
BalloonSat: Missions to the Edge of Space

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ABSTRACT. Access to space is expensive and full of engineering challenges. Students interested in space are willing to take on the engineering challenges but can do little to overcome the high cost of getting to space. A BalloonSat is a low-cost method of accessing space while retaining the engineering challenges. BalloonSats are an excellent way to teach students of any age the fun and excitement of space science, mathematics, engineering, and technology. The Colorado Space Grant Consortium's (Space Grant) BalloonSat program is a hands-on way to introduce new engineering students interested in spacecraft design to fundamental engineering techniques and team working skills.

A BalloonSat, weighing up to 4 kg, can reach altitudes of 100,000 feet for a cost of only \$300. This altitude presents students with conditions that pose both tough and significant engineering challenges. At this altitude, temperatures are close to -80° C and pressures reach near vacuum conditions. When the balloon bursts, initial descent speeds reach Mach I and when the BalloonSat reaches lower altitudes, condensation can be severe. Using on-board GPS and Automatic Position Reporting

System (APRS), a BalloonSat can be tracked throughout its flight and recovered for data retrieval.

BalloonSats can be used to study atmospheric conditions, demonstrate prototype space hardware and technology, and more. There is a wide range of experiments that can be performed on a BalloonSat. Students have demonstrated that they have the creativity and imagination to generate experiment ideas. The design of each BalloonSat is accomplished entirely by the students. Strict requirements are given which are required to be met in their BalloonSat design.

BalloonSats are an excellent way to teach students in a hands-on way the value and fun of science, mathematics, engineering, and technology. The students who go through the BalloonSat program at Space Grant are excited about their future and all the potential it holds. They see the importance of their classes and the benefits of applying what they learn in the classroom to future projects. They are prepared to contribute to more complex rocket, shuttle, and satellite missions at the University and in their professions.

Introduction

Access to space is expensive and full of engineering challenges. Students interested in space are willing to take on the engineering challenges but can do little to overcome the high cost of getting to space. A BalloonSat is a low-cost method of accessing space while retaining the engineering challenges. BalloonSats are an excellent way to teach students of any age the fun and excitement of space science, mathematics, engineering, and technology. The Colorado Space Grant Consortium's (Space Grant) BalloonSat program is a hands-on way to introduce new engineering students interested in spacecraft design to fundamental engineering techniques and team working skills. This paper provides the reader with some background on Space Grant's BalloonSat program and serves as a guide on how to design, build, test, launch, and recover a BalloonSat.

Background

BalloonSat provides an excellent way to teach students of any age the fun and excitement of science, mathematics, engineering, and technology. Space Grant has had great success with the BalloonSat program and the students who go through the program.

Space Grant started the BalloonSat program in August 2000. It was created as a hands-on way to introduce new science and engineering students interested in space studies to some fundamental engineering techniques, team working skills and the basics of space and Earth science.

The BalloonSat program is part of a course taught by Space Grant at the University of Colorado at Boulder called Gateway To

Space. It is taught each semester and is open to all majors on campus. The majority of the class is made up of engineering majors along with science and business majors. The class size is limited to 60 students and is taught in a non-traditional classroom as shown in figure 1. The course teaches the basics of space, space sciences, and spacecraft design through traditional lectures given by the instructor, members of the engineering and scientific faculty as well as individuals from industry.



Figure 1: Students Involved in Gateway to Space Course

Five weeks into the 15 week course, the class forms teams of five students. Each team is given two activities to help them get to know each other better. The first assignment is to take a photograph of the entire team eating together. The second assignment is an in-class exercise called a Design Competition involving Lego's and light bulbs

Upon completion of these get-to-know-you exercises, the teams are given their mission assignment. This comes in the form of a Request for Proposal (RFP). This exercise models the space industry's method of soliciting and funding ideas and projects. The RFP asks the team to write a six-page proposal describing all aspects of their BalloonSat project. The teams are given approximately two weeks to complete their proposal. Contained in the proposal are their team's budget, schedule, testing plan and their team's design.

Science at the Edge of Space

BalloonSats launched at Space Grant reach altitudes of approximately 100,000 feet or 30,480 meters.

With this in mind, the science involved with BalloonSats can be very interesting. A simple experiment that all students can understand is observing how the temperature changes as a function of altitude as shown in figure 2.

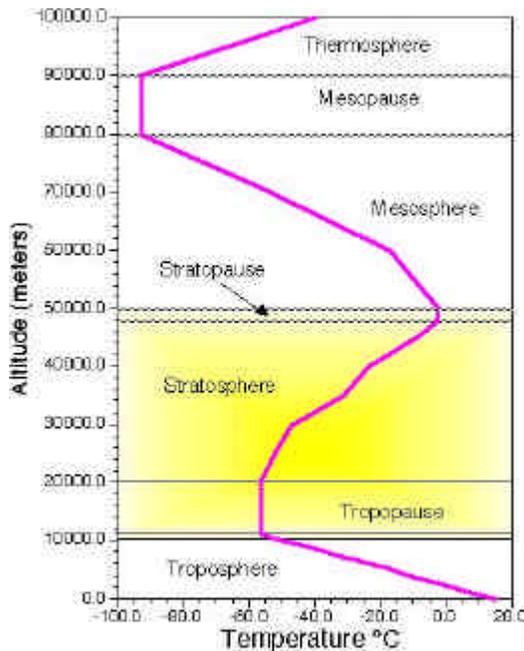


Figure 2: Atmosphere Layer Temperature Ranges vs. Altitude

Imaging the Earth at 100,000 feet excites anyone of any age. An example image is shown in figure 3.

BalloonSats are not limited to these measurements. BalloonSats can be used to study atmospheric conditions or to demonstrate prototype space hardware. There are a wide range of experiments that can be performed on a BalloonSat. Students have shown that they have the creativity and

imagination to think of interesting experiments.



Figure 3: Student BalloonSat Image Taken at 100,000 feet¹

Past experiments have included the following:

- Upper atmospheric radiation levels
- Solar cell efficiency changes as a function of altitude
- Atmospheric soundings
- Video imaging
- High altitude effects on cockroaches
- Digital sound wave recordings of the upper atmosphere

Design

A BalloonSat, weighing up to 4 kg, can reach altitudes of 100,000 feet for a cost of only \$300. This altitude presents students with conditions that pose both tough and significant engineering challenges. At this altitude, temperatures are close to -80°C and pressures reach near vacuum conditions. When the balloon bursts, initial descent speeds reach Mach I and when the BalloonSat reaches lower altitudes, condensation can be severe. Using on-board Global Positioning System (GPS) and Automatic Position Reporting System (APRS), a BalloonSat can be tracked

throughout its flight and recovered for data retrieval.

The design of a BalloonSat is completed entirely by the students. Several strict requirements are given to them which they are required to follow in their BalloonSat design. These requirements include:

- 500 gram weight limit
- 1,000 cm³ max. volume
- Temperature data taken internally and externally
- Data taken during entire flight
- Data taken at landing site
- One additional science payload
- Not to exceed \$400 total cost
- Contact information written on BalloonSat hardware
- Functional testing before launch

There used to be a requirement to make the BalloonSats out of aluminum. This is still

the preferred choice because it presents the students with several engineering challenges and requires them to learn new techniques of designing and working with materials in the machine shop. However, during the last launch we had nine BalloonSat's and this gave us an overall weight problem. Therefore foam core was allowed since it is much lighter and easier to work with for the students.

One additional requirement is the method of attaching the BalloonSat to the balloon string. These methods are illustrated in the figure 4. BalloonSats can be attached to the balloon string by running the string through the center or the side of the BalloonSat. The first method is ideal because it tends to keep the entire balloon string balanced. Attaching on the side works fine but usually adds weight to the BalloonSat due to the use of metallic eyebolts.

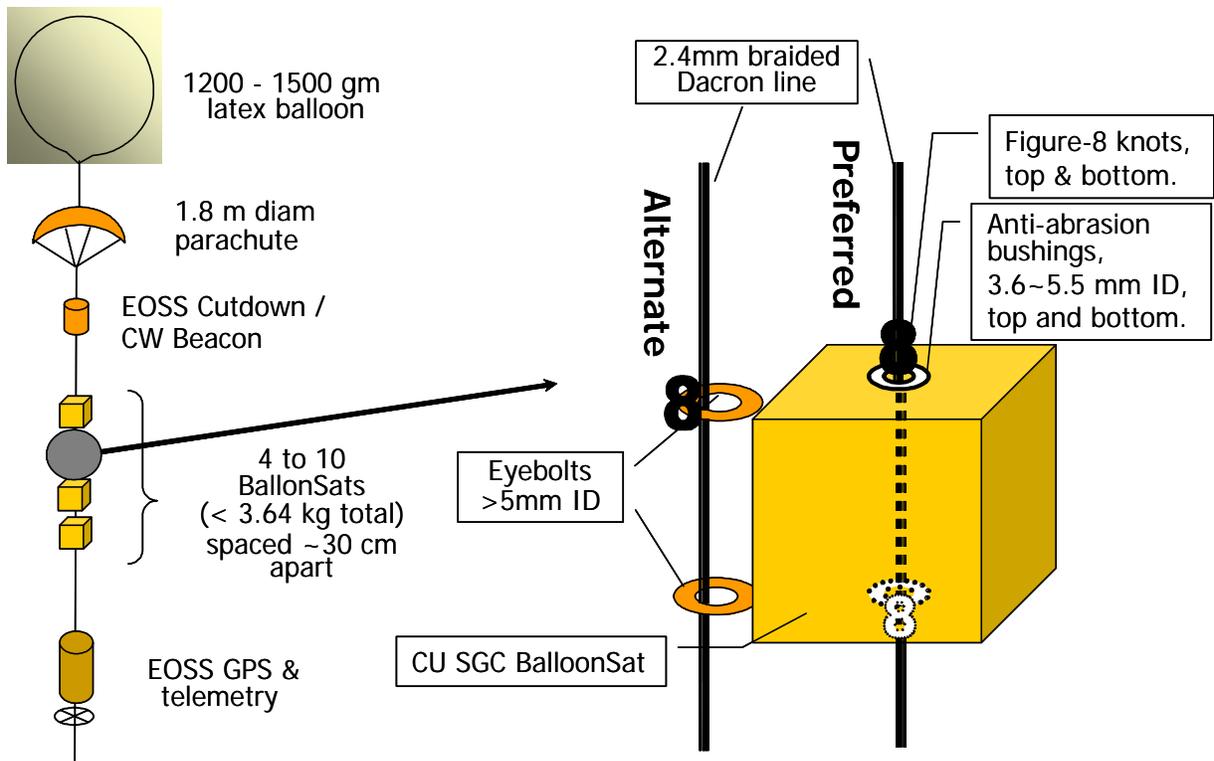


Figure 4: BalloonSat Balloon Attachment Methods²

Hardware

Several items, listed below, have become standard hardware in BalloonSat designs over the past five launches of BalloonSats at Space Grant.

HOBO Datalogger:

A HOBO is a simple and relatively inexpensive (under \$100) data recording device. It stores up to four channels of data from instruments and sensors. Most students use the HOBO, built by the Onset Computer Corporation and shown in figure 5, for the internal and external temperature measurement requirement. The HOBOs are lightweight (under 60 grams) and can take data for over a year at low sample rates. The software required to program them and download stored data is easier to use than most word processing software.

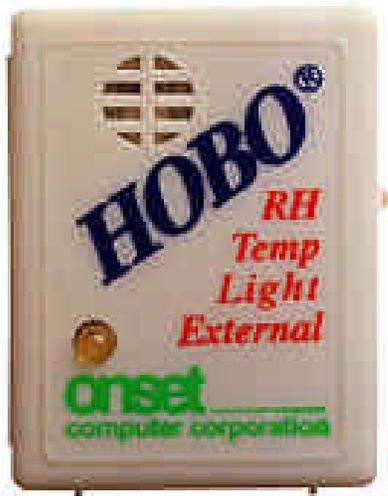


Figure 5: HOBO Datalogger Built by Onset Computer Corporation

Canon ELPH LT Film Camera

This is the film camera of choice for BalloonSats. It is relatively easy to control with the 555 Timer (listed below) at a cost of about \$50. It is also small, lightweight, and durable. The Canon ELPH LT, shown

in figure 6, is an APS film camera that is very easy to modify and interface with the 555 timing circuit. 40 exposure APS film can be purchased for more in-flight pictures. One thing to be careful with on cameras is the light sensor. Make sure the hole in the BalloonSat is big enough for any light sensors so the camera will not think it is in dark room and over expose the film.



Figure 6: Canon ELPH LT APS Film Camera

555 Timer

The timer is essentially a switch activator. It can, for example, be the finger that pushes the camera button. There are many variations and kits available for this simple circuit. Students will have to solder or wire up these circuits to a camera or whatever else they wish to control. An example of a 555 timing circuit built by students from a kit is shown in figure 7. Students find this



Figure 7: 555 Timing Circuit Built By Students from a Kit

process frustrating yet fun. The extreme temperatures experienced on a BalloonSat flight can affect the reliability and functionality of timing circuit. The biggest items affected by the temperatures are the capacitors and resistors. The timing circuit should be tested in the cooler test and appropriate precautions should be taken to keep it close to room temperature for the best results.

Parallax Basic Stamp

The Parallax Basic Stamp is for the more advanced student. The Parallax Basic Stamp is similar to the 555 Timer but requires actual programming and more interfacing. The student can learn much about engineering, testing, and programming with the use of this simple computer (shown in figure 8). The Parallax Basic Stamp can do various types of control that the 555 Timer cannot. It is almost required for more advanced BalloonSat payloads.

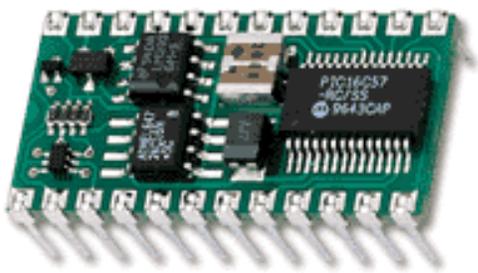


Figure 8: One Type of Parallax Basic Stamp

Silicon Adhesive and Hot Glue

Silicon adhesives and glues are some common construction materials used to assemble foam core BalloonSats. They both have their advantages and disadvantages. Hot glue is much easier to work with and clean up is easy but can break under cold temperatures. Silicone adhesive is messy and slightly toxic but performs well under extreme temperatures.

Velcro

Velcro is a great way to secure components or lids to a BalloonSat and allows for last minute access to the inside of payloads. Velcro is extremely reliable and provides extra assurance that components will not be jarred lose during flight and landing.

Aluminum Tape and JB Weld

Aluminum tape and JB Weld are some common construction materials used to assemble Aluminum BalloonSats. These materials are to be used in conjunction with each other. However, if done right, the JB Weld works fine by itself. The Aluminum tape provides additional assurance that the BalloonSat will survive flight and landing. The Aluminum tape also provides an excellent method of sealing BalloonSats from the outside environment.

Hand Warmer Heat Packs and Desiccant Packs

Heat packs and desiccant packs are an example of student creativity. The Hand Warmer Heat Packs provide some active heating of BalloonSat payloads during flight. This is a great way to keep temperatures of critical items like batteries warm. Some of the heat packs actually absorb moisture, which helps with condensation too. Some students have used just desiccant packs to absorb extra moisture. If the BalloonSat is sealed and insulated too well, over-heating can actually occur.

Digital Cameras

Many student teams have been trying to use digital cameras. The benefit to using a digital camera is the number of pictures you can take. However, digital cameras are difficult to control and the resolution is not even close to a film camera. Digital cameras can be found for as little as \$20. Digital cameras can also require large

amounts of power depending on the storage medium and method.

Lots and Lots of Batteries

Batteries have been the biggest failure point in past BalloonSats. There are many types of batteries available and there has not been enough data yet to determine which batteries work better. There has been a much higher success rate with lithium batteries over alkaline batteries. Whichever brand and type is used, it is recommended that they go through the cold test described later. Keeping the batteries warm helps all types of batteries, but there is always a danger of how batteries will react in a vacuum. So far, no batteries have exploded on our flights.

Other Hardware:

Students' ideas are evolving beyond just temperature data and pictures. This last semester, teams built payloads that contained a Sony MiniDisc recorder to record sound at 60,000 feet. Another team had a Geiger tube to measure radiation levels. Another team had an altimeter and pressure sensor to measure altitude and pressure during the flight. Other teams have used solar cells to generate power and determine rotation rates of the BalloonSat. One team had a GPS system on board and another a remote controlled camera. Another team used a hand-held ultraviolet radiation detector. The ideas are endless and there are many experiments left to be tried or re-tried. Students will continue to learn through all of it.

Construction

Construction techniques are not strict but the quality of construction is important. On our last flight, one BalloonSat was lost due to poor construction quality.

Aluminum Construction:

Typical aluminum construction consists of cut pieces of aluminum sheet metal that are held together by epoxy. Some students have machined their BalloonSats out of solid pieces of aluminum. When using aluminum for construction, some students use brackets, bolts, and nuts to attach the pieces together. Their design is robust and strong but usually heavy. Other students use an epoxy welding kit and then cover dried epoxy seams with aluminum duct tape in case the epoxy bond breaks during cold temperatures or rough landings. Aluminum construction is the most durable method but poses some mass budget problems. Aluminum BalloonSats tend to have more trouble with heat loss than foam core BalloonSats. An example of aluminum constructed BalloonSat is shown in figure 9.



Figure 9: BalloonSat Constructed of Aluminum

Foam Core Construction:

Foam core is much easier to work with than aluminum for building a BalloonSat. Typical foam core can be purchased at any hobby store. ¼ inch foam core works the best. Students constructing BalloonSats out of foam core find that hot glue or silicone adhesive works well on the seams.

Aluminum tape can be used on seams as well for extra assurance. Some students have used Velcro in their foam core construction. Foam core is inexpensive and provides some insulation that aluminum does not. Figure 10 shows an example of a BalloonSat constructed out of foam core.



Figure 10: BalloonSat Constructed out of Foam Core

Insulation:

Insulation should be incorporated in the design of a BalloonSat. Insulation is lightweight and tends to protect the components during landing. There are many types and methods for insulation. Fiberglass insulation (blow-in type) contained in Ziploc bags is effective. A metallic bubble wrap similar to a sun shield for a car works well on BalloonSats, however the bubbles pop during the flight. Whatever material is used, it is important to insulate the payload. Without insulation, batteries will freeze and glue will break.

Components:

The BalloonSat construction should include methods to securely fasten the components

and the electrical wire the BalloonSat. Liftoff and the balloon burst can cause components to move. On several occasions, BalloonSats have had electrical wires break and batteries disconnect during these two events.

Venting:

The BalloonSat should be sealed but not airtight. It is possible to make an airtight BalloonSat; however, the pressure differences can cause major damage to components and the structure. It is important to provide some venting paths but this should be minimized. Minimum venting will help with heat loss and moisture damage from clouds.

Condensation:

This is a major concern for BalloonSats. If not properly protected from moisture buildup, electronics are damaged. If insulated, sealed and vented properly, condensation should be minimal. Condensation forming and then freezing on optics is another thing to watch out for.

Testing

There are four basic tests that should be done before flight. These tests, listed below, validate the flight readiness of the BalloonSat.

Drop Test

This test is stressful on the students but can provide some valuable information as to the quality of the construction. The test is to drop the BalloonSat down a single flight of uncarpeted stairs. This may sound extreme, but if constructed properly, the BalloonSat should be fine. It is recommended that the drop test be done with mass simulators inside instead of actual hardware. If all is good after the first test, components can be

installed and the test repeated. There is some risk with this test. The thing to remember is this test is simulating the final aspect of the BalloonSat launch. The BalloonSat may become damaged during landing but the data more than likely will survive. Doing a drop test with components before launch may cause the same damage, which may not be able to be repaired before launch. It is recommended if a drop test is done with a component loaded BalloonSat, the functional testing should be completed and run before and after the drop test.

Cooler Test

The students call this the beer cooler test. This is a method to test the extremely low temperatures that the BalloonSat will see in-flight. The fully functional BalloonSat is placed in a large cooler with a block of dry ice. Make sure the cooler is not airtight so that the gases can escape. The BalloonSat should be operating as if it were in-flight. The test should last long enough to allow the BalloonSat to reach equilibrium.

Subsystem Test

While building a BalloonSat it is helpful to test individual components or systems of components together before the big functional test. Students should build upon successful tests until the BalloonSat is fully functioning, as it will be in-flight. This will aid in the debugging phase if anything goes wrong later.

Full Functional Test

This is known as the big test. It involves testing the BalloonSat as if it were being launched. It can be as simple as turning on the BalloonSat and letting it run for 3 hours, stopping it and then downloading the data. It is recommended that students run this full functional test at least once (twice if anything goes wrong during the first full

functional test). Figure 11 shows students performing a final functional test.



Figure 11: Students Performing Final Functional Test Just Prior to Launch

Launch

This is probably the biggest thrill for the students. A high altitude balloon launch is no Space Shuttle launch, but it is still very impressive. Each time I see one go, it gives me goose bumps. It is the ultimate sense of accomplishment for students when they see their BalloonSat ascending at 1,000 feet per minute. Launch operations can be seen in figure 12. A typical launch configuration is shown in figure 13.



Figure 12: BalloonSat Layout Just Prior to Launch

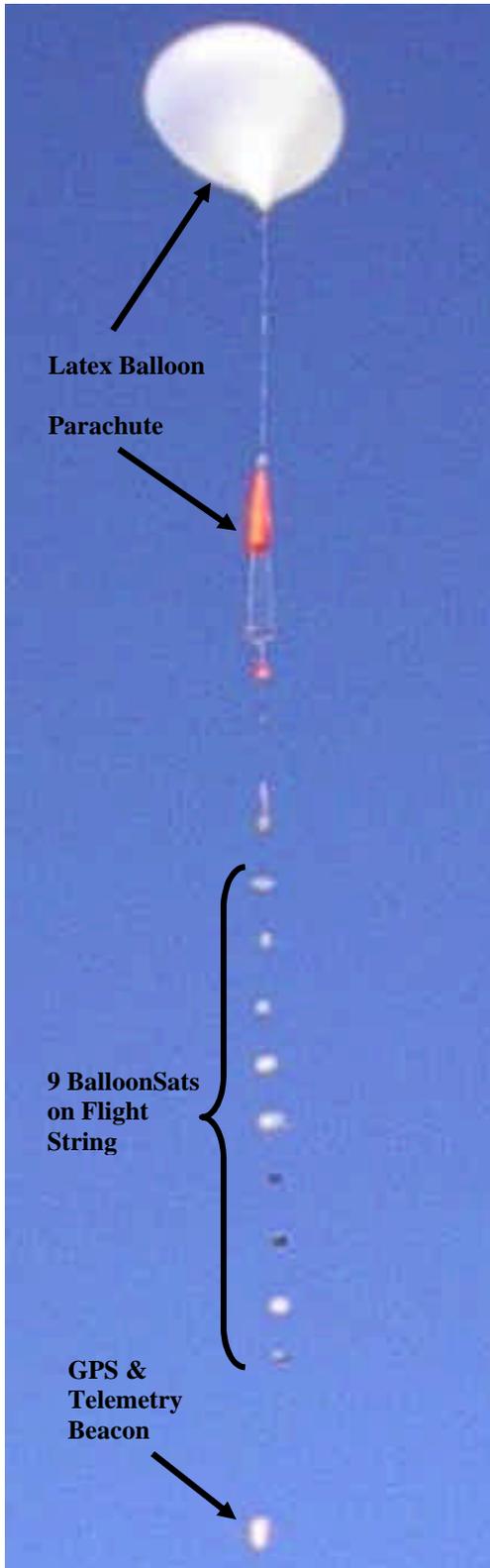


Figure 13: Typical BalloonSat Launch Configuration

In Colorado, we have the benefit of a non-profit organization called the Edge of Space Sciences (EOSS). They provide all the launch, tracking, and recovery services for about \$300, which covers their expendable costs. EOSS works in most parts of Colorado. There are similar organizations in other states. However, balloon launches can be done without the assistance of EOSS. Space Grant is currently working with EOSS and the Montana Space Grant Consortium to better define the launch system so that it may be done by individuals at Space Grant rather than by outside organizations.

The basics of the launch system include the following:

- 1200 to 1500 gram latex balloon (available on-line)
- Gaseous Helium
- Balloon filling system (regulators, balloon adaptors and filling nozzles)
- Flight string (2.4 mm braided Dacron)
- Radio transmitter/receiver
- GPS unit
- Control system to transmit data to recovery team
- Control system to receive simple commands (i.e. cut away balloon)
- Parachute
- FAA notification

Launch typically occurs early in the morning (9:00 AM) before wind conditions deteriorate. Students attach their BalloonSats to the flight string approximately one hour before launch. A test balloon or pilot balloon is launched to determine wind direction. One student holds each BalloonSat. The flight balloon is launched and as the balloon rises, each student lets go of his or her BalloonSat. The whole launch takes less than 5 seconds and is fairly safe as long as everyone lets go of

his or her BalloonSat and the winds are mild. With the proper equipment (listed in the next section), the balloon location can be obtained within 30 seconds after launch. The balloon will rise for about 90 to 100 minutes at which the time the balloon will burst and begin its descent. The descent time is only about 30 minutes. Figure 14 contains six images, of a typical balloon burst at 100,000 feet, courtesy of EOSS³.

Immediately after launch, the recovery operations begin. This is commonly known as the chase.

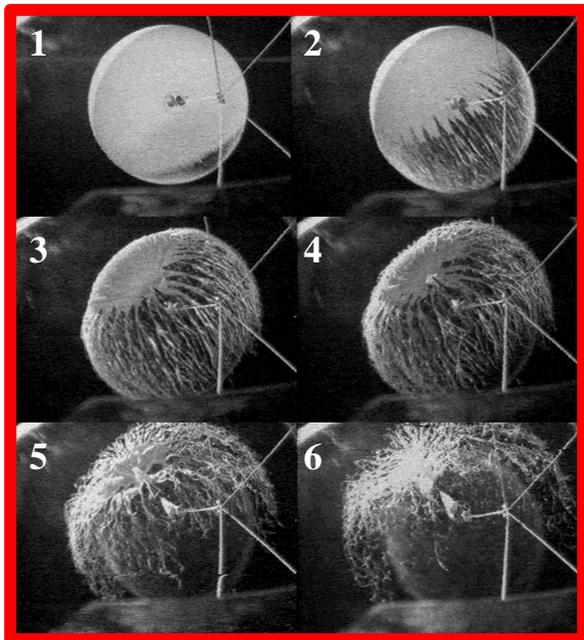


Figure 14: Six Images of Balloon Burst at 100,000 feet

Recovery

The second biggest thrill and the biggest for some is the chase, or recovery, of the BalloonSats. The balloon can travel far and fast depending on upper atmosphere conditions, but a typical balloon will travel 25 to 100 miles from the launch site. Getting to the landing site on roads is not always easy. The chase team usually drives twice the distance on the roads to get to the

landing site. The total balloon flight is about two hours, which does not give the chase team much time.

With the proper equipment and set up, the chase team can track the progress of the balloon in real-time. This provides a unique experience for students as they receive and interpret the telemetry and make decisions while in pursuit of the balloon.

This equipment consists of the following:

- Laptop computer with two serial ports and lots of battery power
- GPS unit
- DC power inverter to power GPS unit and/or Laptop if possible
- Radio receiver
- Magnetic mounted radio antenna
- Terminal Node Controller (TNC)
- 12 Volt power supply to power TNC and Radio
- Street Atlas Software
- Amateur Packet Radio Software (Free on-line)
- Magnetic-Mount Radio Antenna

Setting this system up can take up to a full day. Once complete, realtime ground tracks are possible as shown in figure 15.

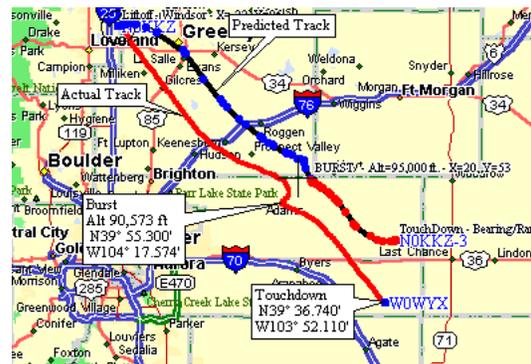


Figure 15: Realtime Ground Tracks of Balloon Flight

Upon reaching the landing site, a hike of one to four miles may occur due to limited road access and terrain conditions. The use of a radio locator device is usually needed to locate the balloon. Unless landing site wind conditions are bad, the BalloonSat should be lying on the ground as they landed. With windy conditions, the parachute acts as a sail and the BalloonSats can be dragged across the area for some time, complicating recovery efforts.

When reaching the BalloonSats, a photographic documentation process starts before anyone handles the payloads. This is used to help understand ways to improve construction and landing techniques.

Students begin downloading their data at the landing site or back in the lab. Usually this process is quick; however, the analysis takes much more time. Figure 16 shows students at the landing site about to begin data recovery.

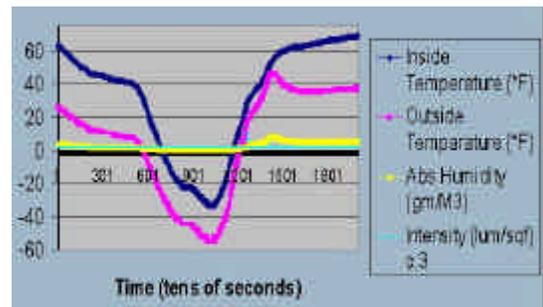
Most of the equipment (except the balloon) can be re-used for another launch.



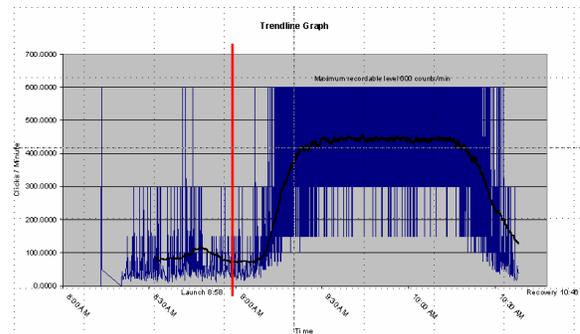
Figure 16: Students at Landing Site

Launch History and Success

At this writing, Space Grant has launched 26 student-built BalloonSats on five different balloon flights. Over 200 hundred students have participated in this program. Nearly 50 percent of the BalloonSats returned all the data expected and 90% have returned partial data. Only one BalloonSat was not recovered and this was due to a mechanical failure on the BalloonSat. Students have presented their results at conferences and symposia both locally and nationally and several research papers have been published. Figures 17, 18, and 19 show measurements resulting from these flights.



**Figure 17: BalloonSat Temperature Data⁴
(for illustration purposes only)**



**Figure 18: BalloonSat Radiation Data⁵
(for illustration purposes only)**

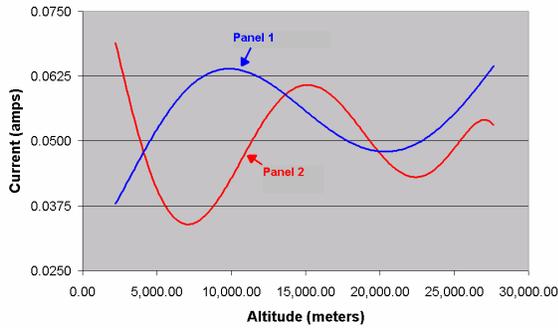


Figure 19: Solar Panel Power Output at High Altitudes⁶

With BalloonSats, success cannot be measured solely on whether data was taken or not. Rather success is measured by the impact on the student. Over 50% of students participating in the BalloonSat program have gone on to more challenging research projects years before they would have expected to if at all. There are more students than one can count that have said this experience solidifies why they want to be an engineer or a scientist. The ability to reach the edge of space as a freshmen will make their remaining years as a student all the more interesting.

Conclusions

BalloonSats are an excellent way to teach students in a hands-on way the value and fun of science, mathematics, engineering, and technology. The students who go through the BalloonSat program at Space Grant are excited about their future and all the potential it holds. They see the importance of their classes and the benefit of applying what they learn in the classroom to future projects. They are prepared to contribute to more complex rocket, shuttle, and satellite missions at the University and in their careers.

Acknowledgements

The author would like to thank Bob Twiggs from Stanford University for giving me the spark for this idea. Bob's CubeSat program is clearly evident in the BalloonSat program. It has always been the hope that any BalloonSat could be converted to a CubeSat if the resources became available to cover launch costs.

In addition, the author would like to thank Mike Manes and all the wonderful volunteers at Edge of Space Sciences (EOSS) for the countless hours of support before, during, and after balloon launches.

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