AC 2011-1021: HIGH ALTITUDE BALLOON INSTRUMENTATION IN UNDERGRADUATE ELECTRICAL AND COMPUTER ENGINEERING

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High Altitude Balloon Instrumentation
In Undergraduate Electrical and Computer Engineering

Abstract

A high-altitude balloon project which received NSF funding in 2008 originated with Taylor University in Upland, Indiana. Since that time numerous other universities have become involved in the project by way of Taylor's ongoing summer workshops. A typical balloon travels to about 100,000 feet in a two to three hour period, bursts, and parachutes its payload to earth. A balloon can be used to launch a 12 pound load into a near-space environment for a modest cost. The balloon and the load can be tracked and the load can be recovered using the Global Positioning System (GPS). This system allows undergraduate electrical and computer engineering students to design instrumentation packages for a harsh environment and the recovered data can be used to judge the effectiveness of the design.

This paper presents details of the use of this system in a junior level project course in electrical and computer engineering. The class uses student teams to design an instrumentation package to specifications that include packaging, severe environmental factors, as well as electrical and computer engineering hardware and software design. We give results from multiple balloon launches along with enough detail on cost and manpower to allow others to duplicate and enhance this project.

Introduction and History

A high altitude balloon as discussed in this paper is a single weather balloon filled with helium which can reach an altitude of about 100,000 feet and carry a 12-pound load. Historically, weather balloons have been sent aloft since the 1890s. Most often these balloons carry payloads that can be tracked and recovered to provide information about temperature, humidity, altitude, wind, ultra-violet, infrared and other types of radiation, ozone and other gases, particulates, and of course, photography of the earth, the sun, and the stars.

The earliest balloons used hot air for lift and had an open bottom. As they cooled they descended and were pushed by the winds on the way up and again on the way down. Recovery depended much on sight or notes to finders. Fully closed rubber balloons were developed shortly after 1900 and were filled with hydrogen or helium. These balloons continued to rise and expand because of decreased air pressure until they burst, at which time a parachute would return the payload. This significantly decreased the amount of drift on the trip down. In the 1930s radio transmitters became sophisticated enough that they could be sent aloft. These were called radiosondes and they were used to transmit collected sensor data back to a ground station and to emit a radio frequency that could be located by triangulation. In the 1950s, meteorologist began to launch semi-permanent balloons into the atmosphere. These could be made to rise to a given height and remain aloft for weeks while sending back data from sensors.

Today the helium-filled balloons that rise and burst and the semi-permanent Mylar® balloons are still in use. The global positioning system (GPS) has been added to the instrument package. The reduced size and reduced price of the electronic instrumentation has made it possible for almost anyone to launch a weather balloon from the back yard.

It has been estimated that about 2,000 weather balloons are launched daily, most on a regular basis. The marvel is how few of us have actually seen a weather balloon and how seldom their instrument packages descend into populated areas.

Our own interest in weather balloons began in 2008, when faculty at Taylor University, through an NSF grant, sponsored workshops that provided basic information for those interested in incorporating weather balloons into the undergraduate science and engineering curriculum. The workshops, which are ongoing, feature a balloon launch, in which participants are loaned much of the equipment needed to do their own first launch.

Balloon Specifications

The balloon itself folds up into a small box but when filled with helium can expand to about 25 feet in diameter before bursting. The balloon carries a parachute and up to six, two-pound sensor packs. Most of the balloons are equipped with radio transmitters to send data back to a ground station and allow for real-time tracking of the balloon path. Indeed, the ham radio operators have set up a frequency to receive signals from balloons and add a balloon's path to a web site so that it can be tracked in real-time by anyone interested. Care must be taken so that, should the payload freely fall from the balloon and strike something on the ground, no significant damage is done. FAA specifications for operation of an unmanned non-tethered balloon are available online[1].

Briefly, these specifications are summarized as:

- Balloons should not deploy free falling objects.
- Balloons should deploy a parachute after burst.
- No attempt is made to guide the ascent or descent of the balloon or payloads. (If this is done the balloon is considered a kite and should follow the appropriate FAA guidelines.)
- The fasteners and tethers for the payload containers must break if the load forces exceed 50 pounds.
- The surface of the payload boxes should be visible to radar. One way to do this is to use a foil liner on the outside of the payload box. The foil liner also makes the payload easier to see from passing planes or from the ground.
- The total payload must weigh less than 12 pounds, in at least two packages. The weight/size ratio must be less than three ounces per square inch. This is measured by dividing the total weight in ounces by the area of the smallest surface in square inches.
- The length from the bottom of the balloon to the bottom of the last payload must be less than 50 feet.

A Typical Balloon Launch

A typical balloon launch takes place at dawn. It can be done at just about any time and in just about any weather, but dawn tends to be a time when the winds are calm. Balloons have been launched in rain storms but these are difficult. We know of no one who tries to launch at night since finding the instrument package after it parachutes back to earth relies on both GPS and good vision. Trees are a major problem and doing a launch in late fall after the leaves are down or in early spring before the leaves come on is usually best if you live in an area with lots of trees.

Requirements and costs: The total cost for a balloon launch ranges from a few hundred dollars to several thousand dollars. Much of the cost can be spread over several launches provided you can recover your balloon and payload. Here is a list of typical expenditures:

Item	**Low**	**High**	**Typical**
Real Time GPS Command Pod		$4500	
APRS[Note 1]		$600	$600.00
Helium[Note 2]	$100	$200	$150.00
Balloon 1200 grams	$100	$200	$150.00
Vehicle Gas	$50	$100	$100.00
Instrumentation Pod	$20.00	$50.00	$20.00
Instrumentation	$40.00	$300.00	$45.00
Total	$310	$5950	$1065

Table 1
Balloon flight total costs.
Note 1: APRS is the Amateur Public Radio Transmitter for Shortwave with Google APRS tracking.
Note 2: Typically about 225 ft^3 or 1.5 tanks.

A "bare minimum" flight costs about $310. It includes a simple GPS-enable phone which can be located after the balloon lands – there is no real-time tracking and all data must be recovered after the balloon lands. The simplest payload is a single pod but adding up to five more pods does not greatly increase the price.

A typical mid-range flight costs about $1065. This includes APRS tracking in real-time, but data is not transmitted during the flight. The APRS tracking plots a new position about every five minutes.

A high-range flight costs about $5950 and includes APRS tracking as well as a separate transmitter that sends data back to the ground station in real-time and provides real-time tracking data at 1200 baud.

Instrumentation: For instrumentation you need a way to track your balloon's flight and also appropriate sensors to gather the data in which you are interested. For our first launch, we had students collect only temperature data, store it onboard, and write software to upload the data to a standard PC and create a temperature profile after recovery. It is easy and inexpensive to collect data to measure temperature, humidity, pressure, g-forces, and to take pictures. Having students construct their own sensors is more challenging. Environmental conditions can be severe. A typical balloon flight may take two hours to rise to 90,000 feet and another half hour to descend by parachute. The temperature may change from room temperature to 70^{o} F below zero. All instrumentation and batteries must be protected from the cold. Balloons are also subject to turbulence and on touchdown an instrument package may bounce off tree limbs or rocks. Packaging is critical. This is a great project for undergraduates!

Prediction flight path software: Flight-prediction software is available (at no cost) online. Near Space Ventures, Inc.[2] is one such online site. The user typically enters the date and time of the launch, the latitude, longitude and elevation of the launch site, and the estimated ascent rate, descent rate, and burst altitude. Empirical formulas are available for estimating the ascent rate based on the amount of helium used and the weight of the payload. Typical numbers range from about 100 ft/minute to 1500 ft/minute for the ascent rate and about 1200 ft/minute for the descent rate. The burst altitude ranges from about 60,000 to 110,000 feet. The flight-prediction software gathers the present weather conditions in the area including the speed and direction of the upper level winds, and forecasts the flight path and the landing point. The software is surprisingly accurate and can predict the landing point within a few miles. See the appendix, Figure 2 for an example screen shot.

Tracking: GPS tracking is inexpensive and easy to do. In the simplest case, a prepaid cell phone that has GPS tracking can be included in the payload. (Such phones are available to allow parents to keep track of wandering children.) A call to the phone after touchdown reveals the GPS coordinates of the balloon. We rely on a radio link to transmit continuous GPS data in flight which allows for real-time tracking of the balloon. A "chase team" with a laptop computer can follow the balloon to touchdown. Typically a balloon may travel a few miles from the launch point up to about 50 miles from the launch point. (Under the right conditions a balloon can go several hundred miles.) In the ideal case, the tracking is good enough that a chase team can be close enough to see the balloon's descent. See the appendix, Figure 1 for a sample real-time flight path.

Students can track the balloon in real-time on a Google map using Amateur Public Radio for Shortwave transmitter and receiver (APRS). (To do this someone on the team needs an Amateur Public Radio General Class license.) Commercially available transmitters and receivers along with a GPS unit cost from $400 to $600. The balloon location is sent to the shortwave network, which adds the locations to a Google map. Students with a browser can watch the progress of the balloon. This is a very good thing to have when using this with a class.

Weather: It takes about 45 minutes to fill the balloon with helium, and as the balloon grows larger it must be held down and in place. Wind at the launch site can cause serious problems. Multiple balloons are being launched every day in Antarctica so it is possible even under extreme conditions. Nonetheless, we don't launch in rain, storms, or when the wind increases to more than 10 mph at the ground.

Payload: A typical payload fits into a Styrofoam® box with two-inch walls that are coated with foil on the outside. Some boxes are heated but nearly all have lithium ion type batteries for power. The Styrofoam® provides much needed insulation, a soft package that will minimize damage in a fall, and a convenient platform on which to attach instruments. Note that you can use any material for the payload box – Styrofoam® is not required. The Styrofoam® box along with the batteries and instrumentation must weigh no more than 2 pounds. Six such payload boxes may be dangled from the launch balloon to provide a total payload weight under 12 pounds. A single balloon launch can support 12 students in teams of 2 or up to 30 students in teams of 5. The payload boxes are attached to the balloon so that if the attachment to one fails, it will not cause the loss of all those below it.

Recovery: Recovery of the instrumentation payload is important for two reasons: First, even a low-cost flight will typically have a few hundred dollars of instrumentation that can be reused. A high tech flight can have several thousand dollars in instrumentation. Second, if the data is not radio linked in real-time, it is lost if the balloon is not recovered; this would mean you have completed a class project with no results.

There is a tradeoff in recovery methods. You can either 1) add in the more expensive instrumentation that sends data back to the ground in real-time so that the data is not lost or 2) you can opt for the low-cost route, store data inside the payload itself, and forego the expense of the real-time data download. For the first option, it becomes critical that you recover the payload since you lose your expensive instrumentation if you don't. On the other hand, you have a better chance of recovering the payload because the instrumentation provides better tracking. If you choose the second option, you have less chance of recovering your payload but you have much less to lose if you don't.

There are several major risk factors that come into play when you are doing a balloon payload recovery. The biggest risk is trees. Getting a balloon payload down from a hundred-foot tree is very difficult and sometimes impossible. Fifty miles due east of our location is a national forest, so we typically drive 25 to 50 miles west to launch and avoid the forest. Even so, trees remain a major hazard. The second biggest risk is water. The payload floats, but finding it may require a boat. Finally, the payload may come down in an urban area although this is rare. Tall buildings and traffic can make recovery impossible.

Ideally, the payload comes down in an unfenced open field near a road without much traffic. Using real-time GPS data about 90% of balloon launches have a successful recovery.

Using the Balloon in Class

Class structure: We use the balloon launch in a class called EE 380 which is taken by all electrical and computer engineering majors during the spring semester of their junior year. This is an open-ended project class in which each student is required to complete four projects in four different areas. The balloon project is the only team-based project in the class and counts as one of the four required projects in the area of electronics or microcontrollers. The class meets once a week for organizational purposes and status reports. The class size is limited to 12 students and we use teams of 2 for the balloon project.

The launch date and project details are given on the first day of class in January with the launch itself in mid to late April. The balloon project is unique in that it has a hard deadline – either the student is ready at the time of the launch or the project doesn't go and there are no excuses for illness, etc.

We provide transportation for the class to the launch site and projects are subject to testing prior to the launch. Those that do not meet minimum standards and specifications are excluded. Weight, packaging, and some demonstration of a working project are typically required. A small group of 3 or 4 students are chosen for the "chase team" which is accompanied by a faculty or staff member.

Team assignments: We allow students to choose their own team members with the only stipulation being that everyone has to participate in a team. Team members rate others on the team as to effectiveness but in most cases all members of one team get the same grade.

Results from a recent launch: A balloon launch in spring 2010 had 12 students divided into 6 teams. Each team had to design a device to collect temperature data as a function of time for the duration of the balloon flight. The data had to be stored on board the instrumentation package. Students were free to design any mechanism they wanted as long as it met specifications. Most used a low-power microcontroller with a 10-bit A/D converter and stored data in either flash memory, EEPROM, or battery backed-up RAM.

The launch was successful with calm winds on a Saturday morning near dawn. The balloon was tracked in real-time and we used two "chase teams". The balloon traveled about 30 miles due east and came down in a small woods. When we eventually recovered the payload, we discovered that the bottom two payload packages were missing. They were never recovered. Two teams successfully recovered data for the entire flight and the other two had data for part of the flight – their sensor had failed at low temperatures.

Assessment

Taylor University has been doing balloon launches under an NSF grant for several years and has collected extensive data on assessment. A paper outlining the assessment methods and results was given at the ASEE Conference in 2009 in Austin, Texas[3]. The assessment posed 119 questions to 141 science and engineering students involved in atmospheric research and instrumentation projects at an introductory level. A pre-test and a post-test was given to determine student growth in five areas: motivation, value of science, application knowledge, cognitive skills, and content knowledge. The tests showed improvement in all five areas with the greatest improvement in application knowledge and content knowledge.

Our own balloon launch involved just 12 students. Students were asked to write a paper describing their experience and evaluating it relative to other projects which they had completed as part of their class experience. Comments were generally very positive.

> "These design conditions are certainly unique for a class project and allowed me to learn about cold weather protection for electronics." B.Sturgeon

> "The weather balloon project attempted by my EE380 class in the Spring semester of 2010 was an exciting and adventurous one to say the least. While planning and designing the pods to go up with the balloon, I felt like everyone put more effort into their projects because it was such a real-world application that we could see actual results from." T. Wagler

> "The launch of the Balloon Project was exciting because all the work put into the projects was put to the test. The balloon was sent on its flight across a few counties, and a 'Storm Chasers'-like pursuit followed. Recovery of the projects turned out more difficult than expected, but after extracting the data from the microcontrollers, the work put into the project had paid off." J. Bittner

"My experience with the EE380 balloon project was both informative and fun. I was able to use the skills and concepts I learned in class to apply them to a real world application." K. Miller

Future Activity

The balloon launch is now the centerpiece of the junior level projects class which developed into one in which students look forward to and tell their parents and friends about. The success of this class has led to two further developments involving high altitude balloons. In the spring of 2011 we will hold the first high altitude balloon contest involving our own students and those from other universities. The contest is primarily aimed at the engineering community and the focus is on design of instrumentation. For this first contest, student teams must build a pod which measures temperature, pressure, humidity, altitude, and g-forces. In addition it must provide photographs from specified altitudes. At a given altitude range, the pod must extend a flag that can be photographed from a down looking camera at the base of the balloon.

In the fall of 2011, we plan to introduce the high altitude balloon project to the freshman Engr 101 class. This is a nearly ideal project for freshman engineering students who know little of real engineering design. Much of the instrumentation package will be given and student teams will focus on the packaging to make the environmental conditions survivable.

New technology

High-altitude balloon launches have "taken off" in the last 10 years due to lower cost technology such as GPS and to efforts like those sponsored by NSF and Taylor University. New technology is being added rapidly. Four new modules which are starting to be used include:

1. Autonomous Flight Termination System: this is a balloon release system that cuts the balloon free from the payload at a specified altitude or time.

2. Fixed altitude flight system: this is a control valve which allows helium to escape and can keep a balloon at a fixed altitude for several hours. It can also be used to bring down a balloon without a burst.

3. Spectroscopy module: allows collection of spectrographic data at a reasonable cost from high altitude.

4. Pointing platform: based on the position of the sun, this provides a platform that points in one direction for use in photography.

Bibliography:

1. This is a link to the electronic code or Federal regulation (e-CFR) site which sets the legal specifications for a balloon launch:
http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=cfba6e857da5454aa0c4b22bc054b25a&rgn=div5&view=text&node=14:2.0.1.3.15&idno=14#14:2.0.1.3.15.4.9.1

2. Near Space Ventures, Inc. located in Missouri, is a not-for-profit corporation which supports high altitude balloon launches. http://www.nearspaceventures.com/

3. Snyder, Stephen, Romines, Elise, and Dodge, Rachel, "New Heights High Altitude Balloon Research Program", ASEE Conference, 2009, Austin Texas.

4. http://www.nearspacenetwork.com/ This is a network for academics and students. It has photos, blogs, forums for discussion, and lists of balloon events.

5. http://www.stratostar.net/ This site sells a complete turnkey system.

Appendix

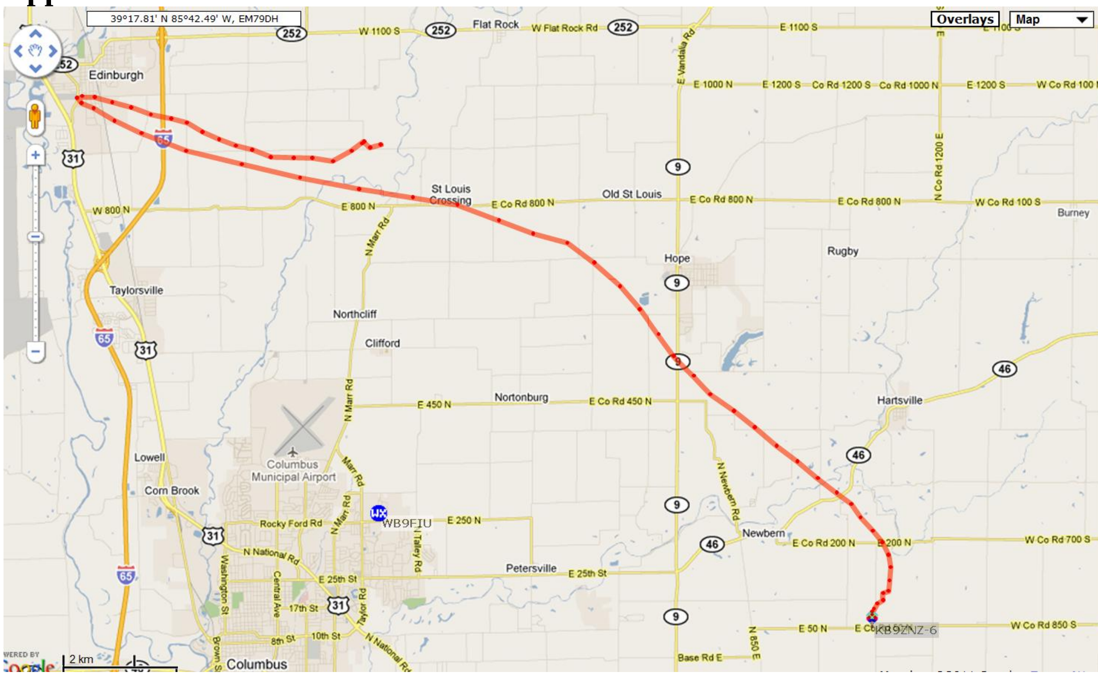

Figure 1

A typical balloon flight path. The balloon began flying west as it rose. When it reached a certainaltitude the wind direction changed and the balloon traveled back to the east. The small red dots indicate sample points that are equally spaced in time.

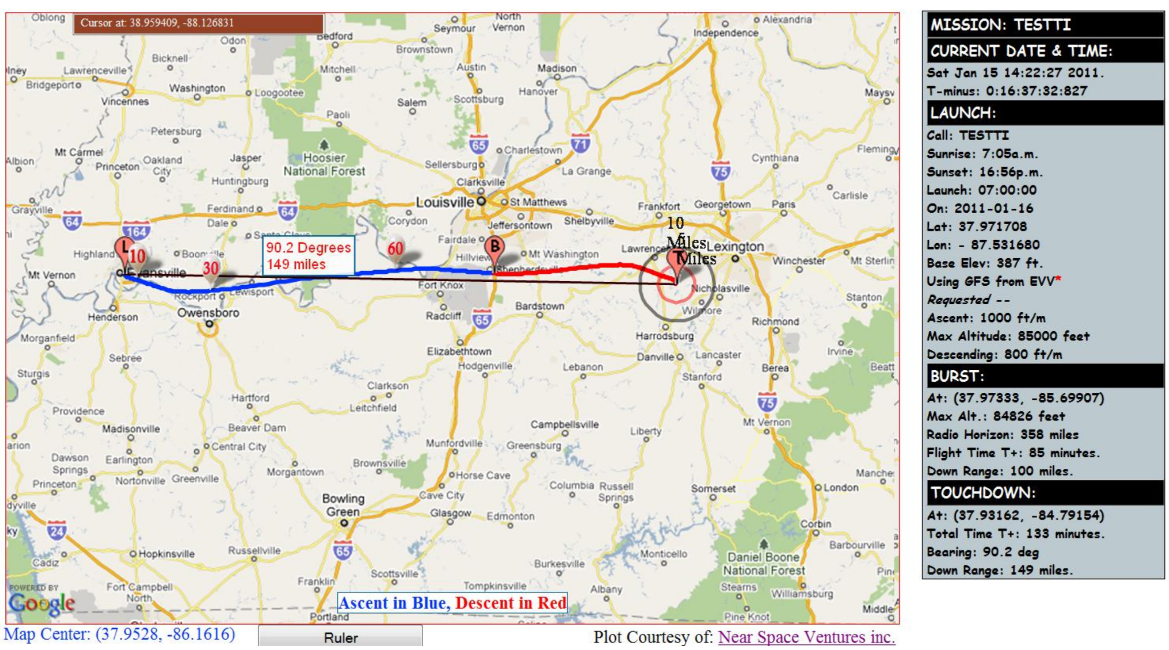

Figure 2

This figure shows a predicted flight path from the flight prediction software at Near Space Ventures, Inc. This path was predicted for a flight in mid-January, 2011 and strong west to east winds drove the balloon due east for 149 miles.