Qu8k

By Derek Deville
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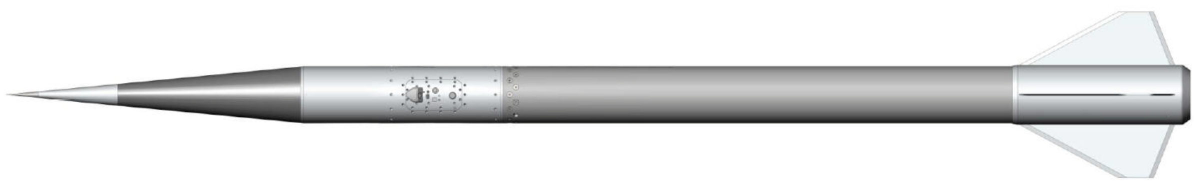
8" diameter
167.5" long
320 lbs liftoff weight
Q-18,000
143,000 N-sec
4,000 lbs of thrust for 8 seconds
121,000' Max Altitude
3,200 ft/s Max Velocity
92 seconds to apogee
8.5 minutes total flight time
900 ft/s maximum velocity during recovery
Full recovery 3 miles from launch site



Summary

The Qu8k rocket (pronounced "Quake") was launched successfully from the Black Rock Desert on September 30, 2011, at 11:08am PST. Qu8k boosted perfectly straight, clearing the tower in three tenths of a second. Accelerating at up to 15g's, Qu8k was traveling at a peak velocity of 2,185 mph as it passed through 17,000 feet in only 10.5 seconds. Coasting upwards for another 80 seconds, a maximum altitude of 120,926 feet was achieved before the parachute was deployed. At that point, Qu8k was above 99% of the atmosphere, causing the sky to go black in the middle of the day. The curvature of the earth is clearly visible in the videos from the two on-board cameras and is accented by the thin blue line of atmosphere. These on-board video cameras captured the magnificent views of the desert and surrounding areas of Northwestern Nevada, with a geometric horizon extending to the Pacific Ocean. The full-length video was posted on YouTube on October 6th and, as of this report, has over 800,000 views. The summary video, as of this report, has over 300,000 views.

Qu8k deployed its recovery parachute 90 seconds into the flight and descended to Earth over the next seven minutes. Landing only three miles from the launch point, the rocket was fully recovered and could be easily prepared to fly again. The rules of the Carmack Challenge state that a GPS reading over 100,000' must be obtained. Although there were four independent GPS systems onboard Qu8k, none were able to maintain positional lock through the high acceleration

and velocity of the flight's boost phase. Nonetheless, accelerometer data and knowledge of the time to apogee from video made it possible to verify the 121,000 foot flight with high certainty.

History Leading Up to Qu8k Design

I started building high-power rockets in 1997. Almost immediately, I began to dream of building an all metal, mach-busting, high altitude rocket. A few years later, I was successfully making 6 inch motors and envisioned making an 8 inch. I purchased an 8-inch diameter, 8-foot long aluminum tube in anticipation. Time passed and I never built anything with that tube. Fast forward to 2011, while on vacation in North Carolina during the Fourth of July holiday, I learned about the Carmack 100k Micro Prize. It had been a few years since my last project and I believed that my work schedule could accommodate a rocket build, so I thought that this was my chance. After researching the Class 3 waiver requirements, I realized that I would have to submit my data immediately just to have a chance to fly at BALLS 20. Over the long holiday weekend, I designed Qu8k in SolidWorks. During that time, I downloaded BURNSIM and RAS Aero and ran simulations. By the end of the weekend, I had a complete package to submit to the

Tripoli Class 3 committee. Kent Newman and the Class 3 committee were able to turn over my submission quickly and, by the end of July, I was ready to submit my application to the FAA.

It was now time to decide if I was going to do this or not. So far, the only hardware I had was that 8-inch motor tube. Could I even get this thing done in time? I ran a quick schedule and it looked possible, but tight. But I still didn't know how I could afford this project. My employer, Syntheon, had agreed to support the effort with machining time but I still needed some help with all the other expenses. I started talking to my friends and co-workers. Greg Mayback our patent attorney stepped forward. He and his firm, Mayback & Hoffman, P.A., which specializes in patents and trademarks, agreed to help out financially. With that added support and my wife's approval, Qu8k was a go.

I began ordering metal stock and refining the design. On August 8th, chips started to fly in the machine shop. The first big challenge I encountered was how to get the rocket to Black Rock. I explored driving it myself but, without anyone to ride with me, that became insurmountable. Not accepting defeat, Mark Clark introduced me to Tom Blazanin and Dave Rose of Tripoli Pittsburgh. They said that they could make space for just my motor if I could get it to them before they departed Pittsburgh on the 23rd of September. This seemed like the only way. I could drive to Pittsburgh, but now I would be required to have the project done about a week earlier than I had planned. The race was on. I set the deadline to be Labor Day weekend (Sept 3-4) for casting the motor. If the motor wasn't done by then, I would surrender the project.

Launch Tower

Importantly, I needed to know how I would launch Qu8k. My initial plan was to borrow a launcher at BALLS. This plan had a few issues. If there were to be multiple teams all making launch attempts for the Carmack Prize, then I wanted to have the best chance of launching first. I was concerned that anyone who would loan their pad would want to launch first, especially in view of the possibility that if my rocket failed it could destroy their pad. Also, most pads require use of a launch lug or rail guide. These protruding parts on a rocket create lots of drag. By removing these parts, simulations showed I was able to increase peak altitude by over 10,000 feet. The desire to keep drag low and have full control over when the pad would be setup and available for launch drove me to make my own launch tower.

The tower that was used for CSXT had been destroyed by the forces of launch and caused a slight tip-off that sent the rocket further downrange than planned. I did not want to repeat this. So, I set about designing a sturdy tower using Unistrut. I called my good friend, Guy Kress, who had built the large launch pad for Tripoli South Florida that I had used to launch Black Dragon. I asked Guy if he was willing to build Qu8k's tower. He seemed agreeable, but when I told him that it had to be done in 5 weeks, he almost fell over. This was a huge undertaking. Ever the optimist, Guy agreed. He labored tirelessly on the structure for weeks on end. I kept pulling in the timeline because I needed part of the tower for casting the motor. I pulled it in further when I decided to do a full scale up-righting test. Finally, I pulled the schedule in even further by deciding to ship the launch tower by ground freight all the way across the country. Guy continued to deliver time and again. In the end, he created one of the most amazing launching structures I have ever seen. And of course, it proved itself in practice, meeting and exceeding all the requirements. It supported the rocket well, was easy to assemble and disassemble, was easy to up-right, and gave Qu8k a perfect start on its stratospheric flight.

Recovery

So far, I only had a placeholder for recovery. It is widely known that recovering rockets over 100k feet is a daunting challenge. I knew that black powder charges are efficient and reliable for nose cone ejection. However, at 100k feet, where there is virtually no atmosphere, burning black powder is a real trick. Lots of experimentation has been done using surgical tubing or other constraint methods to use black powder in a vacuum, but the problem is greater than just making it burn. In a vehicle that is going over 100k feet, the atmospheric pressure at that altitude will be well below 1 psi. This means that if sea level atmosphere is trapped inside your rocket, it could create over 14psi of internal pressure. With an 8" diameter rocket, there are about 50 square inches of area on the bottom of the nose cone. At 14psi, means that 700 pounds of force would be driving the nose cone off just from this pressure. Trying to resist that force with nose-cone shear pins would be practically impossible, so I knew that the payload air must be vented. Given the anticipated high acceleration and velocity, I knew the change in pressure would be rapid and that the need for ample venting would increase. But, as the venting is increased, the ability to capture gases produced by a traditional nose cone ejection charge (even with surgical tubing) is diminished. This makes nose cone ejection a balancing game that cannot be played with certainty -- a decrease in the venting to hold in ejection gas risks popping the nose off during boost and an increase in the venting risks not being able to generate enough pressure to push the nose off at apogee. So, I knew that a different solution was needed.

I decided to go with a pneumatic cylinder, powered by compressed air that was controlled with a solenoid valve. Although heavy, I had faith that it would work. I asked Korey Kline to review my design and he made a brilliant suggestion: why not use the black powder to stroke the cylinder? Would that even work? Why not? The only way to know for sure was to test it. We scrounged up an old 2-inch diameter, 4-inch stroke cylinder from our days of competing in BattleBots and threw a gram of 4F black powder in the cylinder. After stacking 160lbs of concrete on top of the cylinder and attaching an analog gauge, it was time to put this theory to practice. High-speed video showed that the rapid pressure rise inside the cylinder was enough to shear the gauge needle right off its pivot. The piston stroke literally threw the concrete into the air. It worked perfectly! I was off to order a 6-inch long version for the rocket.

This new Powder Operated Piston (POP) fully constrained the Black Powder inside the cylinder along with some ground-level air. The reduced diameter of the cylinder piston lowered the area over which the atmospheric pressure would be acting and, now, would generate less than 50lbs of push-off force. Venting could now be as much as desired without impacting recovery actuation.

There would be three forces driving to push the nose cone off during the flight before apogee. Along with the atmospheric pressure trapped inside the air cylinder, there would be the pressure delta associated with inadequate venting of trapped air in the rocket as well as drag separation forces at the time of motor shutdown. The combination of these forces would need to be retained by the shear pins of the nose cone.

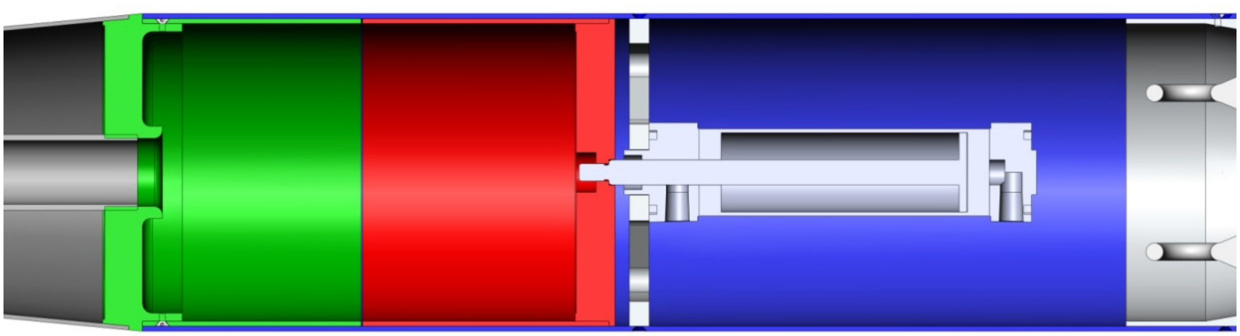
With ample venting, I made the assumption that a maximum of 2 psi delta would be generated during the boost. This would create a push off force of about 100lbs when applied over the area of the back of the nose cone. Through the RAS Aero simulation, I determined that the maximum deceleration would be 6 Gs. With the nose cone estimated to weigh about 17lbs, the drag force would be up to 100lbs. This meant that the shear pins would have to resist the combination of the 50lbs generated by the air trapped in the cylinder, the 100lbs of pressure delta force and the 100lbs of drag separation force. This totals to 250lbs of force.

For shear pins I used 0.125” PolyStyrene rod. I fabricated a quick shear-test fixture and found that it took about 60lbs to shear a single piece of this rod. By using 6 pins, 360 lbs would be required to shear them all. This yielded about a 100lb margin over the needed retention force.

Based on a 2” diameter air cylinder, it would take a little over 200psi inside the cylinder to push the nose cone off with 720lbs (a 2-to-1 margin over the shear pins). The cylinder was rated for 250psi and I guessed that I would take a good bit more than that. Even though this design was a bit heavier, I chose to use a tie-rod style cylinder because it was easy to tear down and clean up after use. This meant that I could ground test all the actual flight hardware and I believed that it was more likely to be able to go to an even higher pressure without failing. Below is a picture of the cylinder design.

Once all the flight hardware was fabricated, the shear pins were installed and the POP cylinder was prepared with one gram of 4F black powder. The black powder was put into the corner of a small ziplock bag and match heads of two DaveyFire 28B igniters were buried in the powder. The bag was pinched off to form a tight ball on the end of the igniter wires. A 3/8” NPT fitting was bored out to form a cavity and a 1/8” hole was drilled through the fitting. The igniter leads were passed through the hole and epoxy was used to seal it all together. This fitting was Teflon taped and attached to the cylinder to form a sealed cavity. The igniters were to be activated by a pair of Adept ST231 timers set to 90 seconds. In this manner, all the recovery system was tested at one time with flight hardware and settings. After manually simulating a launch and waiting 90 seconds. The charge went off and stroked the cylinder. The force was enough to throw the nose cone about 20 feet horizontal across my lawn, more than I expected. I was concerned that the shear pins weren’t providing the calculated resistance, so I decided to test the shear pins in the final flight configuration. We anchored the nose cone to a column in the shop through a load cell to measure the peak force while we pulled the payload section off with a forklift. The maximum force was 349lb before shearing occurred, confirming my earlier test of the single shear pin and giving me confidence that the recovery system was going to work.

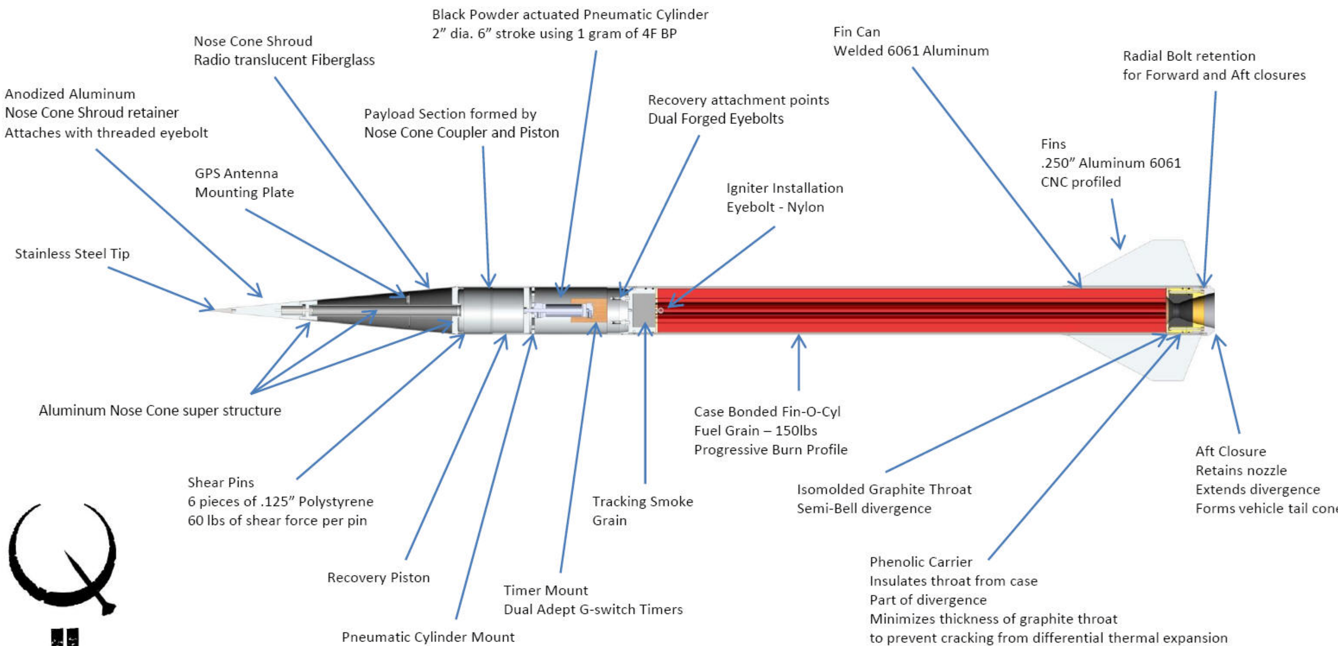
The diagram below shows how the ejection cylinder was mounted. Specifically, the ejection cylinder was hard mounted to the payload section (blue) and was directly attached to a full diameter piston (red), which, when stroked, would transfer the driving force to the nose cone coupler (green). This is an arrangement similar to what PML has been using for decades. The volume between the piston (red) and the coupler (green) defined the area to house the parachute and shock cord. For these components, I used a Rocketman R7 Mach II chute and tubular Kevlar. I knew that this was probably stronger than was required, especially given the more gentle ejection of the pneumatic cylinder, but my experience with CSXT, where the recovery system failed to stay attached to the booster of the CSXT rocket, had me nervous for underestimating loads.



<u>Design Philosophy for Qu8k</u>

In every rocket launch there are innumerous risks. What I tried to do with Qu8k was to look at every phase of the rocket flight and determine what the failure risks could occur along the way. Then, I sought to design Qu8k to minimize each identified risk. The table below shows some of the risks and what I did to mitigate those risks. While I knew that the concessions made would not make for the highest performance rocket, I know that they would incrementally increase the chance of success -- which was far more important to me. I would have loved to have Qu8k fly to 200k feet, which it could easily do if optimized for mass fraction or volume loading, but this flight was not about flying over 200k feet, it was about a successful flight. Those skilled in rocketry might point out that Qu8k's motor casing wall is thick, that its recovery system is heavy, that its propellant solids loading is low, or that there are many other sub-optimal performance aspects, but that would not take into account that the important optimizing metric was probability-of-success, not total performance. For me, Qu8k *was* optimized.

Risk	Mitigation
Motor overpressure	Thick wall case – good for 3x anticipated pressure
	Radial bolt end closure – good for 3x anticipated pressure
	Well characterized propellant
Erosive Burning Pressure Spike	Progressive Burn Profile – lower initial pressure to account for erosive burning spike
	Large Port-to-Nozzle Ratio – port Mach number below 0.5
	Port Mass Flux below 2
	Round off the sharp propellant corners
Case Burn Though	Spin cast liner with nozzle installed
	Case-bonded fuel grain
	Forward and aft insulating phenolic discs
Nozzle Failure	Thinner graphite section supported by phenolic – reduces CTE related stress
	RTV and o-ring graphite into carrier
Grain Collapse	Monolithic Fuel Grain – Case Bonded
	Robust propellant (lower solids loading)
Nose Cone collapse	Central aluminum structure
	Analyze drag loading and calculated strength of structure
Nose Cone Retention	Ground-tested full system shear force (multiple shear pins)
	Analyzed maximum separation forces during flight
	Sufficient venting of payload section
Fin Can failure	Full length welded fin can
	Analyze fin loading and test completed fin can
	Minimize Angle-of-Attack through precise alignment
Flight Stability	Stability margin >1.5 at all mach numbers
Recovery Actuation	Redundant timers
	Redundant e-matches (high quality DaveyFires)
	Ground tested complete system
GPS data	Multiple independent systems
	Antennas mounted facing sky on pad – probable reacquisition during boost



Design Details

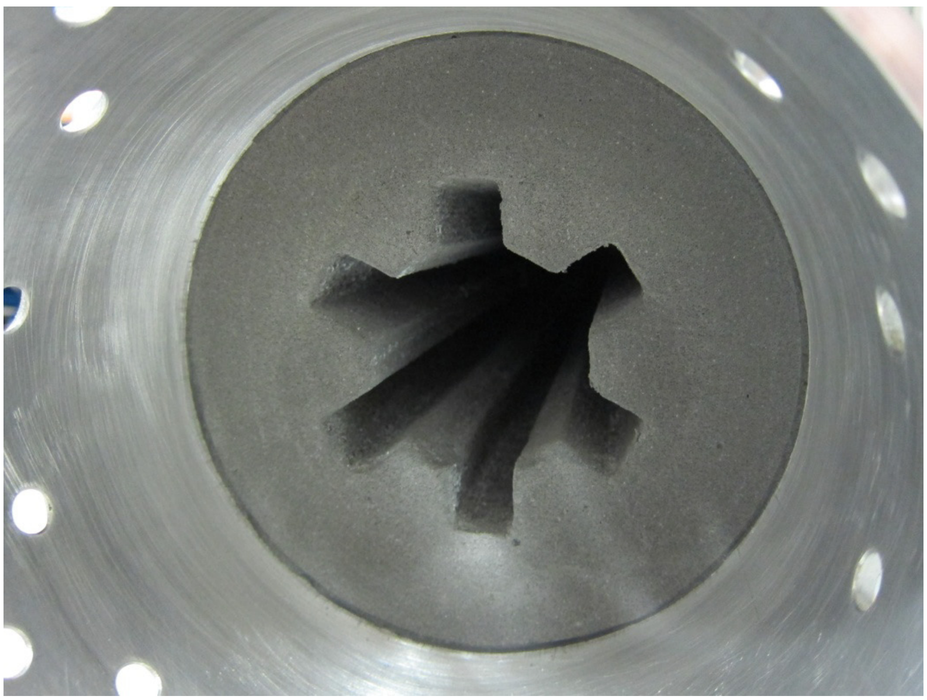
Fuel Grain

The defining characteristic of the Qu8k motor is the Case-bonded Fin-o-cyl fuel grain. This design eliminates a lot of issues that plague smaller, traditional, BATES-grain amateur motors. The space between grains and the space at the ends of the grains allow for the hot gasses to get on or near the casing, making proper insulation difficult. However, when the propellant is poured directly into the motor casing, it bonds to the casing all along its length. This seals the grain to the case and to the nozzle and uses the un-burnt propellant as insulation for the casing. In a long BATES-grain motor, the weight of all of the propellant is supported by the bottom grain. With a high acceleration vehicle and a large propellant mass, this can be significant.

In the case of Qu8k, the total propellant mass was 153lbs, and the acceleration at liftoff was over 10 Gs, making the propellant down-force over 1500lbs. In a BATES-motor, that down force can compress the lower grain and cause it to close down the port opening or, even worse, make the grain deform to the point where it fractures and chunks of propellant block the nozzle, causing a potentially catastrophic pressure spike. In a case-bonded design like Qu8k, however, the load is spread and the grain stays well-supported.

One issue to address is that high solids loading of propellant reduces adhesive qualities of the propellant. This can result in delamination from the casing. To address this issue, Qu8k's casing was cast first with a liner having very little solids. This very tacky layer served several purposes. First, in addition to increasing bond strength, the low viscosity liner material filled all available surface areas and form a good seal with the casing. The liner for Qu8k was just HTPB with a few percent of air-float charcoal as an opacifier.

The nozzle was installed into the casing for creating the liner. When casting the liner, a small "dam" was installed at a position of the forward end of the grain. The catalyzed liner material was poured in and the casing was hand-rotated on its longitudinal axis to evenly disperse the material. The entire motor was then spun on a so-called "spin casting" machine. Spinning of the casing continued until the liner was cured well enough to not sag. This stage of curing kept some of the cross-linking sites of the liner available for bonding with the propellant, which was cast therein immediately after the liner.



The central port of the fuel grain for Qu8k is a Fin-o-cyl, short for "fin-on-cylinder." As the name implies, the grain has a normal cylindrical port but, extending radially, there are a number of rectangular "fins." The dimensions and number of these fins is determined from iterative simulation. The goal is to create a near neutral surface area as the propellant burns back "normal" to any burning surface. For Qu8k, the geometry was set for a slightly progressive thrust profile. This was done to reduce the initial pressure to protect against erosive burning spikes. Erosive burning occurs from scrubbing action of combustion products passing through the port. Predicting the affect of erosive burning is very complex because so many factors are involved (burn rate, hardness, particle size, flow rate, geometry, etc.). From previous experience, I have a basic feel for how sensitive my propellant is to erosion. Some good guidelines I use include keeping the local Mach number in the port below 0.5 and the maximum mass flux below 2.0

lb/s/in^2. Setting the Mach number is easy, just make sure the area ratio of the port to throat is greater than 2 (it was 2.12 for Qu8k). The mass flux takes a bit more effort but can be easily calculated by taking the burn rate times the burning area to find mass flow rate and dividing by the minimum port area to find mass flux. For Qu8k, the maximum mass flux was 1.6 lb/s/in^2. Analysis of the acceleration data showed no significant spike in thrust from erosion. These limits can be pushed, and some levels of erosion can be tolerated or even desired, but, in an effort to reduce risk, I kept everything within the non-erosive bounds. More information on erosive burning can be found at http://rasaero.com/.

To create the port geometry, a foam mandrel was mounted on a support tube. A picture of the mandrel is shown below. In this case, I used a local company to employ a CNC-controlled hot-wire cutter to create a long foam piece having the Fin-o-cyl outside geometry and an internal round hole sized for the support tube. This was attached to a length of 1 ¼" EMT. The end is trimmed at a 45 degree angle to match the convergence, and a bushing is made to support the nozzle end. A small plastic piece is cut to go over the forward end of the mandrel and centers the support tube while allowing enough area around which to pour the propellant. This entire assembly is inserted into the motor casing as soon as the liner is cured enough to not move. Then the motor was put into the lower half of the launch tower and stood upright at a slight angle.

Before this point, all of the propellant was pre-mixed. This includes all of the oxidizer and metals but not the catalyst. The propellant is mixed in smaller batches of 25lbs using five-gallon pails as mixing containers. Then, the curative is added and each batch is mixed under vacuum to remove entrapped air. The vacuum mixing takes place in a separate steel chamber that has a ferro-fluidic bearing to allow for mixing while under vacuum. The formula is 78% solids loading with 8% of the solids being magnallium, a magnesium-aluminum alloy. Manual scrape-downs during mixing ensure that the side walls of the containers are well-mixed but the bottom is less so. To address the potential for poor catalyzation of the mixture at the bottom of the pail, when the propellant is poured, I do not scrape out any of the propellant from the pail. This slightly reduces the yield of each mix. Therefore, for the 153lbs of propellant Qu8k required, seven batches of 25lbs of propellant was mixed. This is another area where efficiency was traded away in favor of simplicity and reliability.

To help protect the nozzle, the propellant formulation is varied along the length of the motor. By placing cooler burning propellant near the nozzle, a layer of protective gases is generated that helps to guard the nozzle from the most extreme exposures. This is done by making changes to the formula, such as reducing or eliminating the metal content or reducing the oxidizer levels. An additional reason for these changes is to vary the burn rate across the length of the grain. As the mass flux increases moving down the port toward the nozzle, there is an increase in erosion and, therefore, the local burn rate increases. By placing slower burning propellant in these areas, this affect can be counteracted to create a more even motor shutoff and to reduce the exposure of combustion gases to the liner.

Once all the propellant is poured and has cured, Acetone is used to dissolve the foam, thereby freeing the support tube to be removed from the finished motor. A scraping device shaped to match the port geometry is attached to a long dowel and is passed through the port to clean off all residual foam. The forward end of the fuel grain is trimmed and the forward insulating disc is installed. In all of my large motors to date, I have used a simple forward closure with a full diameter insulator. For Qu8k, I wanted to have some smoke trail to help track the rocket to higher altitudes. Therefore, the forward closure housed a 6” diameter by 4” long grain of tracking smoke. The insulator, therefore, had to have openings matching the port to allow the generated gases to pass through. A ¼-20 Nylon eyebolt was mounted in the center of this insulating disc, through which a length of line is passed that extends all the way to the nozzle. This configuration allows the igniter to be attached to the eyebolt and be “flag-poled” to the forward end of the motor just before launch for forward end ignition.

Nozzle

The nozzle is made from four pieces. Upstream first is a graphite throat, which was CNC-lathed from a piece of iso-molded graphite. I usually source this from one of several graphite machining shops, as the work is very messy and requires special setups. This throat has some length of convergence, a straight throat, and some divergence. To maximize the available length of material, I use a bit of a bell curve right after the throat and transition to a straight 15-degree taper before getting to the end of the material. The take-off angle for the bell section is designed to not exceed 35 degrees to avoid flow separation.

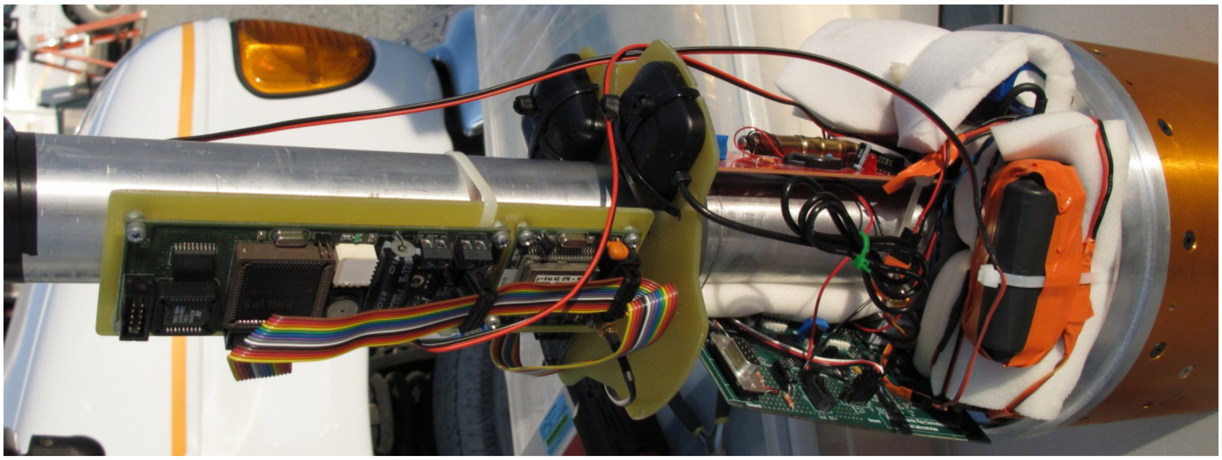
The throat section has two external o-ring grooves that seal it to phenolic carriers -- two sections of 3” thick, XX-grade phenolic sheet that are rough cut to size and then lathe-turned before being RTV glued and bolted together. These phenolic insulation discs also have external o-ring grooves that seal them to the motor casing. By having a thick layer of phenolic between the graphite and the casing, the high temperatures of the throat are not carried to the casing and the wall of the graphite throat is minimized. This is important to prevent cracking due to differential thermal expansion within the graphite.

The final component of the nozzle is the aft retainer, which has the radial bolt pattern drilled and tapped into it. The aft retainer holds the phenolic carrier and also forms the final section of the divergence and the tail cone of the vehicle. By having the tail cone and divergence come close together, motor performance and vehicle drag are optimized.

Nose Cone and GPS

Knowing that GPS data was needed, I understood that the nose cone needed to be something a little different than the norm. Inclusion of GPS is not something that I normally do nor have I ever done in the past. Nonetheless, I was familiar with the COCOM limits that prevent use above 60,000’ and 1000 knots. My main concern was the following: if these limits triggered the GPS to lock out, would it successfully resume normal operation once it fell below the combined limits? The first thing I needed was a GPS system that I knew had the “and” of the COCOM limits properly enabled. Searches through what had been proven to work in the high altitude balloon world led me to the Garmin GPS 18x. This unit outputs a detailed data string that I could capture in its entirety and analyze later. I used a data logging card from Sparkfun to record the data. With this as the primary GPS, I decided to use the RDAS GPS as the backup. The unit I have is a few years old, but the manual indicated that it had proper COCOM implementation. So, the main concern for this device was antenna placement. The R-DAS uses the GPS-MS1E made by u-Blox with a separate patch antenna. To give these GPS systems the best chance to reacquire during boost and, therefore, log apogee altitude, I decided that they had to be in the nose cone with their antennas pointed toward the sky having the most unobstructed view possible. This configuration would allow the GPS systems to get a solid fix while sitting on the pad before launch and give the best chance of reacquiring during coast should lock be lost. To do this I needed a radio-transparent housing for the systems. Even though carbon fiber is one of my favorite materials to use, the radio transparent nature of a fiberglass or Kevlar structure for the nose cone was required. Kevlar was rejected because it is so hard to work with if not using molding techniques. This would have to be constructed as a hand layup. I had concern that an all-fiberglass structure would not be able to survive the flight conditions. At Mach 3 at 10,000 feet, the stagnation temperature is 840F and the drag force on the rocket is almost 1,000 lbs. So, I settled on a combination design that utilized a central aluminum structure that held a fiberglass shroud.

Using a 24” section of 1½” NPT pipe seemed like the perfect choice for the central column. I could easily attach to both ends and it was cheap and accessible. With further study, however, it turned out to be a poor choice. Once the forward and aft nose cone parts were fabricated and tapped to accept the NPT pipe section, I assembled the parts and discovered that the threads were not cut straight on the ends of the pipe section. The tip was a full half inch off center from the base plate. I didn't have time to change it all. So I did what I had to do, I simply bent the pipe in-place and brought the parts back into alignment. To achieve the final alignment, I had to flex the tip of column a full five inches from center. Needless to say, I won't be using threaded pipe as a structural piece in the future.



The third GPS system was part of the Cosmic Ray Detector payload. The CRD is part of the ERGO project that is being led by the Symbiosis Foundation. The hardware includes a Geiger counter, a GPS (Navsync CW12-TIM), and a data acquisition section. There would normally also be an Ethernet section that transmits the data to a central server, but this was left out for obvious reasons. This unit is only capable of recording one ray event per second, which is good for most situations, but Tom Bales, the director of the ERGO project, realized that we might be getting a lot more detector hits than that. Therefore, he designed a circuit that would translate the number of hits into a rate that is based on a voltage, which would then be feed into an analog channel of the payload's data acquisition board. With this data, Tom was able to detect a large surge in radiation just after launch. Unfortunately, for unknown reasons, the unit stopped working right after motor burnout. Theories about temperature, vibration and deceleration forces have yet to lead to anything decisive. Additional studies are on-going.

The fourth and final GPS system was a 70cm BigRedBee. This unit was a late addition thanks to Al Bychek. I own a 2m BRB but it would not turn on the morning of the launch during final prep. Al stepped in and had enough faith to let me strap his BRB unit into Qu8k. This unit was the only one of the group with an antenna facing out to the side. This is a common orientation for these units, especially when used in smaller diameter rockets. In spite of the fact that I unknowingly mounted the unit upside down, it did acquire data that we were able to access later. Most importantly, this unit was transmitting the latitude and longitude of the landing location, which allowed us to drive right up the rocket after the flight (see video mentioned above). Many thanks go to Al and to Moshen Chan, a fellow ham operator who assisted us with tracking.

All the GPS systems were completely independent with their own battery packs. Based on voltage needed, the batteries were either three-cell LiPo or three-cell LiFe packs. Both types of packs were tested in a vacuum chamber to ensure that they would provide continuous voltage and that their capacity was not significantly diminished.

Fin Can

The fin can was one of the first parts to be started and one of the last to be completed and proved to be a great challenge. The design seemed simple enough, a standard 8” pipe section machined inside and out with some guide slots milled on the outside where the fins would be welded. It turned out, however, that machining the ID and OD of a pipe that big is not easy. I had to find a specialty shop that had a giant lathe and a matching giant boring bar. Even with the right equipment, it was still a challenge for them. The turned tube was setup on the mill at Syntheon and guide slots for the fins were cut. The fins were cut from flat stock and the leading and trailing edges were CNC profiled. A jig was cut from ¾” MDF that, along with the slots, would hold all the fins in perfect registration during welding.

Everything seemed to be going fine until the welding was complete. Once the fin can was removed from the support jig, it became clear that the heat from the welding caused movement. More specifically, the ID of the tube was no longer round. At this time, it was about one week from shipping day and there was no way to fit the fin can onto the motor casing. There also was no time to change the design; I had to make it work. What followed was about 7 to 8 hours of aggressive, manual, internal grinding. It was a very unpleasant experience and proved to me that welding is not the right way to make a fin can.

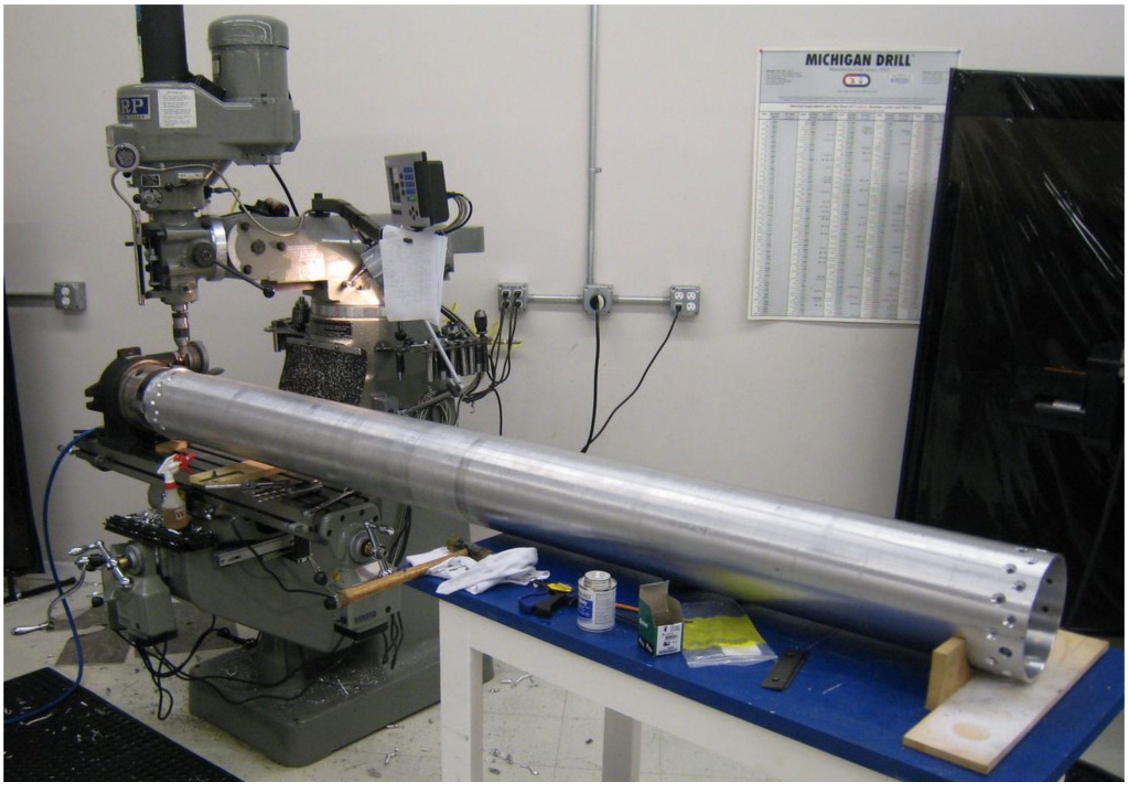
Once the fin can fit over the motor, I was able to drill and tap the holes that would lock the fin can in place. For securing the fin can on the motor, the aft motor closure was shaped to extend outwards from the motor housing to the diameter of the fin to create a ledge that prevented aft motion. The holes and matching screws were used to provide rotational support that would keep the fin can from sliding forward during deceleration.

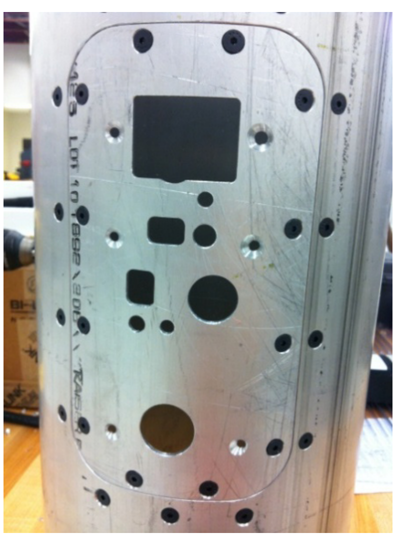
The high heat exposure from the welding was my next concern. If exposed to great enough temperatures, high-strength aluminum alloys can lose their temper. I needed to know what kinds of loads the fins would see during the flight and determine if they could survive them. Charles Rogers helped me to estimate fin loading. He gave me a computation method that required parameters including the angle of attack (AOA), the burnout Mach number, the fraction of the drag attributable to the fins, and the maximum drag. This method provided me an estimated maximum fin load of 959 lbs per fin for a 5-degree AOA. I was officially freaked out. With the annealed fins, I was unsure they could each support that load. I ran a finite element analysis on the fin can and found that the maximum stress at that loading would be 18 ksi. I knew that the T6 temper of aluminum is around 36 ksi. So, the big question I had was whether the anneal reduced the temper below 18 ksi. Literature searches came back with everything from 8 to 20 ksi after welding so research was inconclusive. During this time, Charles ran the numbers again and separated out the drag borne by the vehicle body. With the second calculation, Charles came up with a new number of 576 lbs for the 5 degree AOA. This result assumed a loading at the center of each fin. So, I decided to test the completed fin can. I placed the fin can on the floor and had a couple of 200 lb guys stand on the tips of two opposing fins. They hopped up and down slightly. The fins did not budge. That, along with knowing that a 5 degree AOA at Black Rock was unlikely, gave me the confidence to move forward with fin can as is. Obviously, the same fin can design will not be used in the future; it was just too much trouble. The best thing about the design was that the fins were perfectly straight, likely being the reason why the rocket barely rolled at all throughout Qu8k's boost phase.

With regard to Qu8k's low roll rate, one of the best parts of the launch has to be the fantastic video that was captured during the flight. I have made several prior attempts at on-board video. In my launch of the P-motor Black Dragon, the camera battery died minutes before launch. That same camera met its demise aboard the Tripoli Nebraska Pershing II, which failed to deploy the parachute and crashed at LDRS 26 after being powered by one of my Q motors. To ensure that I got something on the Qu8k flight, I decided to include a trio of HD cameras. Two GoPro Heros and a FlipHD were designed to be mounted to the hatch of the payload bay as a single component. This modular configuration allowed me to work on the cameras independently of the rocket. Before launch, I made sure they all were fully charged with cleared memories. I also wanted to have two different manufacturers of cameras to improve the odds of success should either of them be susceptible to aspects of the flight that cause failure to function. I wanted one view straight out to the side and another looking down the side. The down-looking view was a challenge because any protuberance from the vehicle body creates substantial drag and greatly reduces maximum altitude. By turning a GoPro sideways, and removing it from its protective outer case, I was able to have the lens just peak out from the modular camera hatch sticking out from the rocket body by only 3/8ths of an inch. To prevent the Mach 3 flow from tearing up the camera, I had planned to make a CNC machined aeroshroud. Because my CAD model of the GoPro camera was a bit rough, I decided to 3D-print a prototype version of the aeroshroud before machining it so that I could check its fit. Because this seemed to be the part that kept dropping on the priority list, it was only a day before going to Nevada that the first printed part was ready. As such, there was no time to machine the aluminum version. Ultimately, I ended up attaching the plastic printed shroud in place at 2 a.m. on the morning of the launch. As you can clearly see in the downward looking video, this printed part did not fare well in the extreme heat of the flight. Melting plastic rained down over the lens and ended up obscuring the view of the side looking GoPro. Thankfully, the FlipHD camera that was also looking straight out the side was spared, most likely because it was inset from the rocket skin a little bit so the molten plastic passed it by.

Machined Parts

Being nearly an all metal rocket, most of the fabrication happened in the machine shop. My employer, Syntheon, donated extraordinary amounts of machining time. Coming at the perfect time as we transitioned between projects, I was able to have the attention of two excellent machinists Jorge Pinos and Angel Fernandez. Day after day they would accept yet another drawing from me for “just one more thing”. The size and nature of the parts they were asked to fabricate forced them to get creative and use the tools they had in novel ways. Qu8k would not have been possible without them.





Setup

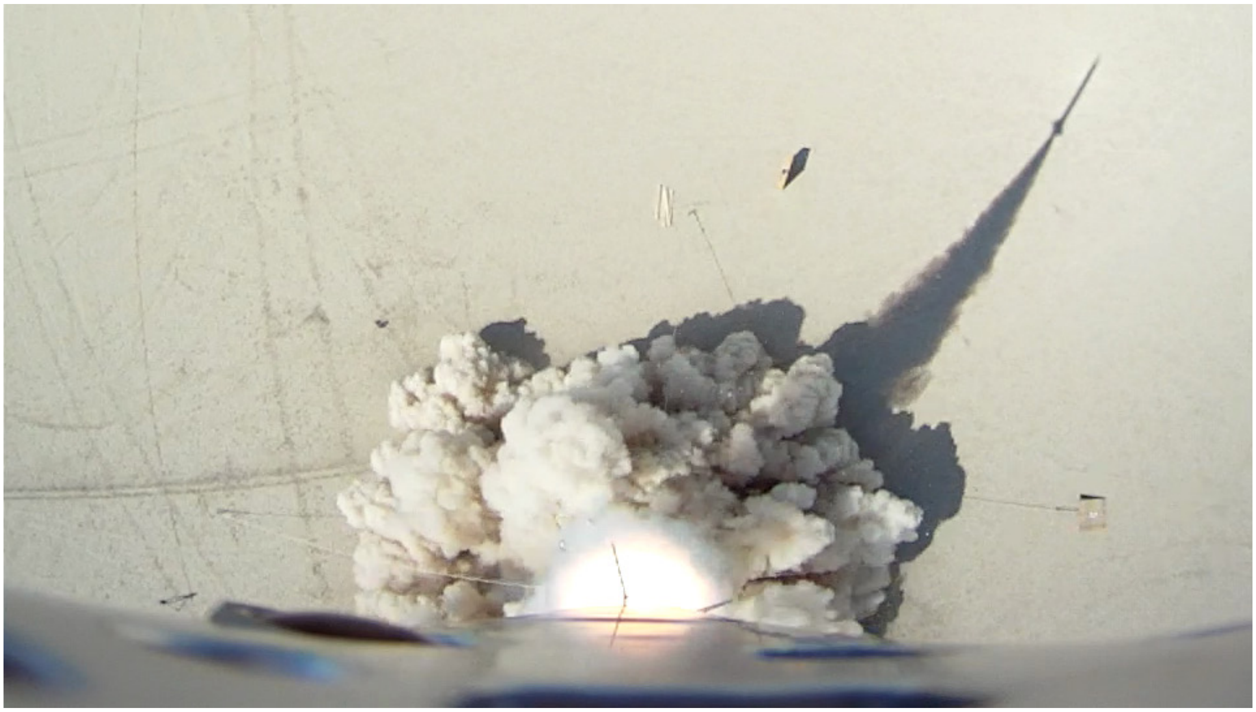
Getting to the desert and getting it all set up was the final hurdle. After spending too many long days and late nights lifting the over 250 lb motor, my back finally had enough. On the drive to Pittsburgh to drop off the motor, my back seized up and began to hurt badly, but I was only focused on returning home to finish preparing the nose cone and fin can. I left for Reno a mere three days later with some comfort knowing that Greg Mayback, Greg's daughter Rowan, and Bret Ranc were going to meet me there to help with the launch. There were a lot of logistics that held me up once I arrived in Reno before heading to Gerlach for the BALLS event, including constant back pain, but the launch team was able to help me out and we were finally headed to Gerlach a day late.

At 2 p.m. on Thursday, September 29th, we arrived on the playa of the Black Rock Desert and began assembling the tower. By 8 p.m., the tower was done, but there was no time to rest. I wanted to launch early on Friday, the first day of the event and the first day of my Class 3 waiver. And, if there were going to be multiple teams competing for the Carmack Prize, I wanted to fly first.

I was also aware that the weather was predicted to decline through the weekend, so after grabbing a quick dinner at Bruno's, we were back on the playa at 10pm to begin prepping the rocket. By 3 a.m., things seemed to be in pretty good shape. Before turning in for the night, we spent another hour getting all the electronics on charge. The next morning, we started the day early, at 6 a.m., to be on the playa at first light. Even with such an early start, it took several more hours of preparation before the rocket was ready to head out to the pad. Jim Jarvis graciously loaned us his trailer-hitch cargo platform, which we used to transport the prepped rocket to the tower. Arriving at the tower around 9 a.m., it took another 2 hour for the final prep, rocket tower up-righting, pictures, electronics arming, and igniter fabrication.

Launch

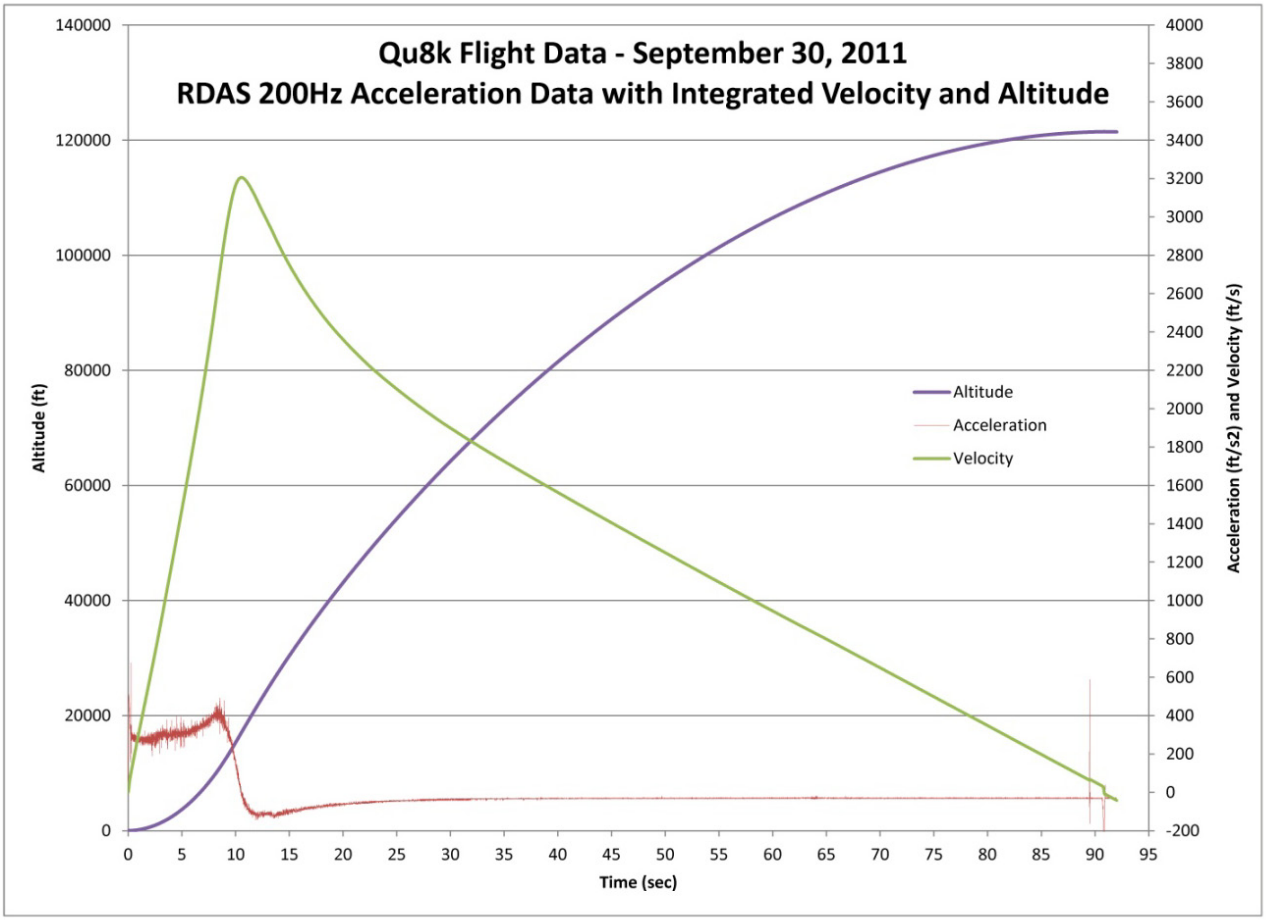
At 11:08 a.m. PST on September 30, 2011, Qu8k blasted skyward from the Black Rock Desert in Nevada. Two months of design and preparation were put to the test. With minimal roll and no weather-cocking, Qu8k pierced the sky at over Mach 3 and attained an altitude of nearly 121,000’ before deploying its parachute 90 seconds after liftoff. Descent took only seven minutes under the high-velocity Rocketman chute. During that time, Qu8k slowed from a peak descent velocity of 900 ft/s in the thin upper atmosphere to just 120 ft/s, when it impacted the desert floor *only* 3.2 miles from the launch tower. The flight itself was a complete success.



Reviewing all of the GPS data was not as satisfying. This facet of the flight became the one obstacle to perfectly fulfilling every aspect the Carmack Prize. Thankfully though, the other flight data proves that Qu8k definitively exceeded 100,000’ above ground level.

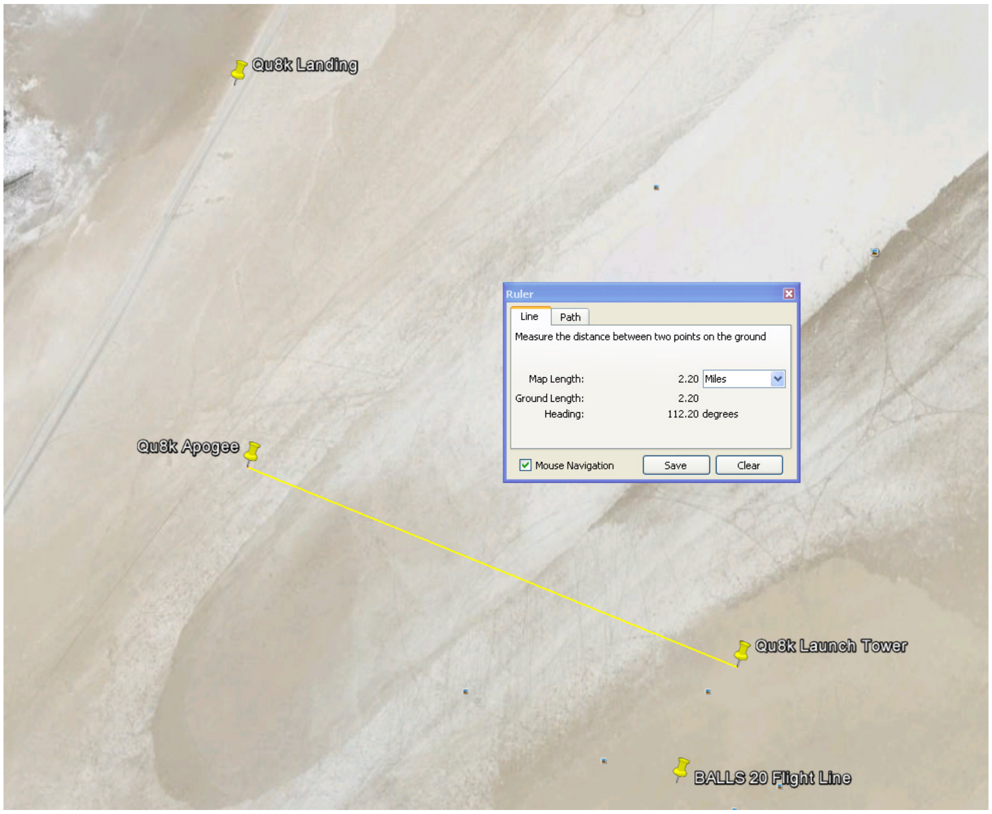
Data Analysis

The primary flight data ended up being the 200Hz accelerometer data from the R-DAS. This data also included barometric pressure data limited to 40,000'. The chart below shows the accelerometer data integrated twice for velocity and altitude.

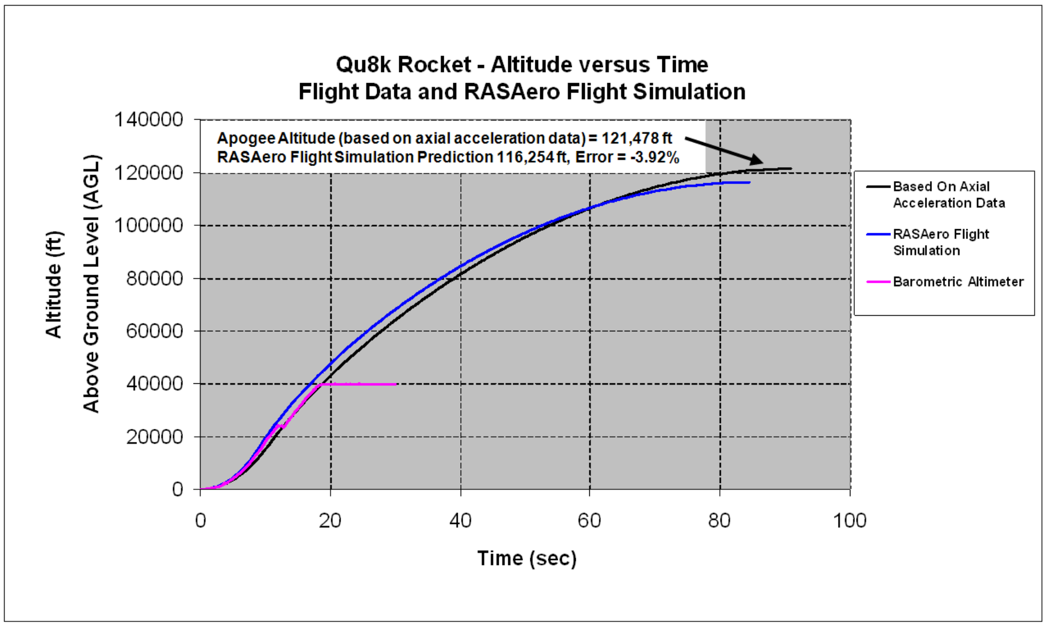


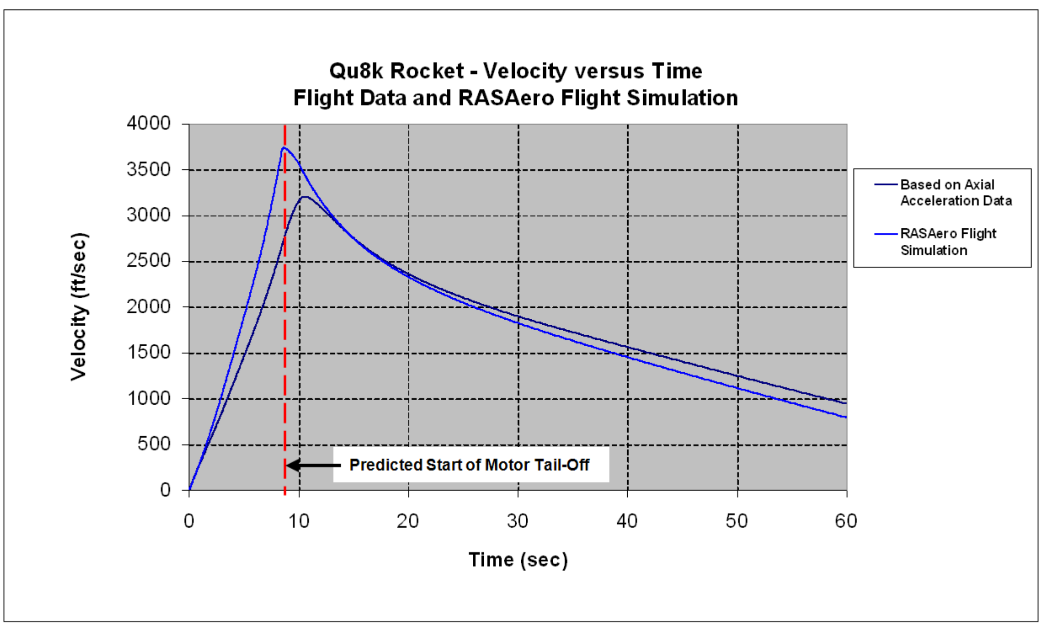
This integration tells how far the rocket travelled and this would be the altitude if the rocket flight was perfectly vertical. The video of the launch confirms that the Qu8k flight was very nearly vertical. The recovery site being so close to the launch site further supports this, especially given the low winds at the time of launch and Qu8k's rapid descent. To be able to approximate the deviation from vertical, a 2-dimensional (Lat,Long) fix from the GPS acquired just after apogee projected on a satellite photo below, shows that Qu8k's apogee was a mere 2.2 miles from the launch site.

From this data, Qu8k's actual vertical altitude at apogee can be calculated using the geometry of a right triangle. Taking the total traveled distance of 121,478' by accelerometer as the hypotenuse and taking a horizontal traveled distance of 11,616' as the opposite leg of the triangle, a total flight angle can be calculated as 5.46 degrees. From this, the vertical height above ground is calculated as 120,926'. This number is less than half a percent reduction in altitude as a function of flight angle.

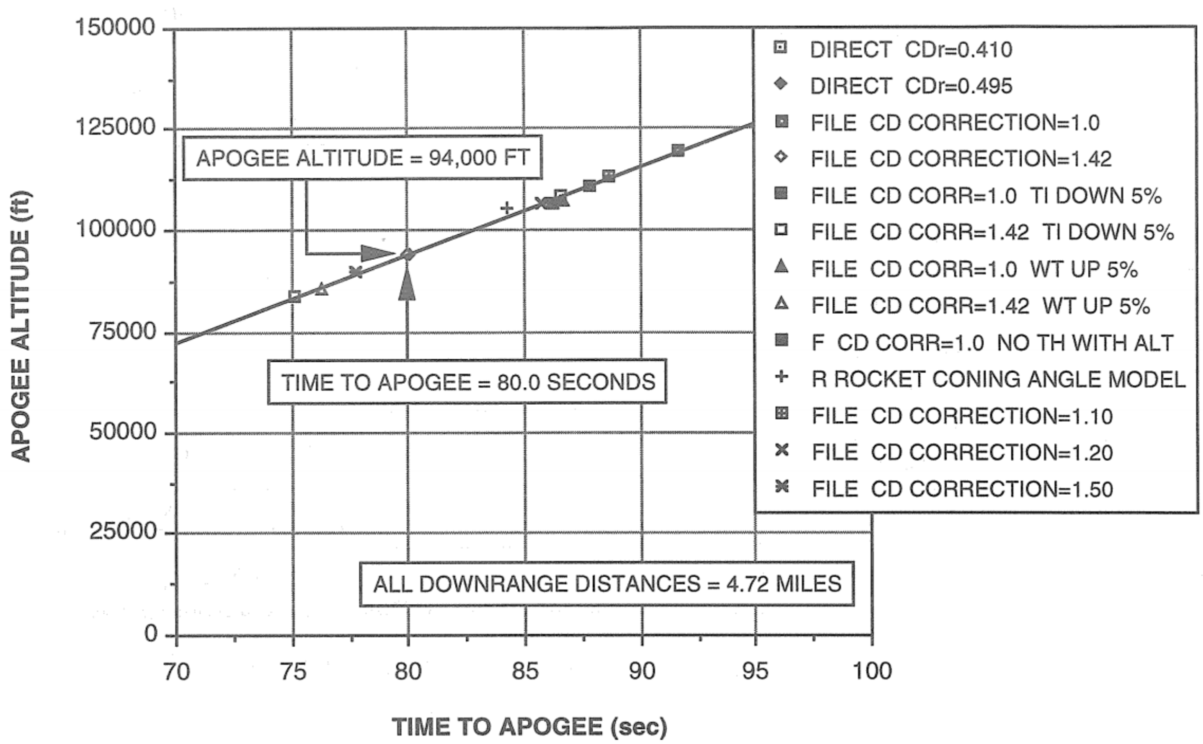


Charles Rogers was given Qu8k's data and performed an analysis of his own to confirm the accuracy of the calculated actual altitude from the integration of acceleration data. Charles generated the following graphs, which also include his revision to my original RAS Aero flight simulation. He was able to get the simulation to match within a 3.9% error. One interesting aspect of this simulation is that the curves of the barometric altimeter match very close to the actual flight and simulation data. This confirms that, through 40,000', Qu8k was on track to follow the simulation. The second graph below compares the velocity of the simulation to actual flight data. Qu8k's motor burned slightly longer than predicted and had a smoother shut down but the deceleration portions were very similar after burnout. This analysis confirms that the aerodynamic assumptions of the simulation were good.





Another supportive way to confirm Qu8k's altitude is through a Time-to-Apogee (TTA) analysis. For rockets that are of a substantially similar design (i.e., a single stage, Mach optimized, three or four fin rocket with a nose cone), it seems that there is a nearly linear connection between TTA and altitude. I noticed this while performing simulations for Qu8k and found further evidence of this from Charles Rogers' analysis performed for the OuR Project in 1997. Below is the graph that Chuck made, as part of that analysis, where he varied a number of factors including the CD by up to 50%. The result was a very good trend line showing a linear relationship between TTA and altitude. From this, it is possible to estimate that an altitude of near 120,000' is achieved when a 92-second TTA occurs. The on-board video shows Qu8k just beginning to pitch over very nearly at apogee when the timers set for 90 seconds activate. This is an indication that, if left to coast through apogee, an approximation of 92 seconds would be accurate. The full article on the OuR Project can be found at http://www.rasaero.com/.



GPS Data

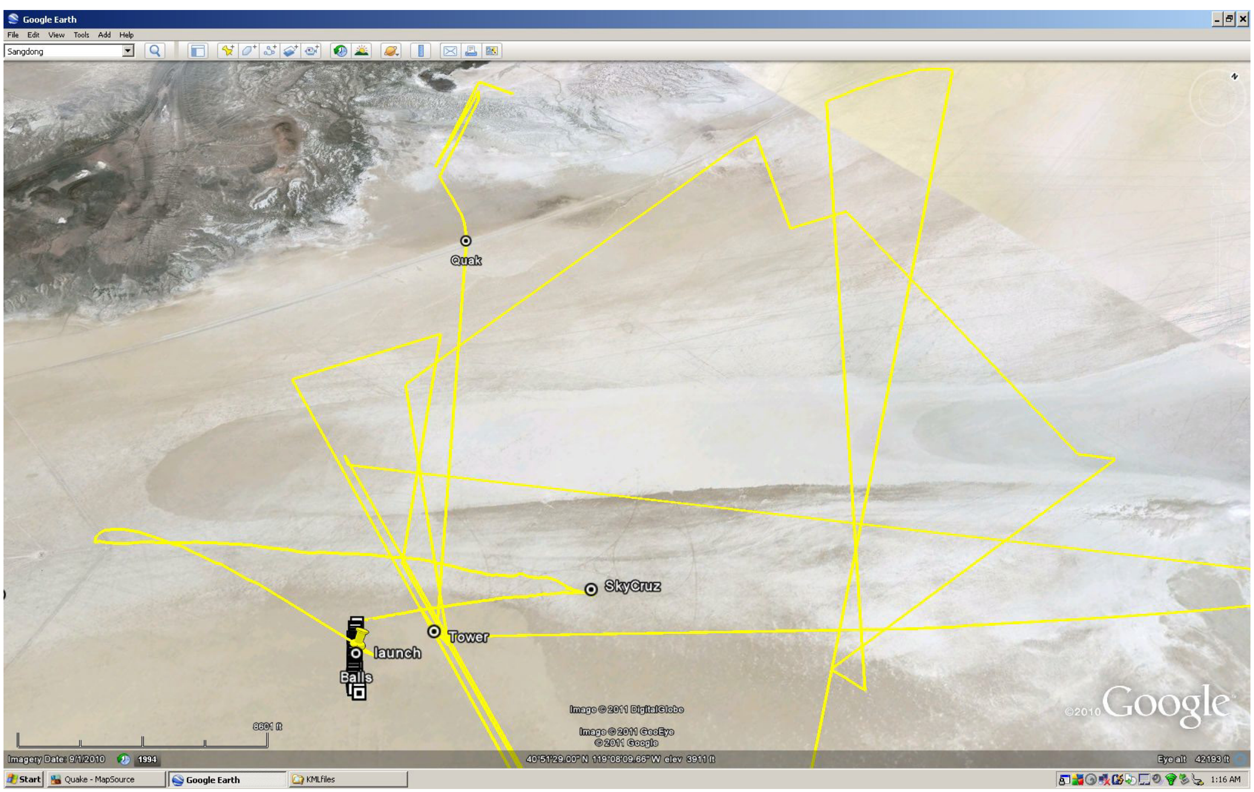
The GPS-18x lost lock immediately upon launch, but it did obtain some data on the way back down. At around seven minutes after launch, it recorded some altitudes in the 16,000' foot range during descent. It also had an intermittent 2D fix during much of the descent.

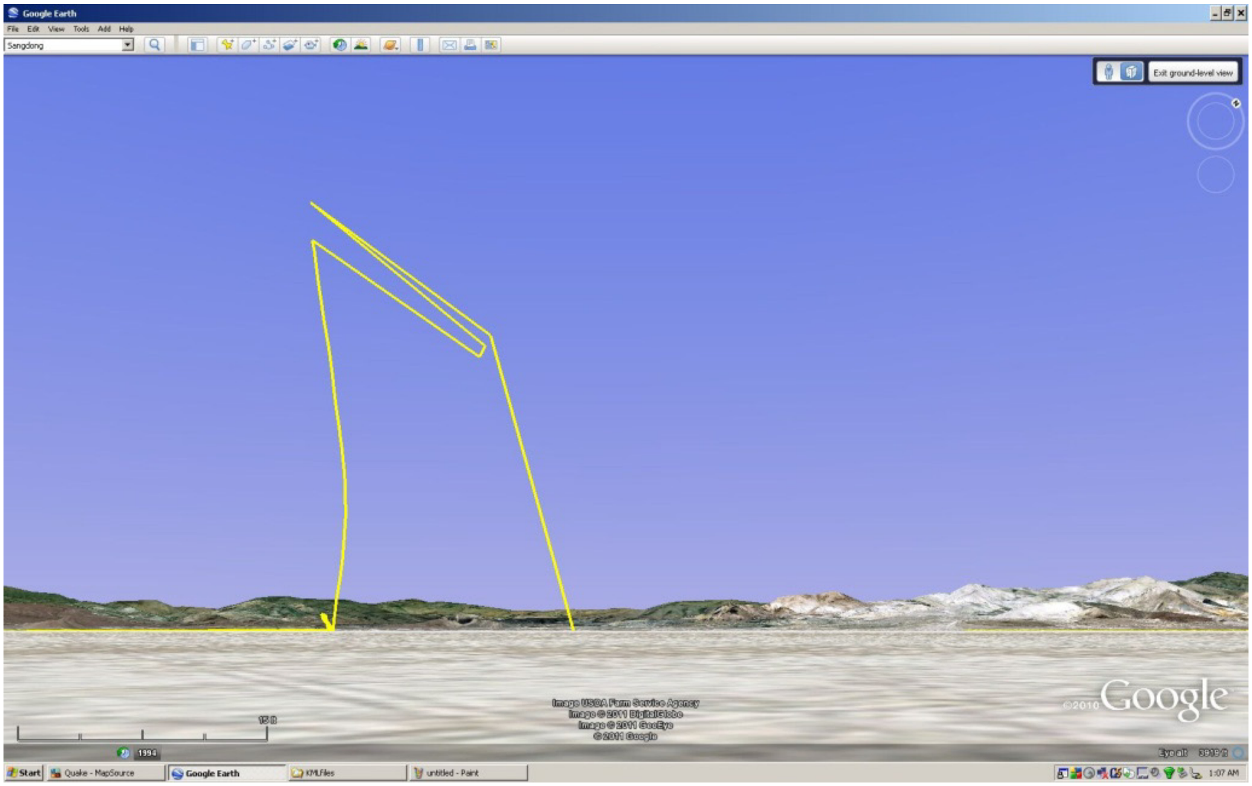
The GPS in the R-DAS lost lock immediately and did not re-acquire lock until well after landing.

The BigRedBee 70cm unit obtained sporadic data but did not obtain data during the boost. The data obtained thereafter is not believed to be reliable. "Greg" at BRB went through the data and made the following comments:

> 0x3471 equals 13426 decimal , which corresponds to time 18:08:13 -- that's the launch detect time, and, as you can see, the earliest timestamp in the flight -- so that is where things begin. We've got just 4-5 sats in view, which is not really all that good.
>
> Launch should occur 20 seconds after that. Yep -- at time 18:08:32 we see num sats drop to 3, and then 21 seconds of no data -- that is where we lost GPS lock.
>
> At time 18:08:54, we regain, but with just 3 satellites, this continues for a *very* long time -- in fact, it is not until time 18:16:00 that we get more than 3, and even then, the altitude is not right.
>
> Looks like we are on the ground before it finally figures out the right altitude -- and even then, just 3-5 satellites.
>
> My best guess us that the nosecone is blocking the GPS signal. I'm used to seeing 8+ satellites, you never had more than 4 or 5 for the entire flight.

Below are projections on satellite photos of the sporadic data from the BRB.

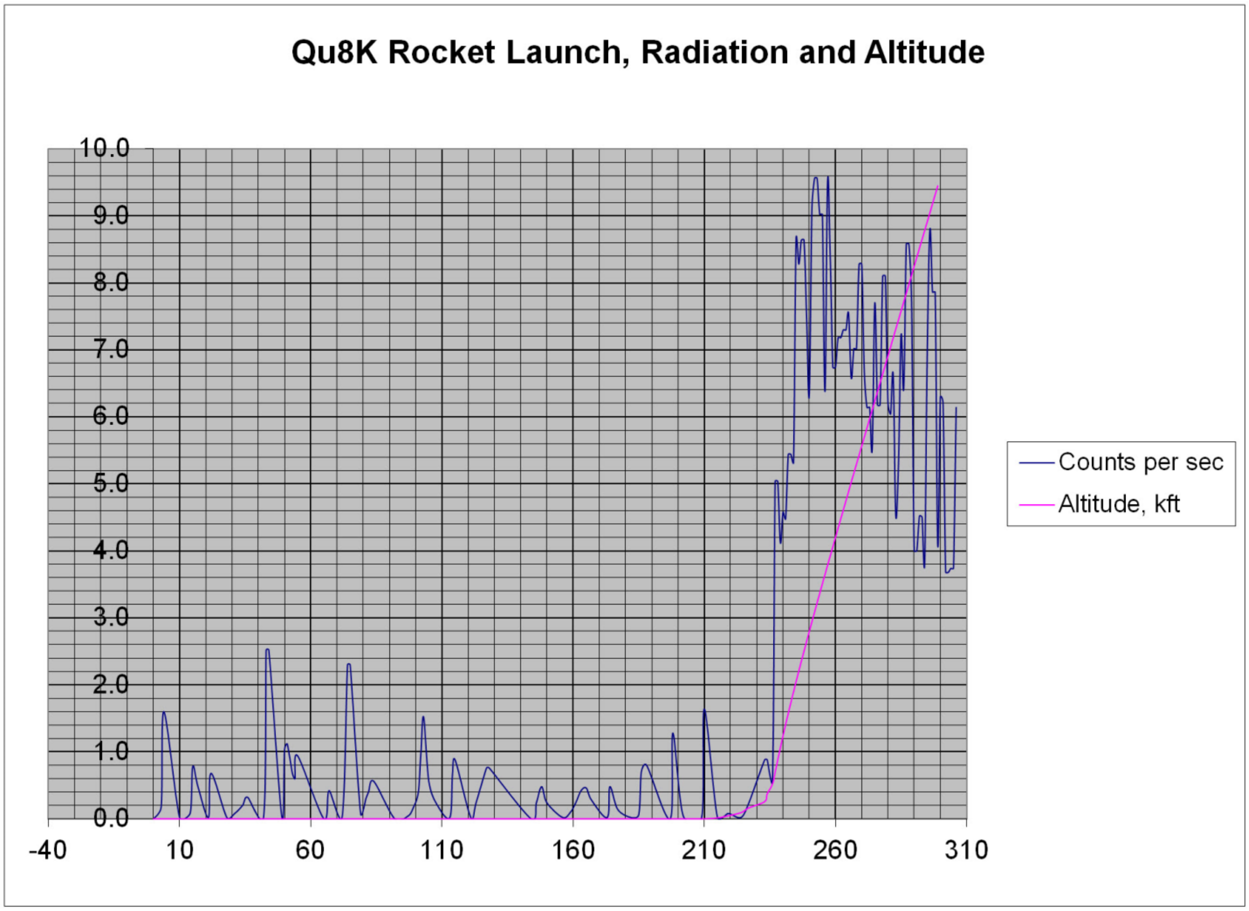




The fourth and final GPS was a part of the Cosmic Ray Detector package. Tom Bales, the founder of the Energetic Ray Global Observatory (ERGO) project provided the following explanation of the ERGO payload:

> The instrument launched in the Qu8k rocket was a modified ERGO cosmic-ray detector instrument. The instrument contains a 1cm X 9cm Geiger-Müller detector, a GPS receiver, a timestamp generator, and a datalogger. Each time the instrument detects a charged particle, a recording is made of the position (lat/lon/alt) and the date and time (accurate to 100 nanoseconds) of the event.
>
> The ERGO instruments are limited to reporting one event per second, so an additional circuit was added that allows recording an analog value indicative of the rate of detections per second, and that value is stored along with the timestamp. The maximum rate of events recorded during the flight was 9.6 events per second.

The ERGO unit shut down right after motor burnout. This was likely due to deceleration forces jarring something loose. The ERGO instrument was the largest of the payloads and presented a challenge for mounting. The substantial increase in charged particle detection is very interesting and the team is continuing to analyze the data. The ERGO instrument is being reduced in size and is available to be flown on other rockets should the opportunity arise.



GPS Issues

There has been a lot of discussion in the community about GPS in rockets since the Qu8k flight. The theories about why I was unable to maintain lock are plenty and varied. There is some concern that having any metal in the area in which the GPS units are mounted could have caused a problem. In Qu8k, most of the units were close to the aluminum 1½" NPT pipe. Also, having the BRB transmitting antenna close to the GPS antennas may have caused an issue.

Most theories, however, center on the high acceleration and velocity of the rocket. It may be that the acceleration causes some slight change in the crystals of the internal clocks and that change throws the GPS systems off. One of the more likely theories is that the slow refresh rate/filtering of the hardware causes the GPS to be confused by such a drastic change in position/velocity and, because the units just can't "believe" what they are seeing, they force a cold start or other similar function. This is something that could likely be addressed with changes in software for future flights. There may be units out there that already have this change implemented, but finding such systems seems to be difficult. One interesting solution can be to record the raw data coming from all satellites in view and perform data reduction after the flight. This appears to be possible with a unit such as the U-BLOX LEA-6T (http://www.u-blox.com/en/capture-process.html).

As far as I know, the other teams that were flying to high altitudes at BALLS all lost lock at launch. Some lucky teams managed to re-acquire GPS lock before apogee. The GPS units that I used were all commercially available and affordable units. It may be that some military grade hardware could have handled the acceleration but those are not readily available. It would be great if those that have success with GPS could make public the hardware they used and how it was mounted so that others can learn from their success.

I have heard, albeit only in speculation, that if a GPS is vibration isolated, such as being wrapped in bubble-wrap, they have a better chance at maintaining lock.

One final way to maximize the chance of success for the future is to use a GPS coverage planning tool like http://www.trimble.com/planningsoftware.shtml so that the team can plan its launch time when maximum GPS coverage is available, but this may not be practical.

What is next?

I hope that Qu8k will fly again. I have partnered with the Symbosis Foundation to provide space on-board whatever I fly next. They will be sponsoring a contest for high schools and universities to submit proposals for on-board payloads. The best ideas will be sponsored for fabrication and allotted a place on the next flight.

The next thing will be either be a repeat of Qu8k, an extended version (call it Qu8k 2.0), a two-stage design using Qu8k as the booster, or an upsized version of Qu8k (similar to CSXT). Whatever it ends up being, it will be fun and exciting.

I hope that through this report I have been able to convey some of the things that I have learned over the past 15 years of rocketry. Questions, comments, or interest in the student payload project can be sent to me at ddeville@msn.com.

Appendix (Location Data):

Launch

Latitude	Longitude
40.814817	-119.144133

Degrees, Minutes & Seconds

Latitude	Longitude
N40 48 53	W119 08 38

GPS

Latitude	Longitude
N 40 48.889	W 119 08.648

Apogee

Latitude	Longitude
40.827333	-119.184633

Degrees, Minutes & Seconds

Latitude	Longitude
N40 49 38	W119 11 04

GPS

Latitude	Longitude
N 40 49.640	W 119 11.078

Landing

Latitude	Longitude
40.849467	-119.1875

Degrees, Minutes & Seconds

Latitude	Longitude
N40 50 58	W119 11 15

GPS

Latitude	Longitude
N 40 50.968	W 119 11.250

Flight Line

Latitude	Longitude
40.8083	-119.150717

Degrees, Minutes & Seconds

Latitude	Longitude
N40 48 29	W119 09 02

GPS

Latitude	Longitude
N 40 48.498	W 119 09.043

Landing by BRB

Latitude	Longitude
40.851967	-119.183722

Degrees, Minutes & Seconds

Latitude	Longitude
N40 51 07	W119 11 01

GPS

Latitude	Longitude
N 40 51.118	W 119 11.023

Weights of Qu8k in pounds:

Measured	**154.5**	Weight of rocket right after the flight
	95	Weight of empty motor after flight similar to Pitt without the sonotube
	263	Weight of full motor with sonotube
	8	Estimated weight of sonotube
Calculated	**255**	Weight of full motor
	59.5	Weight of all rocket components apart from the motor
	160	Propellant Weight
	314.5	GLOW

Credits:

Jorge Pinos and Angel Fernandez – Machining of all metal parts

Guy Kress – Launch tower

Greg Mayback – Financial, moral and physical support

Bret Ranc – Launch support

Korey Kline – Inspiration and design

Carlos Rivera –Road-tripping to Pittsburgh

Tripoli Pittsburgh – Motor transport

Al Bychek – BRB, tracking, and launch support

Chuck Rogers – Simulation and load calculation

Miguel Hernandez – Heavy lifting and late night support

Mike and Danah Kirk – Propellant casting assistance

Marc Devits – Electronics support

Lesley, Morgan and Melanie Deville – My loving family – Moral and emotional support and inspiration

YouTube video:

http://youtu.be/rvDqoxMUroA [Long Version]
http://youtu.be/5HTwbpjBUOk [Short Version]

Derek Deville Webpage with Images and Details:

http://ddeville.com/derek/Qu8k.html

News stories:

CNN, Popular Science, Huffington Post, Space.com, Wired, USA TODAY, The Florida Bar News

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