Project Ellie: Hokies go to the Edge of Space
VA Tech High Altitude Balloon Mission as an Introduction to the Space Environment

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Abstract

This paper describes a successful high altitude balloon mission carried out by students from VA Tech's ECE 2984 Exploration of the Space Environment class. The balloon went 32,708 meters (107,310 ft) into the stratosphere and the payload was successfully recovered. The mission was designed to introduce students to the system aspects of space flight. The students ranged from sophomores to seniors in Electrical Engineering, Mechanical Engineering, Engineering Science and Mechanics, and Aerospace Engineering. The students addressed the regulatory environment, mass and link power budgets, sensors, structure, planning and organization, and "test like you fly" mission assurance. The 1.36 kg payload carried two cameras, a VHF amateur radio with an Automatic Position Reporting System (APRS) modem, and a GPS receiver. In addition to the cameras, the payload also carried a simple magnetometer, a three axis accelerometer, an atmospheric pressure sensor, and temperature sensors. The sensor data was recorded with an on board data logger as well as transmitted to the ground via the APRS. One of the mission objectives was to develop the expertise and infrastructure to do more complex missions in concert with VA Tech's Space@VT space science research group.

The Objective

The objective was to send a camera 30 km into the stratosphere to take pictures and then recover the payload. The mission was designed to give the students the experience of working in teams and addressing the systems engineering issues needed to successful complete what is essentially a mini space mission. It is desired that this first mission develop the infrastructure and expertise to do successively more challenging science missions.

This paper describes the high altitude balloon mission carried out by the students. While it describes what the team did, it also outlines some of the system engineering trade offs.

The current trend in engineering education is toward more hands on project based learning. A good project is a combination of challenging objectives, substantial engineering, and interdisciplinary teamwork. For beginning engineering students, a project needs to be engaging and it needs a schedule that permits successful completion in a semester or two. The students can see the results of their work and success is a powerful motivator.

The Team

The majority of the team was recruited from ECE 2984 Exploration of the Space Environment. Dr. Jo Baker of the Space@VT research group teaches this class as an engineering introduction and the balloon mission was offered as a project activity within the class. Dr. Dennis Sweeney from ECE acted as "mission director" and managed the team. The students were primarily sophomores and juniors. An additional ECE senior joined the team. He was an amateur radio operator experienced with APRS.

The team met once a week to parse activities and report on progress. An internal website was set up to facilitate team activities. Team members uploaded information on the various tasks so it was available to the entire team. The team developed a task list and those responsible accomplished the various tasks and reported back to the team.

Figure 1: The Project Ellie team at launch.

Regulatory Environment

One of the first tasks that the team undertook was researching Federal Aviation Administration (FAA) regulations concerning balloon flight. The objective was to avoid the complex permitting process. The regulations that apply to free balloon flight are U.S. Federal Aviation Regulations (FAR) Part 101.1 (1). These regulations limit the size of the balloon and the payload weight. When the team contacted the local FAA air traffic control, they wanted to know if the balloon was less than 6 ft (1.8 m), if the payload was less than 6 lb (2.73 kg), and if the launch would be more than 10 miles (6.25 km) from a major airport. The FAA regulations also require a secondary balloon payload separation mechanism and a radar reflector. Given the size of the balloon, no notification was required at the time of launch.

The FAA regulations set the first important parameter for the flight: the payload weight. The team chose a maximum payload weight of 1.36 kg (3 lbs). There is the almost inevitable growth in the payload weight so setting a maximum at the beginning proved to be an important discipline. The final weight of the payload and rigging (parachute, antenna, etc.) was approximately 1.70 kg (3.75 lb). Controlling the payload weight proved to be an important consideration in achieving the altitude objective.

Camera Selection

A video camera was chosen as the primary payload. The camera had to have reasonable video quality, enough storage capacity and battery life for the duration of the mission, and minimal weight. A Contour ROAM camera was selected. It is small, lightweight, and capable of HD quality video. It was rugged enough to withstand the extremes of temperature and impact posed by the ascent to near space. This camera massed 0.14 kg (5.1 oz) and so it was determined that two cameras could safely be included in the payload, one facing the horizon and one bottom facing.

The team performed battery life and memory utilization tests on the cameras. The cameras needed to operate for the duration of the mission which was estimated to be 2.5 hours plus some cushion time to account for launch. It was found that the cameras could only shoot 93 minutes of HD video. The cameras had a mode that would allow still pictures to be taken at intervals. A three second interval allowed four hours of operation. Operation was ultimately limited by the battery. The camera team created a video from the stills after the cameras were recovered. In addition, the high resolution of the stills resulted in stunning pictures.

Balloon Selection

Critical to mission success is the performance of the balloon. Since the FAA regulation limits the size of the balloon, the team needed to determine the lifting performance as well as estimate burst altitude and mission duration. The lift available from the balloon can be determined from the mass of air displaced by the helium used as the lifting gas (2):

$$L=V(\rho_{air}-\rho_{He}) \qquad 1$$

L is the lift, *V* is the volume of the balloon at launch, ρ_{air} is the density of the air, and ρ_{He} is the density of the helium. The balloon must first lift its own weight, and then any additional lift is available to lift the payload and rigging. This additional lift is the neck lift and it is given by:

$$N=L-B=P+T+R \tag{2}$$

Where N is the neck lift, B is the mass of the balloon, P is the payload mass, R is the residual lift, and T is the mass of the tether. In this case, the tether mass is included in the total payload mass. Equation 2 allows for the residual lift to be calculated, as well as the neck lift. The residual lift is a measure of how much lift force is leftover after all of the applied mass has been taken into account. A higher value is typically desirable because a greater residual lift results in a higher ascent velocity:

$$V_A=(Rg/(0.5C_dA\rho_{air}))^{1/2} \tag{3}$$

Where V_A is the ascent velocity, g is the acceleration due to gravity, C_d is the drag constant for a sphere, and A is the cross sectional area of the balloon. The burst altitude can be estimated by:

$$H_B=102500 \ln(D_B/D_L) \text{ ft.} \tag{4}$$

Where H_B is the bursting altitude, D_B is the diameter of the balloon at bursting, and D_L is the diameter of the balloon at launch. D_B is typically listed by the manufacturer of the balloon and D_L is a parameter that is controlled by how much helium is put into the balloon. Using this analysis, it is not difficult to show that a larger balloon and a lighter payload will result in a greater altitude. The trade off is that additional lifting gas will be needed for the larger, heavier balloon.

The final mass of the payload and rigging at launch was measured as 1.70 kg (3.75 lbs). Typically, a residual lift that is close to the weight of the payload is desired. The desired residual lift was set at 1.36 kg (3lbs). With these parameters, the launch diameter of the balloon was 1.88 m (6.18ft) and 1.98 m (6.5 ft) for the available 600 g and 1200 g balloons, respectively. The estimated burst altitude for the 600 g balloon was 36.7 km (120,377 ft) and 47.8 km (156,763 ft) for the 1200 g balloon. These estimated burst altitudes are based on the manufacturers' claimed burst diameters of 20 ft for the 600 g balloon and 30 ft for the 1200 g balloon. These estimates are probably overly optimistic but they do show that under inflating the larger balloon results in a higher altitude. The team chose the 1200 g balloon. Table 1 shows the lift data and estimated burst altitude for the 1200 g balloon with an assumed payload mass of 1.70 kg (3.75 lbs).

Table 1. Preliminary Lift Data

Mass of Payload (kg)	1.70
Mass of Balloon (kg)	1.20
Diameter at Launch (m)	1.98
Diameter at Burst (ft)	30.00
Lift (kg)	4.26
Neck Lift (kg)	3.06
Residual Lift (kg)	1.36
Bursting Altitude (km)	47.8
Ascent Velocity (m/s)	5.31
Time until Bursting (hr)	2.50

Figure 2 shows the measured assent. The actual assent rate is approximately 4.6 m/sec. This is somewhat less than the estimate, but the actual measured launch neck lift was 2.75 kg. This is somewhat less than the assumed 3.06 kg. Under inflating the balloon results in a higher altitude but a slower assent rate. Figure 2 also shows the effect of the parachute. At altitude, the air density is very low so the parachute has little effect. As the air density increases, the parachute progressively slows the payload decent.

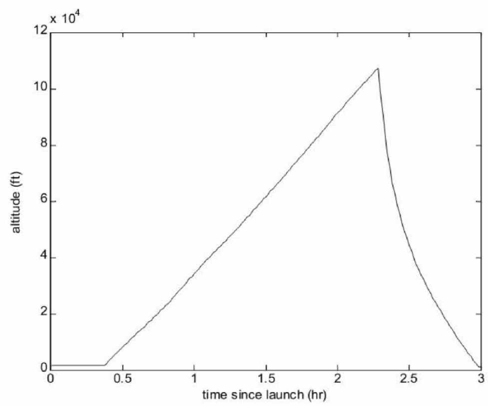


Figure 2: Altitude verses time.

Parachute Selection

One important aspect of designing a high altitude balloon mission is to select an adequate parachute. If the parachute is too small, the payload will impact the ground at too great a velocity and potentially damage the electronics inside. On the other hand, parachutes become more expensive and heavy as they increase in size. A parachute that is too large can also slow the payload down too much. Strong winds may blow the payload off course and make it more difficult to retrieve. Through an understanding of the relationship between the drag created by the parachute, the mass of the payload, and the desired impact velocity, the necessary size of the parachute can be determined. This relationship is given by (3):

$$D=\sqrt{\frac{8mg}{\pi\rho C_D v^2}} \quad 5$$

Where D is the diameter of the parachute, m is the mass of the payload, g is the acceleration due to gravity, ρ is the density of air, C_D is the coefficient of drag, and v is the desired impact speed. A drag coefficient of 1.5 was used because it was assumed that the parachute was dome-shaped. Table 2 shows the impact velocities for a range of parachute diameters.

Table 2. Impact Velocities for a Range of Parachute Sizes

Payload and Rigging Mass (kg)	Speed (m/s)	Parachute Diameter
1.59	7.00	0.9 m (3ft)
1.59	5.25	1.2 m (4ft)
1.59	4.20	1.5 m (5ft)
1.59	3.50	1.8 m (6ft)
1.59	2.89	2.1 m (7ft)

Drop tests were performed with the 1.2 m and 1.5 m parachute and a 1.6 kg (3.5 lbs) load in the payload foam box. The parachute and the weighted payload box were dropped from the fifth story of a parking garage located on the VA Tech campus. Three drops were performed with each parachute. The container withstood the forces of six impacts before a crack appeared in the structure. As a result of the drop tests, the team selected the five foot parachute. The tests prompted the addition of foam insulation inside the container to absorb some of the shock from impact and protect the components.

Communications and Sensor Package

The communications and sensor package contained an ICOM IC-V80 144 MHz amateur radio transceiver, a TinyTrak4 APRS modem, and a Byonic GPS-4 GPS receiver along with an Arduino processor and several sensors. The firmware in many GPS receivers limits their operation to an 18 or 30 km altitude. The Byonic GPS-4 is specified to work to 84 km. It worked flawlessly at altitude.

The IC-V80 was programed to use the 144.39 MHz amateur radio APRS frequency. There is a system of terrestrial APRS digipeters on this frequency that relay the APRS packets to the APRS website (http://aprs.fi). We published the APRS URL prior to the flight and many people followed the flight in real time. The transmitter requires a licensed amateur radio operator.

The IC-V80 transmitter power is selectable at 0.5/2.5/5.5 watts. A link power analysis was performed and the 2.5 watt level was chosen as a trade off between battery life and range. This analysis is shown in Table 3. During the flight, the 0.5 watt power level would have been adequate but the higher power would have been appreciated if an extended ground search had been necessary to recover the payload.

The transmitter antenna is a pair of crossed dipoles. They are horizontally polarized with an omni directional pattern. While the vertical monopole is simple, it has a nadir radiation null. The antenna was built using light, strong aluminum arrow shafts. Sub-miniature RG188/RG179 coax was used to save weight. It was mounted above the payload to reduce the possibility of damage on impact. However, early testing revealed that the proximity of the antenna to the payload caused problems with the data collection processor. The payload electronics were wrapped with metalized mylar film to shield them.

The receive antennas on the chase vehicles were all vertically polarized so there is some polarization loss. A somewhat arbitrary figure of 6 dB of polarization loss was added to the link power budget.

Table 3. Radio Link Power Analysis

Quantity	Value	Unit	Notes
Satellite Name	VT Balloon		
Frequency	144.39	MHz	
Polarization	Linear		
Link Distance	50.00	km	Slant Path Length (Sqrt(2)*altitude)
TX Power	34.00	dBm	2.5 watts
TX Antenna Gain	0.00	dB	crossed dipole
EIRP	**34.00**	**dBm**	**Effective Radiated Power**
Free Space Path Loss	-109.61	dB	
Atmospheric Loss	-1.00	dB	Scintillation/Absorption
Total Path Loss	**-110.61**	**dB**	
RX Antenna Gain	0.00	dBi	dipole
Polarization Loss	-6.00	dB	Ant polarization mismatch
RX Cable Loss	-0.50	dB	Cable Loss
RX Connector Loss	-0.50	dB	Connector Loss
Total RX Gains	**-7.00**	**dB**	Total Losses
Received Signal Level	**-83.61**	**dBm**	**Received Power**
Receiver Sensitivity	-107.00	dBm	1 uV sensitivity
CNR	**23.39**	**dB**	Carrier to Noise Ratio

The radio was modified so that the sensor package could be powered from the radio battery. This saved weight. The IC-V80's 1.4 Ahr NiMH rechargeable battery was replaced with AA Li-ion primary cells. These batteries have approximately twice the capacity of the NiMH battery and yet they were about 100 g lighter. The team did several buttery life tests to insure that the radio and payload would run for the duration of the flight and recovery effort. The radio and the tracker needed to continue to operate after impact so the battery case was taped to the radio and the radio was wrapped in foam.

The sensor package contained an interior and an exterior temperature sensor, an atmospheric pressure sensor, and a nine degree of freedom accelerometer, magnetometer compass, and gyro package. The sensors were obtained from Sparkfun (http://www.sparkfun.com/). The sensors are read by an ATMEGA328P 8 bit processor. The processor formatted the data and sent it to the TinyTrak4 to be down-linked via the APRS and the processor also wrote the data to a data logger in the payload. The data logger is an OpenLog device from Sparkfun (DEV-09530). A processor timer controled the secondary cut down mechanism if the balloon does not burst at altitude. The processor arms the circuit above 6 km and, if the mission went for more than four hours, closes a relay that applies power to a length of nichrome heater wire. The heater wire melted a nylon tie that connected the balloon to the payload. The nichrome heater was powered independently with a pair of 9V batteries.

The barometric pressure sensor (Sparkfun SEN-09694) contained a Bosch MP085 pressure sensor. It is specified to operate from 300 to 1100 hPa. That limits its calibrated range to approximately 9.0 km altitude. Operating it higher did not seem to damage it, but the accuracy of the data at altitude is suspect. The altitude can be estimated by:

$$Altitude = 44330\left(1-\left(p/p_o\right)^{(1/5.255)}\right) = 44330\left(1-(810/101325.0)^{(1/5.255)}\right) = 26.6\,km \qquad 6$$

Where p is the actual pressure and p_o is the pressure at sea level. The sensor appears to underestimate the altitude. It is clear from Figure 3 that the sensor has entered its nonlinear range. A sensor more suited to the low pressure needs to be found.

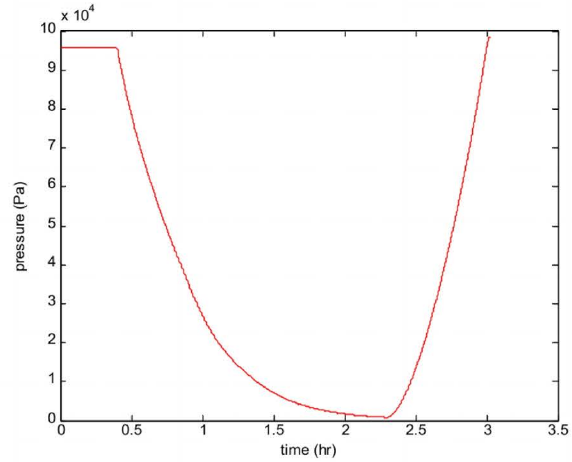
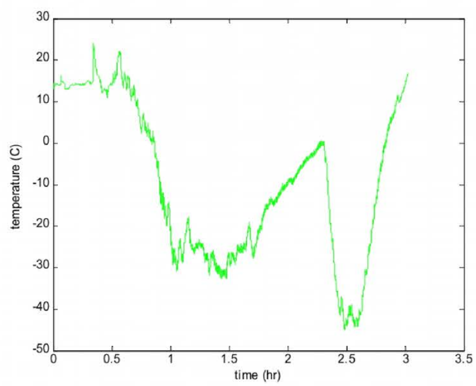


Figure 3: Atmospheric pressure verses time.

The exterior temperature sensor (Sparkfun SEN-09418) employed a Texas Instruments TMP120. It is specified for operation down to -40 C. It reported approximately -45 C at altitude. Finding a sensor that will operate to -55 C is desirable. Figure 4 and Figure 5 show the exterior and interior temperature respectively during the flight.



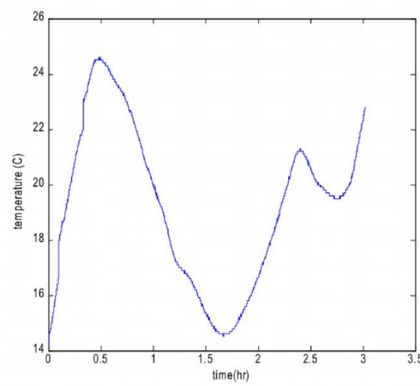


Figure 4: Exterior temperature verses time. Figure 5: Interior temperature verses time.

The interior temperature sensor is part of the magnetometer (Honeywell HMC5883L)/accelerometer (Analog Devices ADXL345)/gyro package (InvenSense ITG-3200). This sensor suit was obtained from Sparkfun (Sparkfun SEN-10724). The data from this sensor package is still being evaluated. These sensors were added as a secondary payload and the data suggests that they were not suitably applied for the mission. These sensors need to be better evaluated or more suitable sensors need to found for future missions.

Dry run and Launch Day

Prior to the actual launch day, the team performed a launch dry run to become aware of any possible kinks and account for them. One of the 600 g balloons was used to practice filling and handling the balloon. The team was already aware that latex gloves were necessary when handling the balloon in order to keep skin oils from weakening the latex balloon. The dry run showed that it was handy to have hats as well since heads were used to keep the balloon in place during inflation. The team also practiced measuring the neck lift produced by the balloon. Neck lift was measured with a small spring scale. The proper neck lift insured that the balloon was not over inflated.

After filling the 600 g balloon, the parachute, the payload, the antenna, and other rigging were integrated. The secondary cut down mechanism was tested. It did not work properly, but, since the actual launch was several days away, there was time to correct the problem. The team also tested the GPS tracker software and radios. The team members responsible for the telemetry also learned the basics of how to read and interpret the data as well as operate the equipment.

For the dry run and launch day, each team member had an assigned task and there was a launch check list. The launch was scheduled for 0830 from the VA Tech research farm where the aerospace department has an air strip for its UAV's (unmanned air vehicles). It is an open area with a minimum of buildings and power lines. Morning was chosen for calm winds.

The payload and rigging at launch weighed 1.7 kg (3.75 lb) and the lift software syndicated about 3.1 kg of balloon neck lift was needed. The balloon was actually inflated to approximately 2.75 kg so the assent rate was a little less than predicted. Figure 6 shows the payload and rigging just before launch.

The launch went off without a hitch except it was delayed for about an hour when the team realized that they had left the balloons on the sidewalk back on campus! Despite efforts to uninvited him, Murphy always seems to show up.

Chase Teams

Three chase teams were organized to follow the balloon after launch. Each team had an APRS equipped radio and a computer with the tracking software. The teams were divided into a driver, a radio operator and two additional team members to take pictures and read maps.

The ground tracking software allowed tracking the balloon in real time independent of the terrestrial APRS network. A commonly used method for balloon tracking utilizes the amateur radio network of so called digipeaters and iGates to follow the flight of the balloon on an Internet web page. This process is slow as it takes time for the web servers to update. In addition, the coverage can be somewhat spotty. When the balloon is close to the earth, the digipeaters or iGates may not be able to

Figure 6: The launched payload and rigging. The payload is in the white box in the lower left with the parachute on top. The silver object is the center is the radar target and the orange streamers are tied to the crossed dipole transmitter antenna. It was hoped that the streamers would improve visibility if were necessary to search for the payload but they did not survive the flight.

receive the position reports from the payload due to propagation issues such as terrain blockage. Real time tracking allowed the chase teams to track the balloon during its flight so they could be physically close at the time of impact. It also permitted a ground search after impact. The chase teams were equipped with light yagi antennas for additional gain if a ground search was necessary.

The tracking software decodes the position reports from the balloon payload and plots the position on a map. The red dot in the upper center of Figure 7 is the balloon position. At the same time, the software is aware of the chaser's position and this information is also plotted on the map. The blue dot in the lower center of Figure 7 is the position of the chase team. Additional balloon payload data such as velocity, heading, and altitude is displayed. With knowledge of both the balloon payload and the chaser's position, it is possible to calculate the azimuth and elevation of the balloon with respect to the chaser. By overlaying the balloon and chaser position data on a map, it is possible for the chaser to make informed decisions about how to navigate in order to stay as close as possible to the balloon during its flight. The small red tail on the red dot shows the direction of movement of the balloon while the red tail on the blue dot shows the heading from the chaser to the balloon.

The software also displayed the payload sensor data. This information is shown in the bottom right of Figure 7. Though not as crucial as the position information, this ensures that even if the payload is not recovered successfully at least some of the sensor data from the flight is captured. The tracking software automatically records all decoded sensor data to a text file for post-flight analysis.

The ground tracking software was written using Visual Basic 2010. The heart of the program is the mapping functions. The program uses the MapWinGIS ActiveX Control developed under the MapWindow GIS Open Source Project and is available from www.mapwindow.org. This ActiveX control allows the programmer to import GIS data to develop custom mapping software. All GIS data used in this project was downloaded from the US Census Bureau TIGER/Line Shapefile repository available at http://www.census.gov/geo/www/tiger/shp.html. These shapefiles contain all the mapping data such as road and water lines that are utilized by the ActiveX Control.

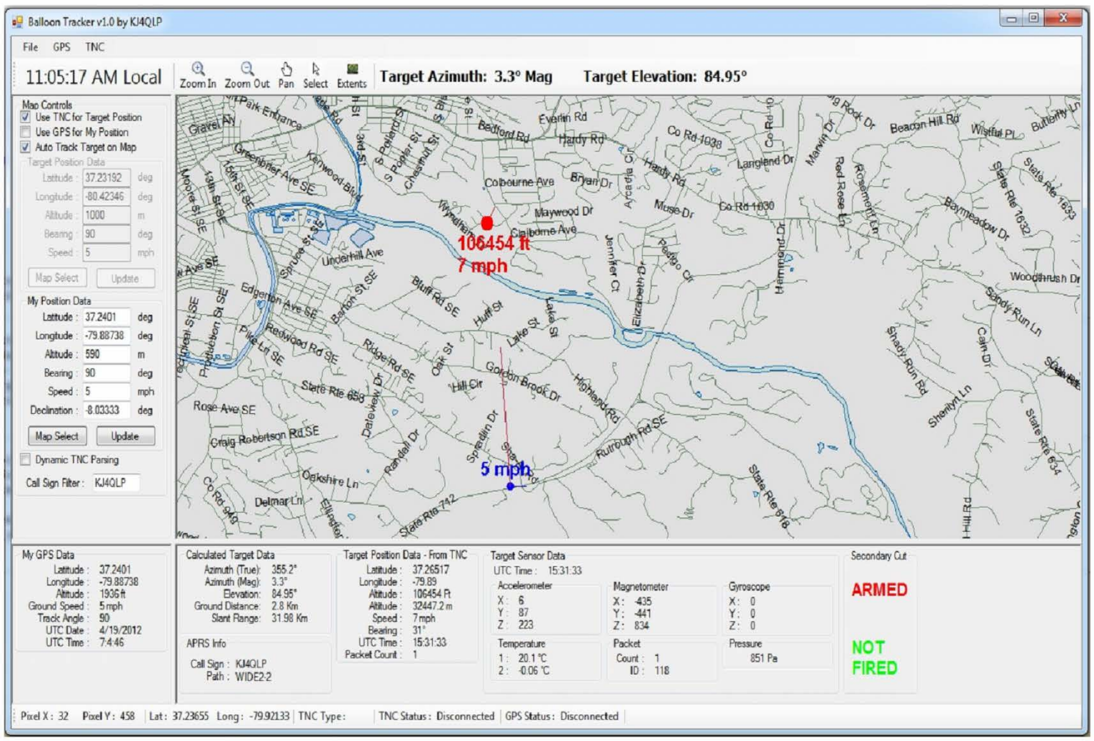


Figure 7: Display of the position plotting software.

Mission Results

The mission was almost a 100% success. Figure 8 is the picture taken just before the balloon ruptured at approximately 32,708 m (107,310 ft). The day of the dry run had perfect clear weather, but launch day was overcast so the bottom camera did not provide the hoped for pictures. Figure 9 is the ground track reported by the APRS website. The jet stream winds carried the balloon almost due east. Above the jet stream, the balloon drifted north. Max altitude was obtained at the northern most point of this drift.

Figure 8: Picture taken by the horizon facing camera at 32,708 m (107, 310 ft). The blackness of space and the curvature of the earth can clearly be seen. The thin blue line at the horizon is the extent of the atmosphere. At this altitude, the camera is above 95% of the atmosphere.

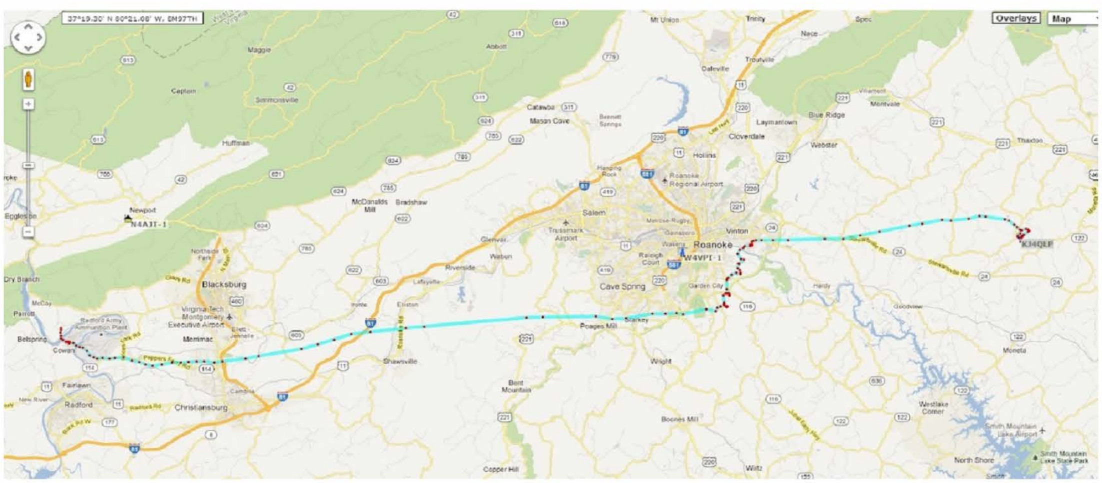


Figure 9. APRS ground track.

The chase teams worked almost flawlessly. One team located the payload within a few minutes of touch down. Unfortunately, it landed in a tree. One of the team members was a former Marine. He had the experience and equipment to climb the tree.

The mission also generated the desired "wow." The students got excited to see their work come together. Half the ECE department followed the mission via the APRS website and the local TV station did a video piece on the mission.

Lessons Learned

One of things learned was that the right project can really engage student interest. This project was challenging, the schedule was tight, but it had a "wow" factor than kept everyone engaged. It was fun too! A number of ECE faculty and staff came out to witness the launch and even some of these seasoned hands got excited.

The team is important. The team had a good mix of talents, but, with a fairly large 12 member team, it is important to parse the tasks. Defining and assigning the tasks assured that everything got done.

The team was interdisciplinary in that several engineering disciplines were represented, but the plan for the next flight is to recruit students from VA Tech's meteorology program to help predict the upper atmospheric winds and estimate the flight path. In addition, students from the geography program could help with tracking and GIS.

Planning and testing are critical. Test what you are actually going to fly, in other words don't make last minute changes to "improve" things. It needs to work, but it doesn't need to be perfect. In the space business, this is called "test like you fly." For example, when it was decided to go from the NiMH to the Li-ion batteries, the battery life tests were repeated. Think about what will happen during the mission and test accordingly. The high altitude cut down failed at the dry run, but there was time to fix it before launch. Everyone had an assigned role and task for launch day. There was a launch checklist. It is easy to overlook charging batteries, clearing memory cards, and being sure camera lens are clean.

If testing isn't possible, analyze. The larger 1200 g balloon was used over the 600 g balloon as a result of the lift, assent rate, and max altitude analysis. The larger balloon was critical in exceeding the mission object of a 30 km altitude.

The clocks in the two cameras and the data logger should have been synchronized. The two cameras and the data logger all had different time stamps. That made it difficult, but not impossible, to relate events and pictures to an altitude.

A cut down mechanism for the payload is needed so it won't be necessary to climb trees. The local area is heavily wooded and the fact that this was not considered turned out to be a significant oversight. The IC-V80 contains a receiver so a DTMF (dual tone multi-frequency) command decoder could be added to command the separation of the payload. A cut down mechanism similar to what was used for the balloon could be used.

This type of mission is more complex and more challenging than it looks. Mission success was due to good people, good engineering, and good organization (and maybe just a little bit of good luck!).

Future work

One of the objectives was to develop the expertise and infrastructure to do these missions on a regular basis. The objective is to do at least one mission a year. VA Tech has a space science program (SPACE@VT) in the ECE department. With this flight as a basis, a new team can now credibly turn to them and talk about flying more science oriented sensors. Humidity, radiation, and ozone sensors have been suggested. The space science group is working on sensors for CubeSat missions and there has been some discussion of test flying some of the sensors being developed for these missions. This will require a step up in engineering because calibration and measurement protocols will have to carefully considered so that the data collected can stand up to peer review.

The cameras are still fun. It would be nice to fly on a clear day so the down camera will give better pictures.

We want to break an altitude record.

References

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(3) http://my.exec.com/~culp/rockets/decent.html