NATIONAL AERONAUTICS and

SPACE ADMINISTRATION

MARSHALL SPACE FLIGHT CENTER: STUDENT LAUNCH INITIATIVE

ST. ANDREWS SLI 2006-2007

ORION PROJECT

Final Report: May 25, 2007

Fluid Dynamics of Rocket Performance
Air-Density Calculation Factors

Temperature, Barometric Pressure, Relative Humidity, Altitude and
Pitot Readings for Velocity and Air Speed

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Table of Contents

Introduction

Team Orion would like to start by thanking Dawn, Julie, Chuck, Vince and Al for all the things they do that makes the SLI program such a great experience. We'd also like to thank all the people that gave us tours of the Marshall Space Flight facilities. Thanks also to the many NASA people involved with the SLI program that we didn't get the chance to meet, and to the Redstone Arsenal people that allowed the use of the field, and had to recover rockets that went into trees, swamps and restricted areas. We know all about rockets in trees and swamps. Thanks to all of our Sponsors and Mentors and Parents also!

Purpose of the experiments:

When we first started thinking about payload design, Team Orion was initially interested in gathering airspeed (velocity) data from 2 Pitot tubes, so we could compare the readings, and get it calibrated and converted from volts into miles per hour. But as we learned more about the pressure sensors and data loggers, we found that we already had the capabilities to collect a lot more data, and the additional data could answer several more questions. Ultimately, we ended up with the capability of running the following tests:

- Nose and side-mounted Pitot tube velocity, calibrated.
- Barometric pressure, calibrated.
- Altimetry via our pressure sensor, calibrated, plus from deploying altimeters.
- Air density throughout the range of the flight.
- Atmospheric Lapse rate.

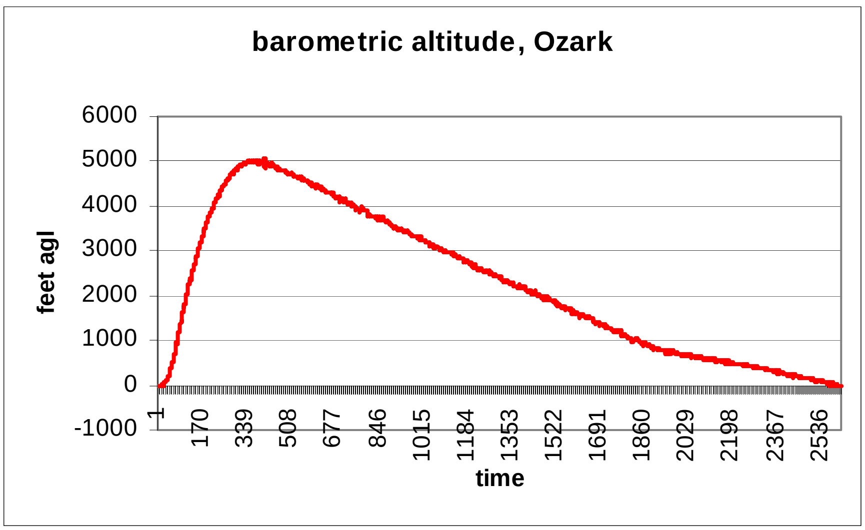
The design and construction had to be robust, capable of several flights. Dynamics (CG/CP) must be proven stable. Learn how to use simple CAD software. Observe professional CAD preparation.

Data from Flight 2, 3/4/07:

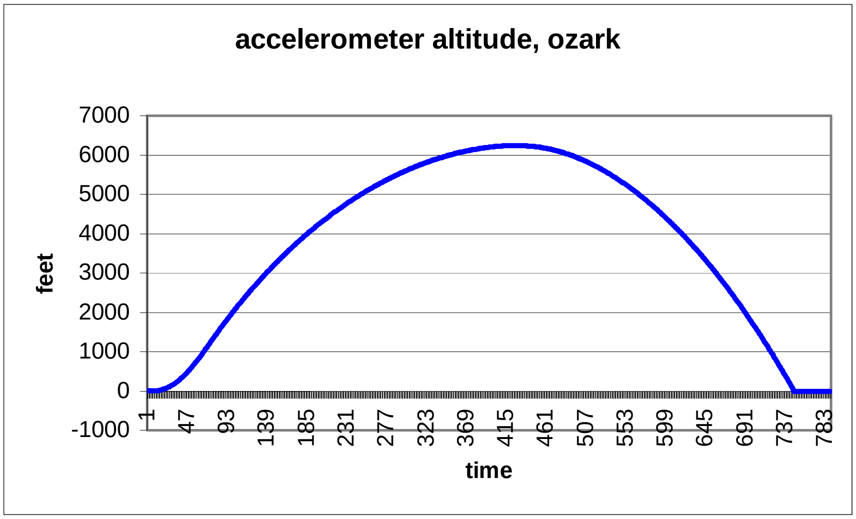
March 4, 2007 started out very cold, with temperatures very close to freezing. The electronics mentor kept worrying about the battery power weakening as a result of the cold, particularly the batteries that ignite the ejection charges. Team Orion came up with a great plan to avoid freezing batteries: the entire rocket prep team would all pile into the back of the SUV, and do all the payload activation, parachute packing, etc, in the warmth of the SUV, then quickly bring the rocket out, our NAR mentor would load the motor, and we'd get the launch off as quickly as possible. This worked great! The electronics technician did properly activate all payloads since his fingers weren't numb from the cold, and Pitot Cruiser flew perfectly, with full deployment of both drogue and main parachutes. This time on landing in a frozen corn field, the parachutes lay down totally flat and were nearly impossible to spot at a distance. If it weren't for the radio transmitting rocket hunter, we might have needed to spend hours searching for the rocket.

We carried Pitot Cruiser back into the SUV, where data downloading went very well (we could immediately tell that this time the nose Pitot data was good), followed by repacking for the trip home.

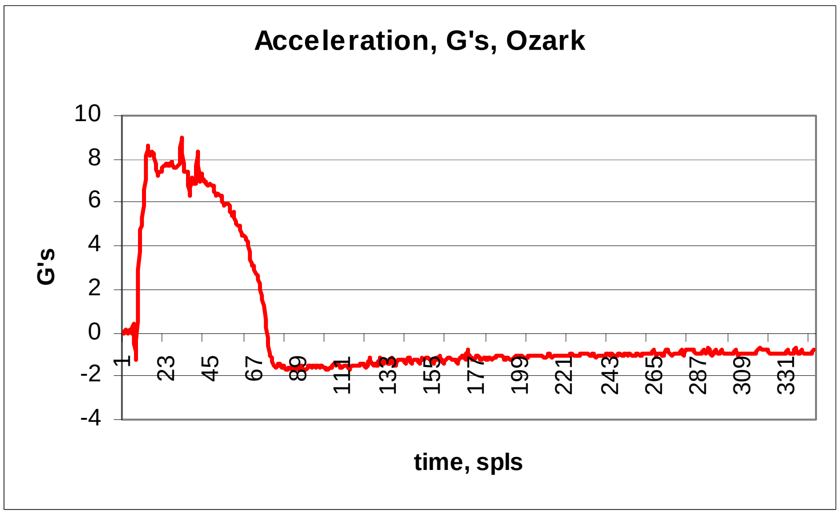
As we examined the data closely several days later, we found more proof of Murphy's Law, that "what can't go wrong will go wrong": The air temperature and dewpoint data were fast-dropping slopes with essentially unusable data for air density and lapse rate. The reason was obvious: our clever scheme to keep the batteries and our fingers warm, created such a huge temperature difference that on takeoff, the temperature was still trying to drop from warm SUV down to cold winter air. Lesson learned: give sensors time to equilibrate before launch. A positive surprise: our investigation and conclusion about the nose payload failure of the 1st flight was correct; it wasn't turned on. This time it definitely was on, and collected really great data, which we'll get into now, starting with the data from the Ozark altimeter:



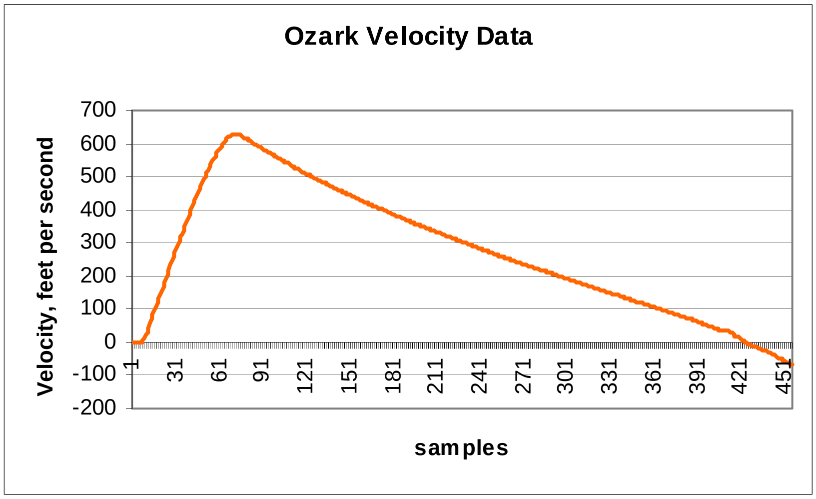
The first chart shows the Ozark result for barometric altitude to 5000' along with a great looking descent profile. The descent on drogue is easily distinguished from descent on main chute. This is what we want our barometric altitude to look like!



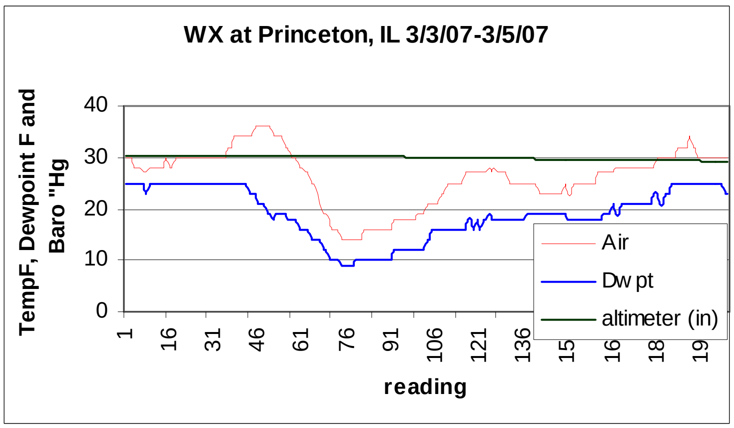
The second chart is altitude from accelerometer, reading a little over 6000' since lower altitudes due to launch angle are not figured in.



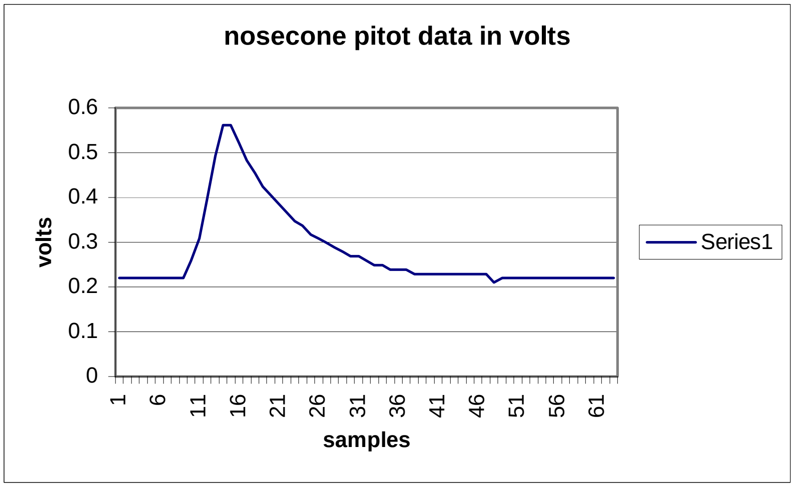
The 3rd chart is G forces, zoomed in to see the launch. 8 G's is the maximum acceleration, with one spike hitting 9 G's momentarily.

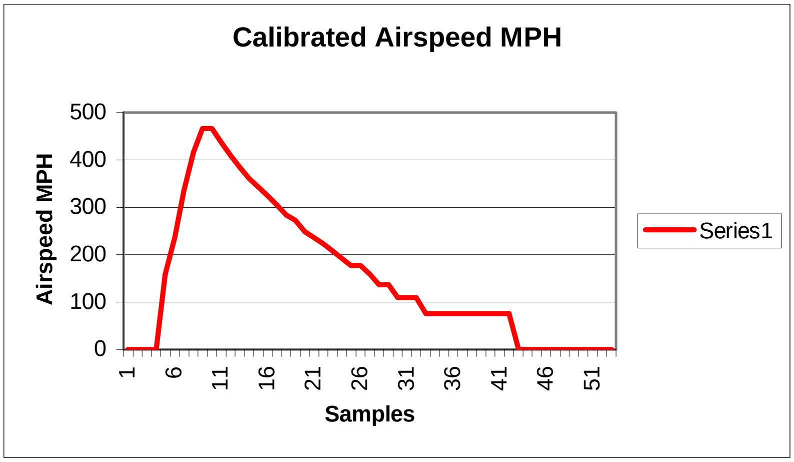


This 4th chart is velocity, from accelerometer data. This is the kind of wave shape we hope to see from our Pitot tube data. This reads about 630 feet per second which is 430 MPH. The body pitot data is shown later. Air drag caused the tube to get twisted around 180 degrees which caused bad data to be recorded. We reinforced the Pitot tube mount for the Huntsville flight.

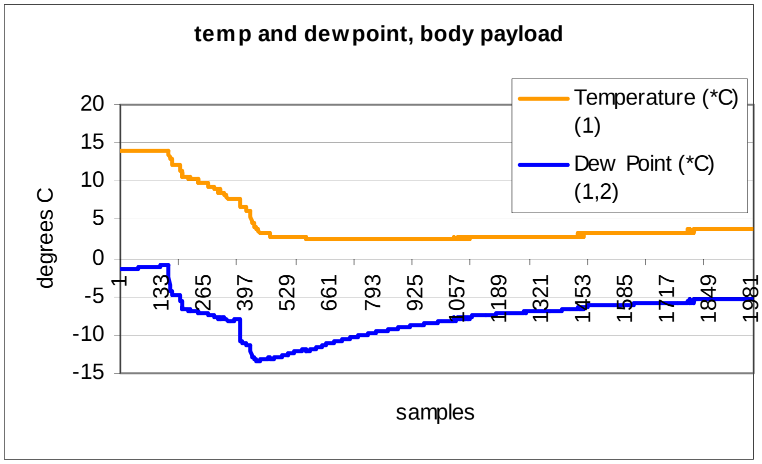


The 5th chart is weather data from the NOAA website, for hourly observations from the Princeton Illinois area. Pressure was stable at 30.0"Hg and you can see the temperatures hovering around freezing! Great Chicago-style rocket flying weather. Using the values for the time of launch, the air density was 1.299Kg/M^3. This may well be the densest air we ever flew in.

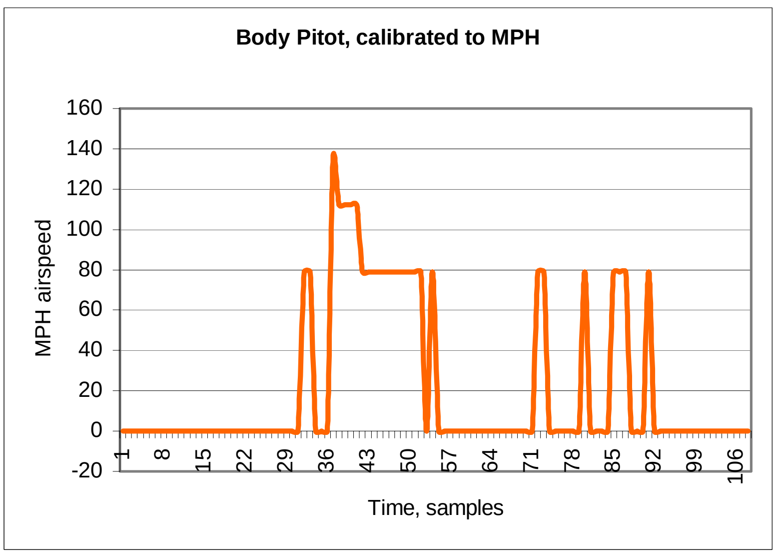




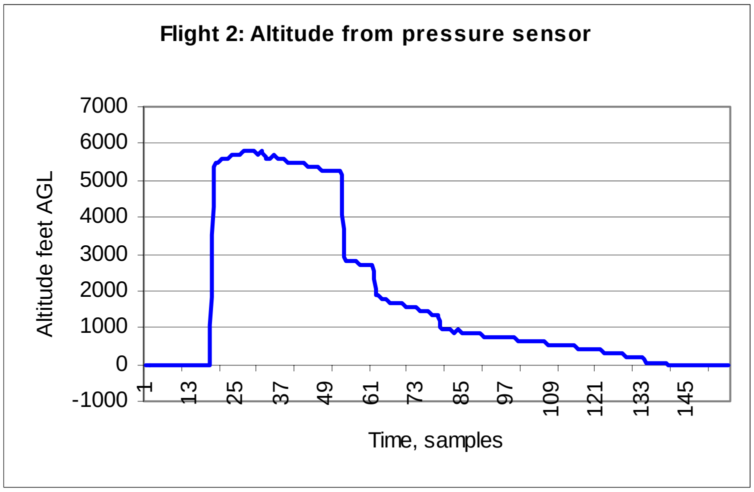
The calibrated airspeed chart above is really cool. This is from the nose Pitot tube, and note that the maximum speed is 470 MPH. Also note that the shape of the curve is very similar to the Ozark data, except for the “steps” at the end. This is exactly the kind of data that Team Orion really hoped to be able to get from a Pitot Cruiser flight, so this chart alone gives us a great feeling of accomplishment. This is the kind of result we’ve been after for many months.



Above is the temperature and dewpoint data. Note the huge drop that was recorded. That was due to bringing the rocket out of a warm SUV and launching quickly. No way to get good air density data at altitude from this mess.



Here's the body Pitot data for the second flight. 140 MPH is obviously way too low. We know what happened here: on recovering Pitot Cruiser, the body Pitot tube was turned around 180 degrees in its mount. This must have been caused by the drag forces on the tube. We reinforced the mount for the 3rd flight in Huntsville by adding more adhesive around the base.



Above is the barometric altitude data calibrated in feet of altitude. The shape is generally correct, but it has the funny steps similar to the 1st flight. We now suspect this relates to the extreme cold. The Huntsville data looks much better. Max altitude: 5800'.

Data from Flight 3, 4/28/07:

Team Orion was very excited to get our Flightworthiness Certificate from Vince on Friday night! Vince gave it a very close inspection, checking everything very thoroughly. On Saturday, we had Pitot Cruiser packed and ready to fly within an hour or so, and got in line to launch. Things got a little chaotic since we have a time limit from when the data loggers are initialized to when launch must occur. If the time limit is passed, the loggers must be re-initialized. The winds seemed to be picking up (west at 14) and the sky was suddenly very cloudy with pendulous-looking cumulus clouds (BKN050). The clouds actually worked in our favor since the body bay with the temperature sensors weren't getting heated by the sun. The loggers were running, with plenty of time to go. 3,2,1, Launch…of the wrong rocket! Now we were getting really nervous about running out of logger time! The launch team expedited as best they could to get us launched before logging time ran out. 3,2,1, launch, and Pitot Cruiser launched perfectly on an impressive column of exhaust. It looked like Pitot Cruiser actually disappeared into a cloud for a few seconds, which makes sense since NOAA was reporting broken, ceiling 5000', and we were heading just past 5000. The drogue deployed perfectly, and Pitot Cruiser began its descent. At 500' we could see a puff of smoke, and nose separation and main chute ejection, but the main chute did not open up perfectly, so Pitot Cruiser continued on down just a little slower than on drogue only (about 45'/second). It landed in what we were later told was a restricted area, so it took a while for the Army to bring it back to us. Thankfully it didn't land on a mine or a missile tube or something like that!

When we got back to our prep table the post-flight inspection began. About 2” of mud was packed inside the engine tube, so clearly we landed hard but with no damage there. The nosecone suffered a small chip at the shoulder; a small piece of gel-coat came off the glass fiber body. Some “crazing” or tiny cracks are visible on the outer clear coat, but Mr. Herrick said this is all easily repairable. We noticed that there was no mud whatsoever on the nose, so we think it must have landed on something really hard and solid, like a tank or a piece of a tank!

Next, we recorded the altitude from the beeps of the Missileworks altimeter: 5394’. Not bad, easily within our success criteria of 5280 +/- a couple of hundred feet. What’s interesting is that this was the lowest air density Pitot Cruiser has ever flown in, but we countered that with the added weight of the fancy paint job. Then we attempted to download the data from the nose and the body payloads, and it was not working. The computer said “check logger connection or logger battery”. We had never seen this message before, so this didn’t look real promising. We decided to wait till we were back at the hotel room to disassemble the payloads and see what was going on. So we packed up Pitot Cruiser for display and enjoyed watching the rest of the day’s launches.

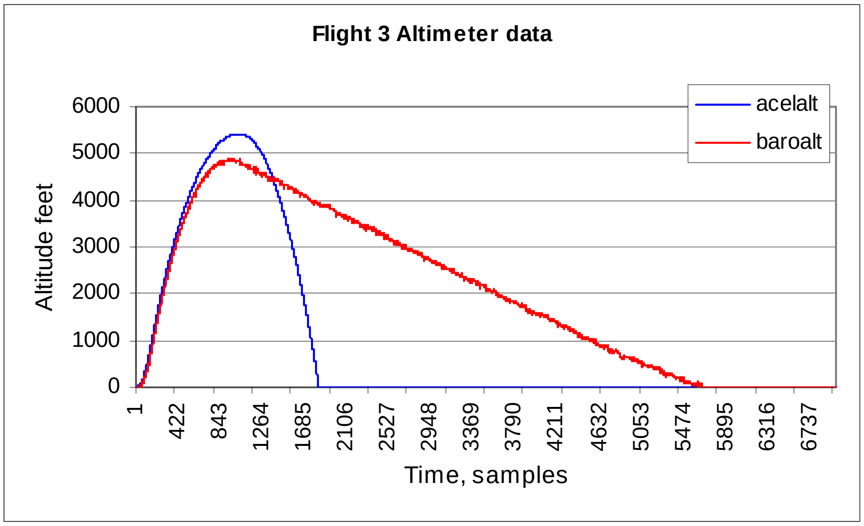
Back at the hotel later that evening, we tried downloading again. Same thing, no luck. So we opened up the body payload, and right away we found that the plug going into the logger had fallen out. We plugged it back in and tried again. Success! We downloaded all the data and it looked good, which means that the plug must have fallen out at the end of the flight, on landing, which makes sense given the minor damage. We made the assumption that the same thing happened in the nose, and on opening it, this was indeed the case. The plug was pushed back in, and all data downloaded fine. The battery holder in the nose also got a little bent up but looks easily repairable.

Here’s the weather data and data collected from Pitot Cruiser on 4/28/07:

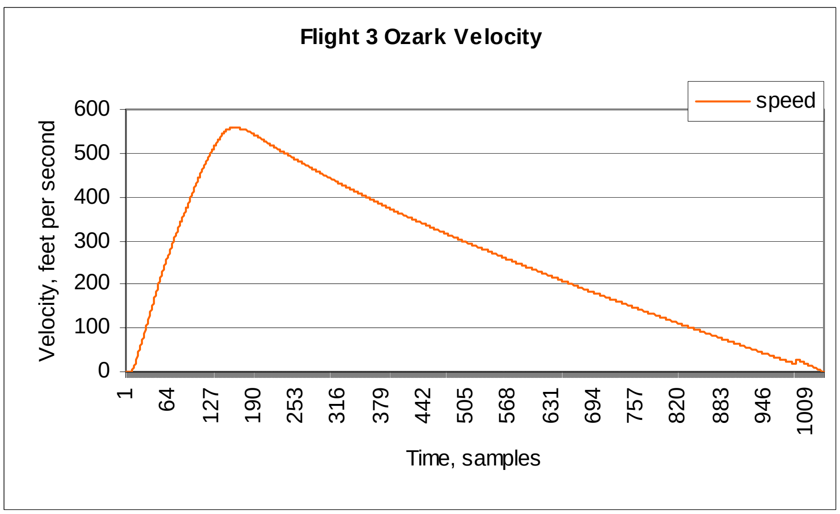
28	14:53	NW 17 G 21	10	Mostly Cloudy	FEW060 BKN100	74	47			30.08
28	13:53	NW 17	10	Mostly Cloudy	SCT050 BKN090	76	49			30.09
28	12:53	W 14	10	Mostly Cloudy	BKN050 BKN095	73	50	75	51	30.1
28	11:53	NW 9 G 16	10	Partly Cloudy	SCT046	73	51			30.11

Above is the weather data from the NOAA site. The readings closest to our launch time is the ones at time=12:53. Note the winds, pressure, ceiling, etc. Using these values to calculate air density, we get 1.19 Kg/M3 at the time of launch.

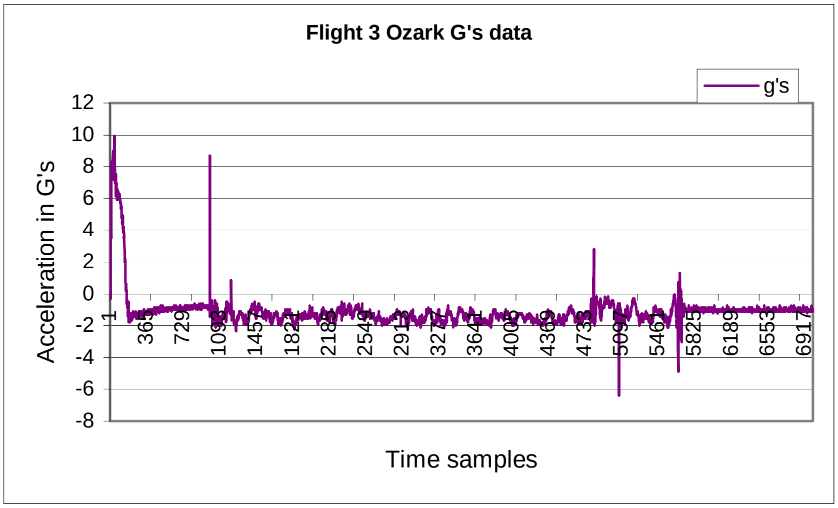
Next, the Ozark data:



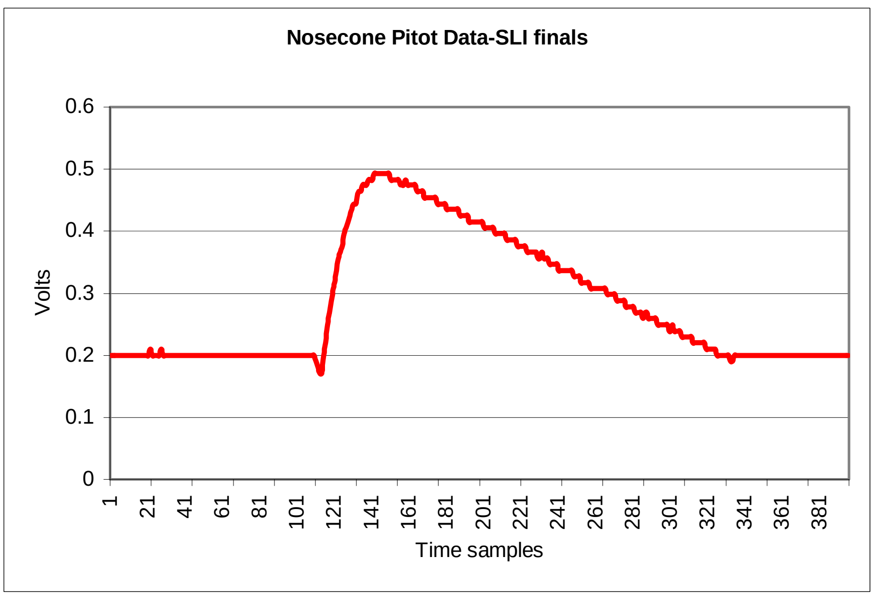
In the chart above, we overlaid both barometric and accelerometer altitude data. As usual, barometric is a little lower. The barometric curve is great, you can see the descent profile very well, including a slight decrease in descent when the main came out but didn't open fully.



Here is the Ozark's velocity data, showing a maximum of 560'/second, which equals 381 MPH.

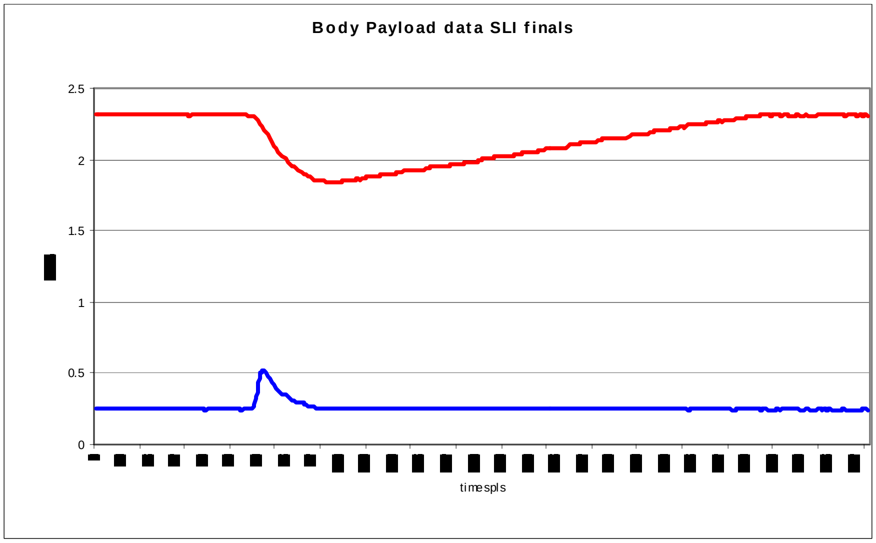


For the Ozark G's data, we plotted it over the entire length of the flight time since we wanted to see if a huge spike was recorded during the landing. There's nothing significant there, but maybe the Ozark does not record fast enough to catch a really fast, high G spike. We strongly suspect that the G's on landing are much higher than what's shown here. Takeoff acceleration was 8 G's, with one spike to 10G's. Next, the data from our payloads:

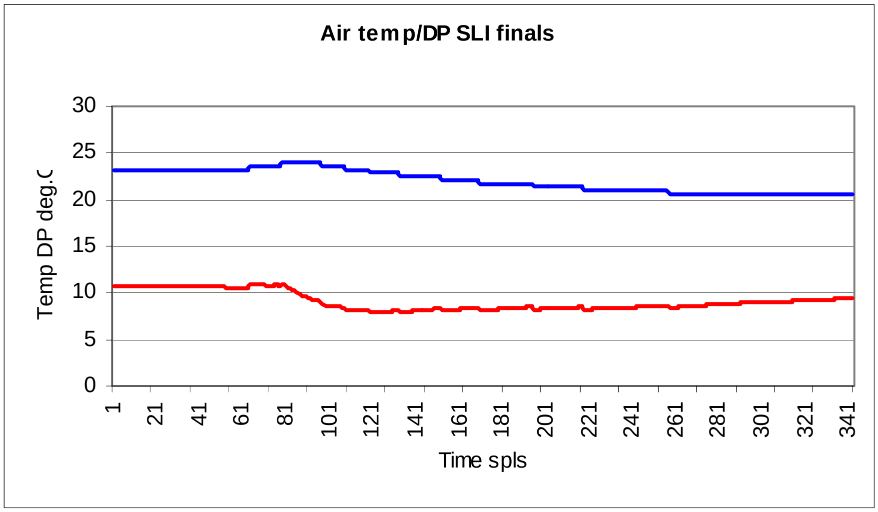


The chart above is what we downloaded from the nose payload. Unfortunately, it is not at all what we expected or hoped to see! This is an upside-down version of a barometric altitude chart! How on earth could we get inverted altitude from a Pitot tube?? This was a real mystery, and we tried to figure out how this could happen but could not explain this weirdness. To our credit, it took the electronics mentor 3 whole days to sort it all out, and here's the theory:

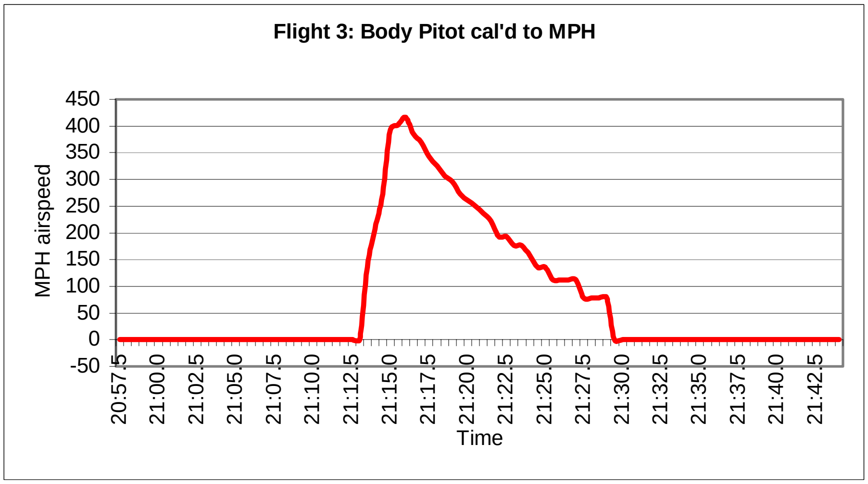
On inspecting the nose payload, an abrasion and small cut was found on the hose connecting the sensor to the Pitot tube. Additionally, on final assembly, it was unusually difficult to get the payload into the nosecone. We now think that the polyurethane hose got bent/pinched shut between the nosecone wall and one of the fiberglass payload supports. So when the payload was slid into the nose, the tube leading to the sensor was pinched shut. From other small vents at the nose bulkhead, the inside of the nosecone now became a static pressure chamber. The pressure sensor we use is a differential sensor, which means that the back side is open to static pressure. This is good for Pitot measurements, but with the front side sealed shut at the tube, the lowering of the backside pressure from increasing altitude was seen by the sensor as an increase in front side pressure!! On the positive side, it is a great looking flight profile.



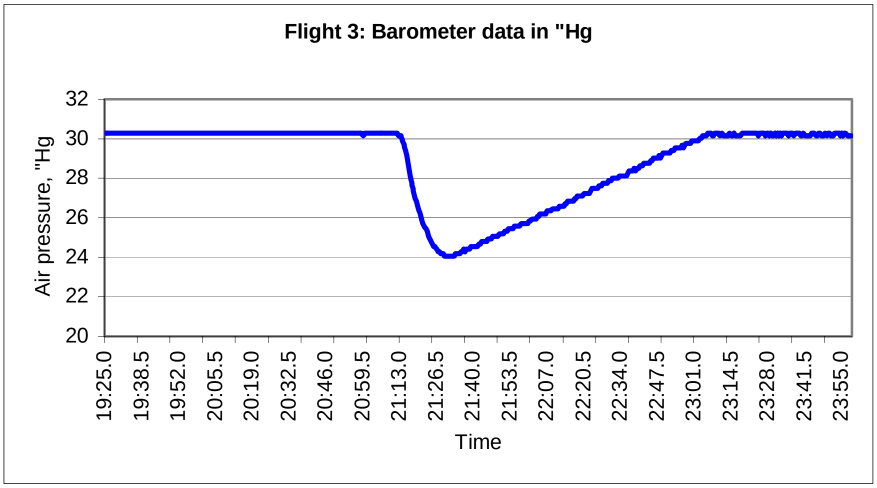
This chart shows a cool overlay of barometric pressure and pitot pressure raw data from the body bay. These look really great, probably the best looking data we ever got from Pitot Cruiser! Note the synchronization of speed and altitude from launch.



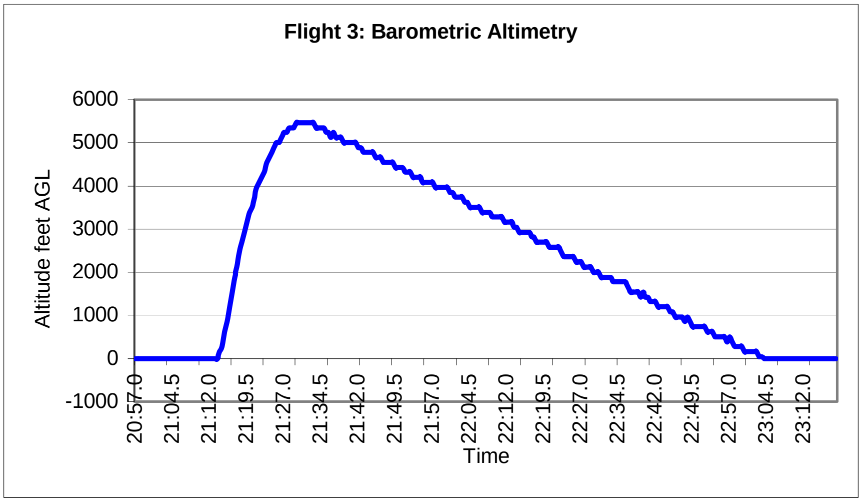
Here's the temperature and dewpoint data from the body payload. From this data, air density and lapse rate will be calculated. Notice that the temperature increases a little with altitude! Very interesting…an inversion detected!



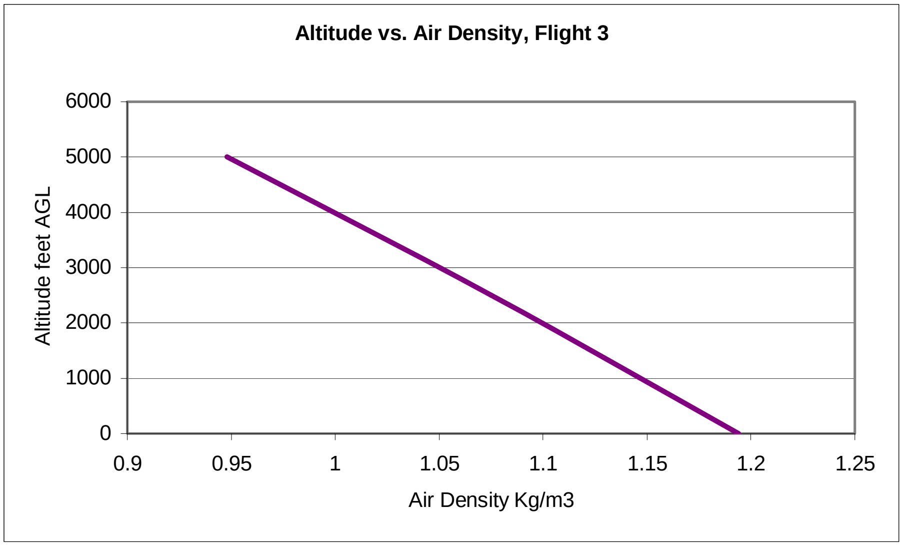
This is the body Pitot data, converted from volts into MPH. This is a great curve, with a maximum airspeed of about 420 MPH.



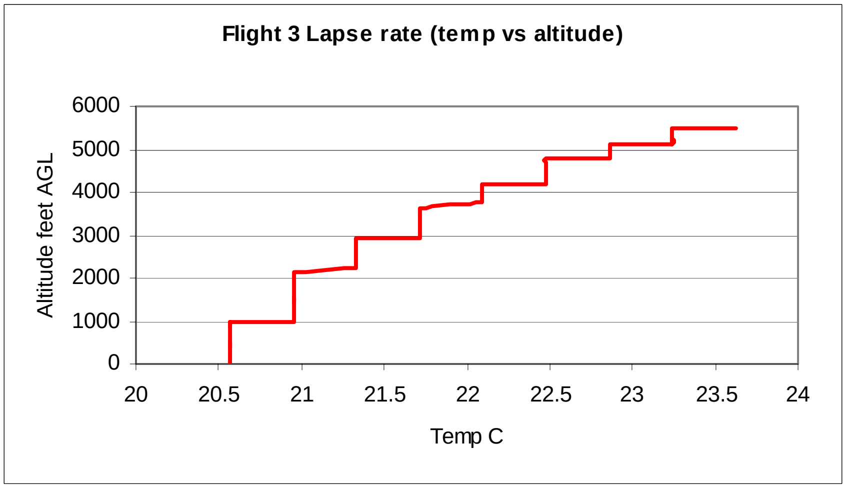
The barometric pressure is also needed to determine air density, so above is the static pressure data converted from volts into inches of mercury.



Converting the static pressure data from volts to feet yields the chart above…very nice! 5400'!



For air density, we take 3 temperature/humidity/pressure values, one at ground level, one at 2500 feet and the third at 5000'. The air density is calculated, and charted in Excel. Above is the result! This time we get a very straight line. Also, our value at ground level (1.194Kg/M3) is a perfect match to the NOAA-derived value of 1.194Kg/M3, which is very good evidence that the data we're collecting is extremely accurate!



Above is the chart of Atmospheric Lapse rate, or the rate at which the atmosphere typically cools with altitude. Very interesting! On this day, the atmosphere was actually warming slightly with increasing altitude, which means we would classify the conditions as an "inversion" which is not really typical, and means the atmosphere is very stable. Team Orion will continue researching this to see if we can confirm that there was an inversion in the area of Huntsville that day. Generally speaking, the conditions did not seem very stable, on the basis of the winds and pendulous looking cumulus clouds and the threat of severe thunderstorms the day before the flight. So, Team Orion is a little unsure of this result.

Conclusions:

The following table summarizes the data collected during all 3 flights of Pitot Cruiser:

	Flight 1 1/6/07	Flight 2 3/4/07	Flight 3 4/28/07
Missileworks altitude	5316’	5185’	5394’
NOAA air density	1.259 kg/m3	1.299 kg/m3	1.19 kg/m3
Ozark baro altitude	4800’	5000’	4859’
Ozark accel altitude	6000’	6300’	5420’
Ozark G force launch	6	8	8
Ozark max velocity	380 MPH	429 MPH	381 MPH
Orion baro altitude	5138’	5900’	5467’
Orion nose pitot Veloc	Note 1	470 MPH	Note 2
Orion body pitot Veloc	471 MPH	Note 3	420 MPH
Lapse Rate	Stable	Note 4	Inversion

Note 1: Payload not activated.
Note 2: Hose pinched shut, turned into upside-down barometric altimeter.
Note 3: Body Pitot twisted 180 degrees by air drag.
Note 4: Temperature data unusable due to rapidly dropping payload temperature.

From this data, Team Orion makes the following conclusions:

- Yes! We can build a reusable, high powered rocket that collects valid information on airspeed, altitude, temperature, dewpoint, lapse rate and air density!!
- Air density definitely drops with altitude as expected; the drop in barometric pressure has the greatest effect on the density. Our density method is very accurate.
- Our airspeed readings are typically higher than the Ozark velocity readings.
- Lapse rate is dependant on the meteorological conditions at the time of flight. We detected a stable day and maybe an inversion as well.
- Our altitude readings are generally in the right range relative to the 2 deploying altimeter barometric altitude readings. But none ever read exactly the same!

- We now know that a descent rate of 25'/sec is good, never any damage, but 45'/sec is not so good, the nosecone got chipped and a battery holder got bent.
- In spite of trying really hard to get every little system and subsystem working perfectly, things (luckily small things) didn't go exactly as planned on each flight. See notes above.
- We can nail the one mile target to within a couple of hundred feet, repeatably!

As is often the case, our research does not finalize anything, but leads directly to more questions, such as:

- Can Pitot Cruiser be used at significantly higher airspeeds? Will the payloads work OK?
- Can Pitot Cruiser detect the Pitot "dogleg" in response at Mach 1??
- Which altitude reading is the best, most accurate reading? They're all over the place from all 3 sources! How do we find out what the altitude really was?? GPS? Ground based radar? Trigonometry from ground observers? All of the above?
- What is the very best paint coating to keep the payload bays cool in full sun?
- What steps are needed to insure perfect opening of the main chute on every flight?
- Why did our payloads give better results on the warm day relative to the 2 cold days? Is the pressure sensor temperature sensitive, or some other part of the circuit?

Pitot Cruiser's and Team Orion's future plans:

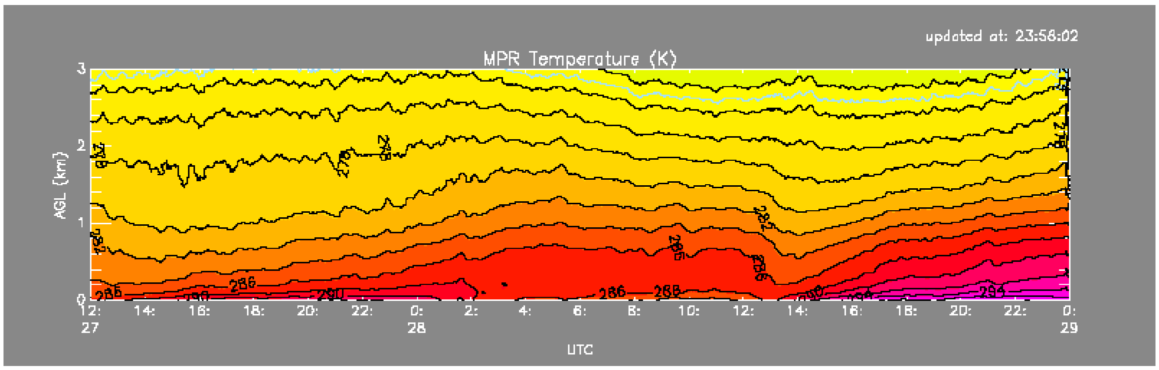
Even though Team Orion's official SLI experience is now completed, we all agree that we are not finished yet! We're still Team Orion, and there's still a lot that we can accomplish with Pitot Cruiser! Pitot Cruiser may have a short vacation being on display at a local college or maybe even at a museum, but after some minor repairs and with Mr. Herrick's approval of airworthiness and the mission, we'd like to see Pitot Cruiser fly one more time, with a different motor with a higher impulse, probably an L, to push it just past Mach 1. Our ultimate question: can the payloads we designed and built detect the interesting "dogleg" in the airspeed/pitot pressure, caused by shock waves, that occurs as an object passes Mach 1?? Can Pitot Cruiser handle going Mach 1? Team Orion thinks we can!! One additional post-SLI project: we still want to know what is the best paint coating color to avoid heating of the air temperature sensors by the sun. Team Orion now has the availability of 2 non-contact infrared thermometers, so one weekend this summer we will get together and take Pitot Cruiser out into the sun, and read the surface temperatures of several areas such as the silver body, red fins, black roll pattern, white areas, and background readings like lawn grass, asphalt and concrete and anything else that can't escape the non-contact thermometer. You never know…this kind of data may come in handy for next year!

ATMOSPHERIC LAPSE RATE ON 4/28/07

Team Orion continued the research into the validity of our finding of an inversion (air temperature increasing with altitude; very stable conditions) by Pitot Cruiser's onboard altimeter vs. air temperature sensors.

Pitot Cruiser data showed a 3 degree centigrade increase in air temperature from ground level to 5000'. This indicates an inversion. On the first flight, the opposite condition was detected; i.e. temperatures dropped with increasing altitude. The general weather conditions in Huntsville during the 3rd flight at 1:30PM on 4/28/07 did not seem "very stable" since it was windy with thick cumulus clouds at that time. Team Orion wanted to find out: was there an inversion in the area of Huntsville on 4/28/07 or not?

We tried contacting NWS through NOAA (National Weather Service, National Oceanographic and Atmospheric Administration) about temperature data for Huntsville on that date, and the next day we got an e-mail in return! It was from Chris Darden, Science and Operations Officer for NWS Huntsville! He reviewed archived data and was able to tell us that no inversions were in the area of Huntsville on that day. In fact it was classified as an "adiabatic lapse rate in the convective boundary". We're trying to figure out what that means, exactly. He also provided links for us to see this actual data from our launch day. Very cool stuff! Besides an immense Excel file, there were also charts prepared from the raw data. One stood out as being very important to our question: a plot of temperature vs. altitude in the 0-3 Km range, shown below:



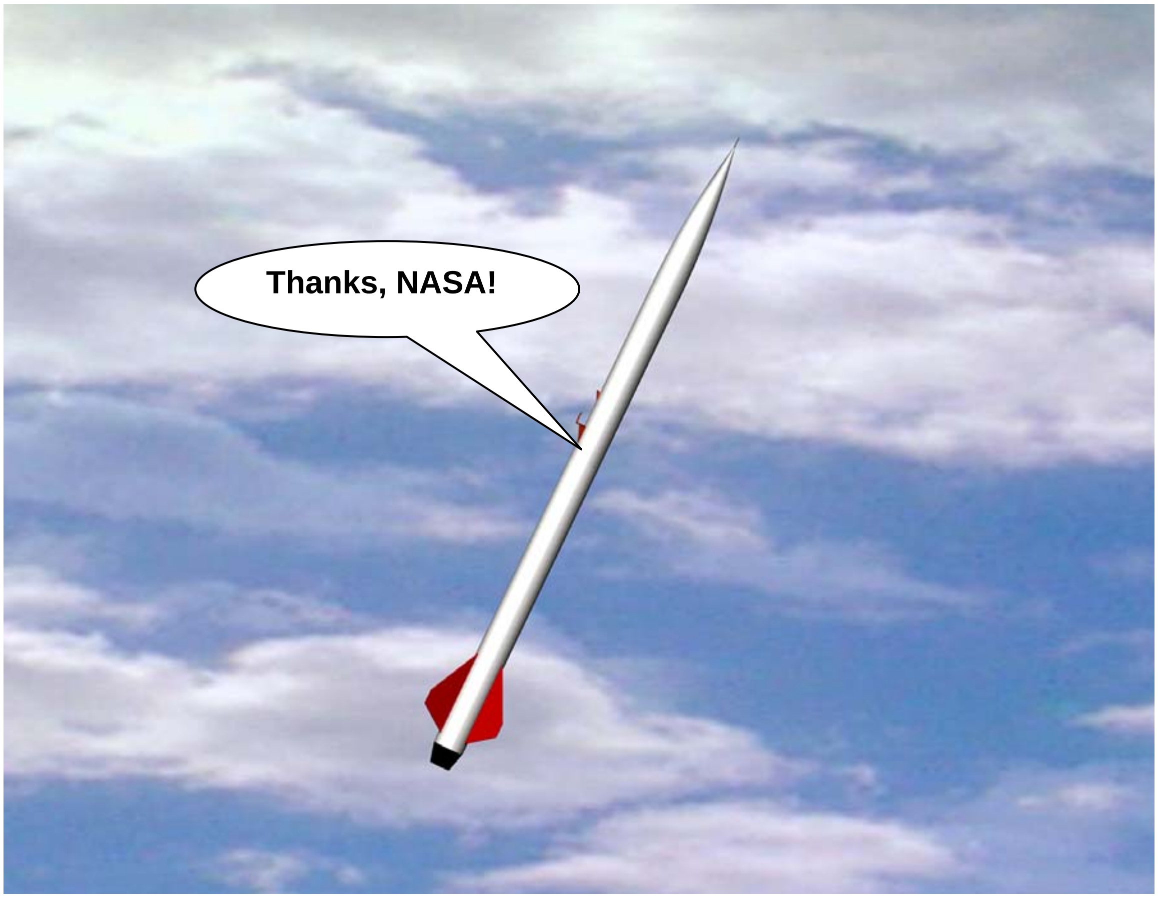
As can be seen, NWS Huntsville was detecting cooler air with altitude, not an inversion. Note that the amount of cooling is not high. This would be classified as a stable day (not VERY stable).

Why did Pitot Cruiser detect an inversion? Team Orion believes there could be 2 reasons for it.

1) The sun heated the payload bays slightly, causing an incorrect increase in temperature.
2) Friction heating of the nose caused a slight increase in payload temperatures.

Of these 2, solar heating is unlikely since, right at the time of launch, it was very cloudy (this didn't prevent most team members from getting sunburned that day!). That leaves friction heating as Team Orion's theory for an incorrect lapse rate value. The amount of heating, and therefore error, was not much.

For future flights, it would be good to try to determine the amount of heating from friction, so it could be subtracted from the temperature data to correct it. Team Orion is trying to come up with other methods to avoid this error. Thanks NWS Huntsville for this weather data!

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BACK ROW (L-R) LEONARD JOHNSON, KENNETH JOHNSON, AJ WITZKE, NICK CINQUINO
(TEAM LEADER)
(ELECTRONICS MENTOR)
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