent premature drag separation during the ascent portion of the flight. Another hole was drilled through the airframe and the avionics bay for venting for barometric altitude sensors and as a hole to activate the altimeter when it is on the launch pad. Inside the avionics bay is a sled that contains a Raven 2 Altimeter and wires that lead from the altimeter to a black powder charge. Figure 7 shows the interior of the avionics bay during assembly. Originally, the black powder charge was located on the bottom plate of the avionics bay. In the new design it was moved to the bottom of the ejection chamber to ensure that the ejection charges would push the parachute out of the cavity. A welded eyebolt was put on the bottom plate, to which the shock cord was attached. Nomex cloth was then attached to the shock cord to protect the parachute which was located 1/3 of the length from one end of the cord. This is the construction that was initially used for the first test flight last December.

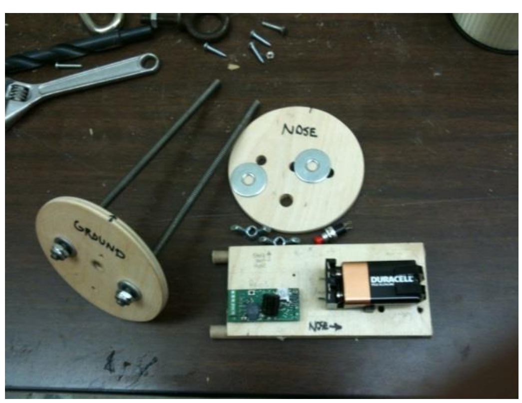

Figure 7 Avionics Bay during assembly

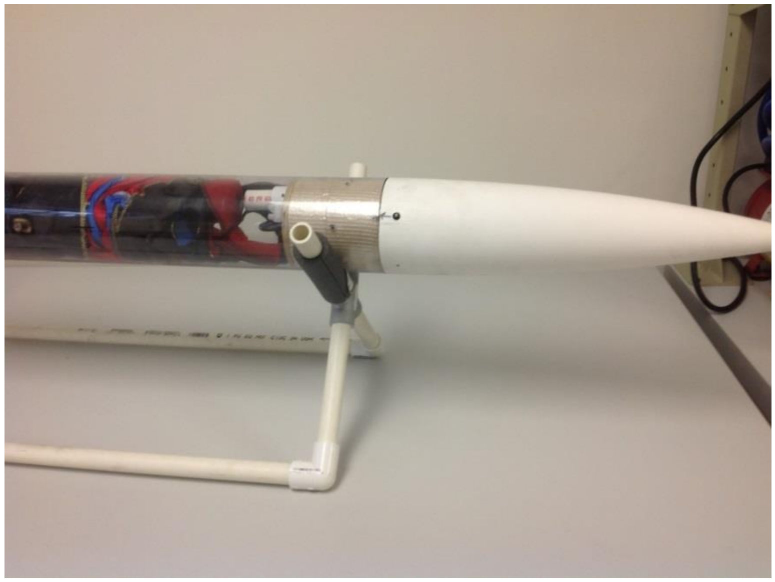

Figure 8 Original Invisible Man, note the ejection capsule mounted to the bottom of the avionics bay.

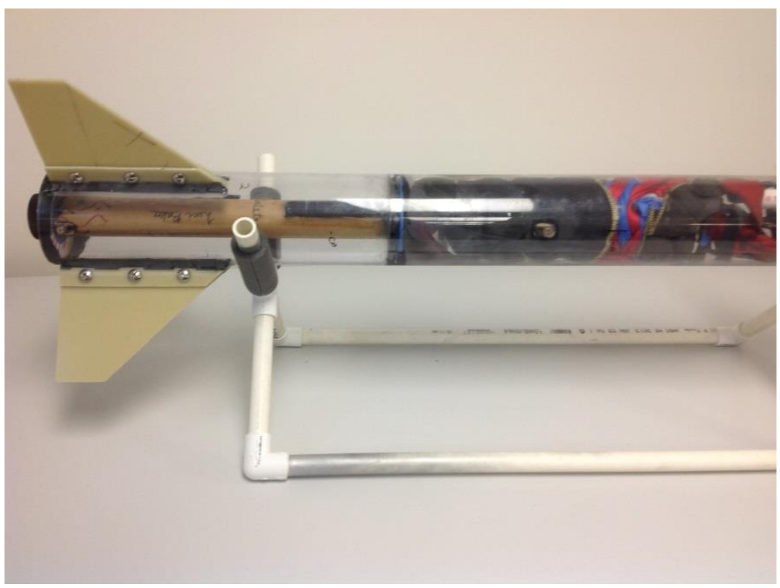

Figure 8 Original Invisible Man view of fin mounting system

Since the Invisible man was already a fully constructed rocket at the beginning of 2013, there was a lot of time to look at the rocket's performance and make modifications to improve its performance before the competition. In the first test launch, the rocket undershot its predicted altitude by over three hundred feet. This would make it impossible to reach a 3000 foot apogee in all wind conditions, so we wanted to make it lighter and decrease drag. We also opted to move the ejection charge from the bottom of the avionics bay facing aft to the top of the top centering ring for the motor tube, facing towards the nose, because another team from the freshman seminar on high power rocketry experienced issues with their parachute not coming out due to ejection charge configuration. This seemed like a better configuration for our parachute to be pushed out of the airframe.

To modify the ejection charge we had to be able to access the center of our rocket. We combined this with our goal to lighten the rocket and decided to cut the rocket above the top centering ring of the motor tube. We then constructed a new bottom half that was shorter and therefore lighter. It also has permanent fins rather than removable ones. To reduce drag due to the bolts and the slots. This bottom half was constructed just as the first one was with the exception that slots had to be cut into the body tube and more filets were done on these fins because they extended into the interior. To prevent the polycarbonate tubing from caving on itself, slots were cut a generous distance from the end of the tubing and the length of the fin inside the tubing was minimized.

A coupler had to be made to be able to reattach either bottom half to the airframe. It was made out of a regular coupler that was sliced vertically and epoxied inside the upper airframe. Cutting it allowed it to fit inside since it had too large of an outer diameter. Six holes were drilled equidistantly around the top of each bottom half and in the coupler. These holes line up and allow the two sections to be attached with six small rivets. To have the charge at the bottom of the airframe and be able to be on either bottom half we designed a floating centering ring that could be bolted into either bottom half. This centering ring has the ejection capsule for the black powder charge mounted to it. Figure 9 shows the new bottom half of the rocket. Note the Floating centering ring and ejection capsule, constructed from white PVC tubing. Wires were then run from the avionics bay down the side of the airframe to the black powder charge. These wires will be held in electrical connection to the aviation bay using solder to ensure they do not separate due to the forces experienced during launch. At the bottom, they are connected and taped with electrical tape to the leads for the e-match which will ignite the ejection charge. As a requirement for the competition, the motor eject charge will still be in place. If the ejection system ignited by the avionics bay fails, the rocket will not lawn dart but will still eject the parachute. Ejection charge testing has revealed that with three sheer pins and considerable friction in that joint the rocket will require 4 g of black powder to fully eject the parachute. Because the motor does not come with that much black powder, the motor charge will be augmented with black powder taped to the end of the motor held tight inside the motor casing.

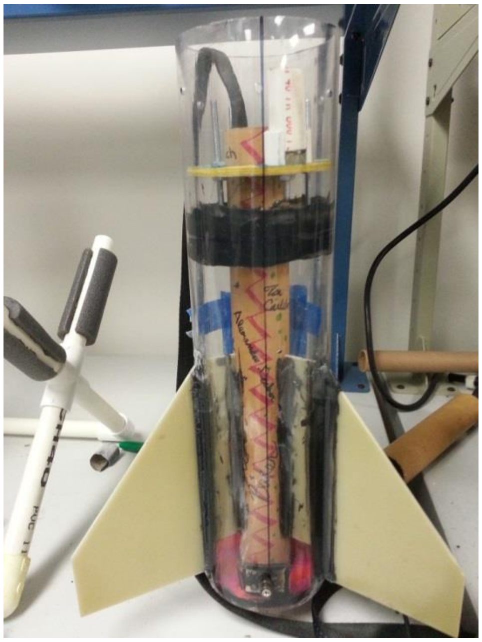

Figure 9 Invisible Man new bottom half

Aerodynamics

The main way to reach the targeted apogee with this rocket is by changing the drag. We wanted to minimize the drag and then have a way to increase it if need be depending on the weather conditions the day of launch. To minimize the drag we went with an ogive nosecone that was sanded down and painted with a glossy clear paint. Only 3 fins of a delta shape were used. Our rocket design is based primarily around manipulating the drag of the rocket and the mass. We rely very heavily on Rocksim simulations to hit our target altitude, and determine what the mass and drag should be so it was necessary to have a very accurate model of our rocket in the program. Rocksim calculates a value for the coefficient of drag, but we needed to determine the value experimentally to ensure it was correct. We were able to test our rocket in a wind tunnel and measure the drag force acting on the rocket at several wind speeds. The wind tunnel's maximum wind speed was about 100 ft/s, and our rocket's maximum speed is about 530 ft/s. However, even at altitude, this maximum speed is only Mach 0.48, which is well below the speed at which the compressibility of air becomes important. Therefore, we can extrapolate the results of our low-speed wind tunnel data to the rocket's high-speed flight.

Using the equation $C_d = \frac{2*Drag}{(air\ density)(windspeed)^2}$ and the data from the wind tunnel tests (subtracting the drag force exerted on the mounting hardware), we calculated our coefficient of drag to be 0.626 (for the rocket with the second bottom half, standard fins). This was much higher than we wanted it, so after refining our rocket, we did another set of tests and calculated our new drag coefficient to be 0.479. The full results of wind tunnel testing are summarized below.

Coefficient of Drag for Each Fin Set

Fin set	Coefficient of Drag
First bottom half, standard fins	0.450
First bottom half, drag plate fins	0.959
Second bottom half, standard fins	0.477

Anticipated Performance

Unfortunately, variations in motors exist up to 20% of the predicted thrust. Our method of attaining a 3000 foot altitude is completely passive, and the apogee altitude will be affected by deviance from expected motor performance. What we can do is configure the mass and the drag of the rocket to reach 3000 feet by our calculations and test launch as much as possible to determine how much of a factor motor variation really is.

Stability

We used wind tunnel testing to find our center of pressure experimentally. By pitching the rocket to a negative angle of attack and measuring the moment about the transverse axis of the rocket and the force exerted normal to the its long axis, we were able to calculate the distance from the center of pressure to the pivot of the mounting hardware with the equation $distance = \frac{M_{trans}}{F_{norm} * \cos(\alpha)}$.

We found the center of pressure to be located 38.6 inches from the nose. The body diameter of the rocket is 4.00 inches. The CG was located by hand for each rocket condition, and the static margin was calculated according to the formula $M = \frac{38.6 - CG}{4.00}$.

Static Margin and Stability Pre-launch, on Pad, and Post-launch

	CG (inches from nose)	Static Margin (calipers)
No Motor	32.55	1.51
Motor Installed	30.30	2.08
Post-launch	31.50	1.78

The rocket's static margin will vary between 1.78 and 2.08 during the flight, and will therefore remain stable or overstable at all times.

Recovery Systems and Avionics

We are using a RavenTwo altimeter to record the flight profile and to eject our parachute at apogee. We have a single main parachute which is 60 inches in diameter; there is no drogue. The altimeter will be wired to the ejection charge through all four pyro channels for redundancy in case any of the wires should fail. Two channels will send current through the ejection charge when the altimeter detects apogee based on accelerometer data; the other two channels will go when apogee is detected barometrically. The channels are programmed with the Featherweight Interface Program, so no coding was required on our part.

Test Launch

Our first test flight took place in December. We used Rocksim to predict the flight profile, taking into account the wind speeds observed at the launch site: almost none on the ground, with an estimated 5 mph breeze at about 2500 ft. The Rocksim predictions and the actual values from the altimeter are compared below:

Rocksim Predictions vs RavenTwo Data for First Test Launch

	Rocksim	RavenTwo
Wind Conditions	3-7 mph	N/A
Apogee Altitude	3173 ft	2843 ft
Top Speed	360 mph	330 mph
Time to Apogee	13.6 s	12.6 s
Time from Apogee to Ejection	0 s	5.2 s
Ejection Altitude	3173 ft	2376 ft
Descent Speed	25 ft/sec	16 ft/sec

There were also some deviations from our expected flight profile. The most significant was the difference between our expected and actual apogee altitude: Rocksim predicted that we would reach 3173 ft, but our actual altitude was 2843 ft. For the competition, this 330 ft discrepancy was concerning. We corrected this by improving the accuracy of our Rocksim simulations in the ways outlined in the next section.

At the test launch, we discovered a significant problem with the altimeter eject: we had a single wire running from the altimeter to our ejection charge, and it came loose during takeoff. We had a backup motor eject that successfully ejected the parachute 5.2 seconds after apogee, causing a dent in the airframe (the strength of the polycarbonate prevented a zipper) but saving the rocket. To correct this, we put in redundant wiring, connecting all four pyro channels on the altimeter to the ejection charge. We also will check that the wires are securely connected at both ends before each launch. To avoid denting or zippering the airframe, we will grind our motor eject delay to just 0.5 seconds after apogee rather than 2 seconds.

Our new expectations for launch day are that the altimeter will eject our single parachute at apogee, and the backup motor eject will fire half a second later. Using our much more accurate Rocksim predictions, we will be able to adjust the mass of the rocket so that it will hit a 3000 ft apogee in various weather conditions.

Simulations

We use Rocksim to simulate our launch. This program takes rocket characteristics, launch site conditions (weather, altitude, launch angle), and motor choice as inputs and returns predictions for maximum altitude, velocity and acceleration; time to apogee, total flight time, range, and velocity and altitude at deployment. It also shows an animation of the simulated launch.

Our early simulations were somewhat inaccurate. However, we have made improvements by entering more complete and accurate information about the rocket and the weather and launch conditions into Rocksim. Instead of using the "3-7 mph" option for wind speed, for example, we can enter more precise custom options, including the condition where there is wind at altitude but not on the ground. We will get this data from aviation weather sites, which list wind speeds for altitudes as low as 3000 ft, as well as general weather sites to get the local ground wind speed. Additionally, we can include factors such as a nonzero launch angle, the elevation of the launch site, and weather conditions such as temperature, pressure, and humidity. The more accurate wind conditions, however, will likely have the greatest effect. This is because a larger wind speed will result in more windcocking of the rocket and therefore a lower apogee altitude.

In addition, we have made the model of our rocket in Rocksim more accurate by determining experimentally the mass, coefficient of drag, and centers of pressure and gravity of the rocket and using them to override Rocksim's calculated values, which we found to differ significantly. When we reran our original simulations with more accurate inputs, we found the simulations to agree pretty closely to the data from our first test flight, indicating that Rocksim is a fairly accurate predictor of our flight profile and, most importantly, our apogee altitude.

Predictions for Next Flight

We will run the final simulations on the day of the competition using the current local wind speed and weather conditions and adjust the mass of the rocket accordingly. However, we can run simulations now for a variety of wind speeds, which gives us an approximate idea of what mass the rocket should be for each range of wind speeds. These predictions assume that our rocket's coefficient of drag is 0.45 (i.e. we are using the bottom half with permanent fins), a launch angle of 5^0 off vertical, and weather conditions of clear and 70^0F.

Predicted Flight Characteristics For Several Wind Speeds, mass adjusted for proper apogee altitudes

Characteristic	Wind Speed			
	0-2 mph	3-7 mph	8-14 mph	15-25 mph
Max speed (ft/s)	554	547	547	547
Max accel (G's)	17.4	17.2	17.2	17.3
Time to apogee (s)	12.9	12.9	12.9	12.9
Total flight time (s)	132	134	216	160
Range (ft)	490	1650	3560	3600
Apogee (ft)	3008	2995	3004	2998
Mass (oz)	104	105	105	104.5

It is interesting to note that the required mass of the rocket differs only within an ounce for wind up to 25 mph. It also does not vary linearly with wind speed. We need to make the rocket heaviest when the wind is around 10 mph and somewhat lighter on either side of that. Because the required mass varies by so little, we need to carefully measure of our rocket's mass after putty has been added and before it is launched.

Launch Checklist

____Wire ejection charges

_____Fold parachute

____ Pack parachute into upper body tube

_____Place dog collar GPS system into nosecone

_____Link dog collar with handheld GPS device

____ Load altimeter into nosecone

____Attach nosecone to upper body tube with rivets

____Attach Avionics Bay to airframe with sheer pins

_____Attach upper body tube section to lower body tube section using rivits

____Cover gaps between sections of the rocket with release tape

_____Load motor into motor casing

____ Load motor casing into motor mount tube and secure using HAMR system

____ Secure rocket to launch rail by rail buttons

____Place igniter into rocket and secure with tape

____Turn on the avionics bay

____Retreat to safe distance and launch rocket by triggering igniter

Budget

There were two different budgets that concern this rocket: money and weight. The initial rocket was built in a class taken at the University of Minnesota, and the money budget for it was $400. After the end of the semester, additional funds were available to help us prepare for the competition. Below is a table of the components of the rocket and their costs. Thankfully all tools were available to us either through the University of Minnesota's rocketry program or the mechanical engineering student shop.

Part	Cost
Ogive Nosecone (x2)	$17.80 (2) = $35.60
38 mm HAMR retention system	$28.95
Centering Ring (x3)	$3.26 (3) = $9.75
10/10 Rail Buttons (x2)	$3.50 (3) = $7.00
Spacer for Motor Casing	$8.95
Motor Mount Tube	$10.50
Harness, 9/16" Tubular Nylon Webbing (x20)	$0.30 (20) = $6.00
Shock Cord Heat Protector (1/3)	$16.95 (1/3) = $5.66
Forged Eyebolt (x2)	$2.00 (2) = $4.00
Quick Link (x2)	$2.25 (2) = $4.50
Rivets	$2.75
Flame Shield	$16.00
LOC Precision Avionics Bay	$31.50
6-grain Motor Casing	$57.15
Polycarbonate Tubing	$54.32
Parachute	$74.00
G-10 sheet (x2)	$26.46 (2) = $52.92
Wood Screws	$5.00
Primer/paint	$20.00
Dog Collar GPS System	$200
Raven Altimeter	$155
Misc. Hardware	$40
DP 420 NS epoxy	$22.62 (6) = $135.72
Additional Polycarbonate Tubing	$27.16
Additional Shock Cord	$4.80
Additional Rail Button	$3.50
Additional Motor Mount Tube	$5.75
Additional Centering Rings	$3.25 (3) = $9.75
Additional HAMR retention	$28.95
Coupler Tube	$8.42

Other (e-matches, wiring, solder, black powder, sandpaper, ect.)	$40
Total	$1133.60

Below is a table illustrating the rocket components and their specific masses.

Part	Weight
Airframe	34.2 oz
Nosecone	7.7 oz.
Nosecone Rivets	0.5 oz.
G-10 Fines	9.1 oz
Parachute	8.3 oz.
Motor Mount Tube + Shock Cord + 1 centering ring	9.3 oz.
HAMR Retention System	4.0 oz.
Centering Rings (2)	1.5 oz.
Eyebolt + Quick Link	4.1 oz.
Epoxy + Primer + Paint	5.0 oz.
Avionics Bay	9.5 oz.
9-V Battery	1.6 oz.
Altimeter	0.8 oz
Wiring	0.3 oz.
GPS	5.5 oz.
Flame Shield	2.0 oz.
Shock Cord Protector	0.5 oz.
Total	103.9 oz