Ballooning-related Laboratory Activities for Science Courses

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An important goal of many college-level science courses (especially for non-science majors) is that students become scientifically literate citizens who understand how science serves as a mechanism for inquiry into the natural world. This goal can be accomplished by engaging students in their own hands-on, experience-based scientific investigations. Ballooning is an ideal vehicle for this type of course because it is highly engaging for students and provides a flexible platform for student-designed and built experiments in a variety of scientific disciplines. In addition to contributions to scientific literacy, ballooning also highlights the role of technology and engineering in scientific research and advances students' skills in these areas. A significant amount of class time is spent on the design, fabrication, and pre-launch testing of student experiments. In addition, students work on activities intended to familiarize them with areas of science and technology directly related to high-altitude ballooning and provide them with hands-on experiences. In this presentation we will discuss several lab activities related to atmospheric science, geographic coordinates and GPS, and microcontrollers.

I. Introduction

Over the past 2.5 years students and faculty at DePaul University have conducted 18 high-altitude balloon flights. These included flights with non-science majors in a scientific inquiry course, science majors in a summer research program, environmental science and physics majors working with faculty on senior theses and independent research projects, members of the Society of Physics Students, and high school students participating in a summer research program. We have found that ballooning is a flexible and engaging platform that allows us to engage all of these audiences in scientific inquiry at the appropriate level. At the last Academic High Altitude Conference at Taylor University many of our colleagues expressed the desire to jointly develop curriculum that could be used to integrate ballooning into existing courses. To continue this discussion we present several classroom activities that are designed connect ballooning to broader science concepts. Specifically, we discuss a data analysis method that uses the temperature, pressure, and humidity data routinely collected with the Startostar command pod and data loggers for understanding convection in the troposphere, activities that introduce students to geographic coordinates and GPS, and activities intended familiarize students with microcontrollers.

II. Using Ballooning Data to Understand Atmospheric Convection

Balloon flights conducted for undergraduate research typically have a scientific payload that is designed to test hypotheses concerning phenomena in the upper atmosphere. But most balloon packages also record basic meteorological data: temperature, pressure and relative humidity referenced to height. For example, the Stratostar command pod we use on all of our flights automatically records these data. Many groups also regularly fly HOBO data loggers and sensors attached to microcontrollers. Analysis of these data can lead to greater understanding of the structure of the atmosphere and atmospheric convection. Because convection is a key concept for understanding some types of thunderstorms, this is a gateway to a larger understanding of the principles behind weather and climate.

Most high-altitude balloon flights begin in troposphere and the burst occurs in the stratosphere. These atmospheric regions are defined by the relationship between temperature and altitude (Figure 1). Typically, air temperature decreases with increasing altitude in the troposphere. Next, the slope of the line changes when the balloon reaches the tropopause, and increases with height as the balloon ascends through the stratosphere. If students have been exposed to some atmospheric science while preparing their balloon flight, they will know that the stratosphere

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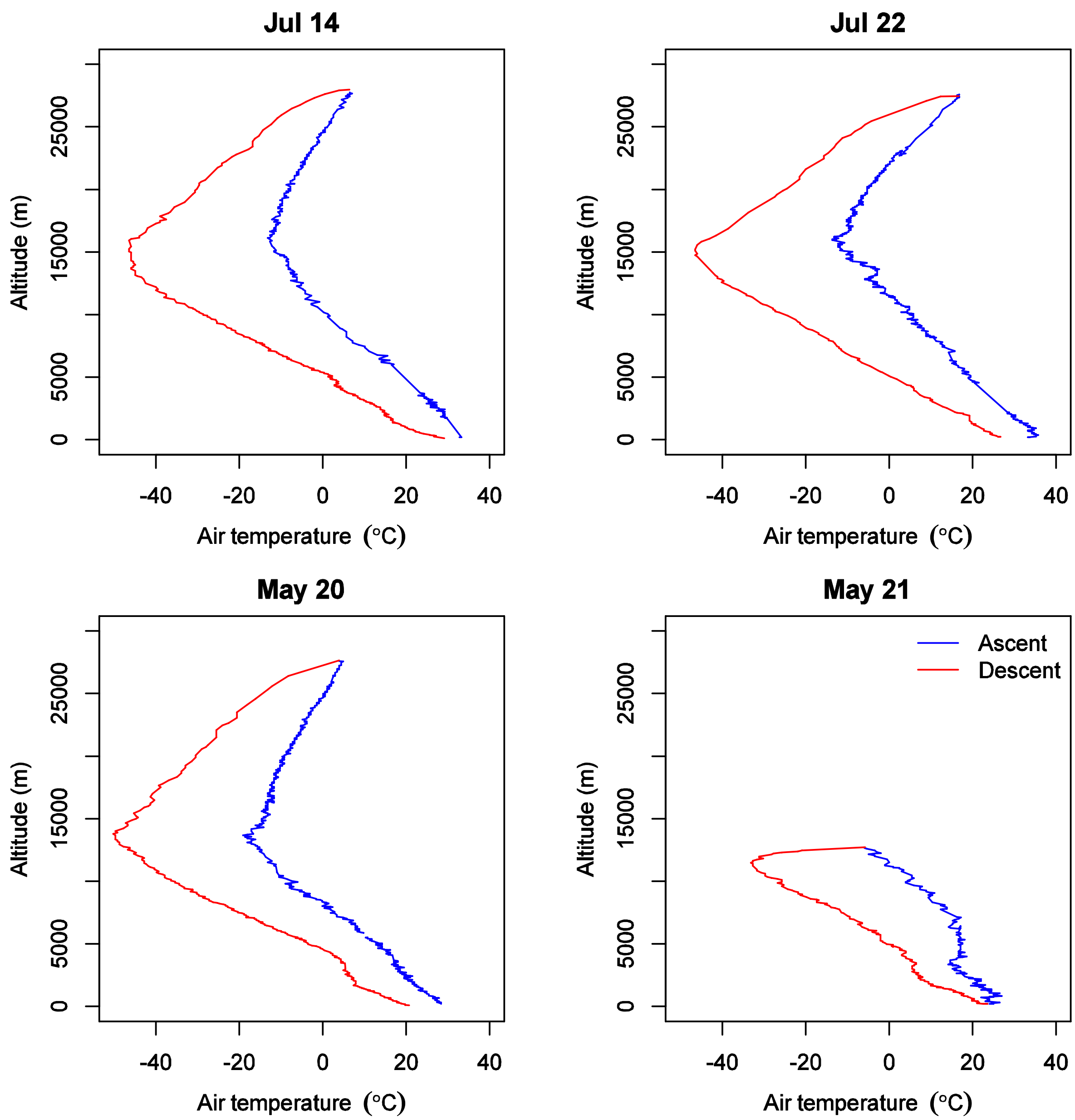

Figure 1 Profiles of air temperature versus altitude for 4 flights. The two July flights were from 2010, and the two May flights were from 2011. Altitude was determined from the GPS. The May 21 flight was designed to only reach the top of the troposphere.

is the region that contains the Earth's ozone layer. A brief explanation follows, but there are also excellent web resources that describe the ozone layer (e.g., http://www.windows2universe.org/earth/Atmosphere/ozone_strato.html). First, intense ultraviolet (UV) radiation from the Sun is able to split diatomic molecular oxygen. The resulting single oxygen atoms are highly reactive, and rapidly combine with other diatomic oxygen molecules to form ozone (O_3). Finally, the ozone molecule is also split by UV radiation. Because ozone is a less stable molecule compared to diatomic oxygen, the UV radiation that splits ozone can be less intense. Through this process, the ozone layer shields organisms on the ground from UV radiation that would otherwise disrupt their DNA and lead to skin cancer. Turning away from these interesting processes in the stratosphere, we will now focus on the lower portion of the atmosphere for our analysis of the balloon data.

The temperature structure of the troposphere is governed by different processes. Most of the net energy input occurs at the Earth's surface, where the atmosphere is either directly heated (sensible heat) or heat is added by evaporation of water (latent heat). As air moves away from the Earth's surface, it cools because of the decrease in pressure with altitude. While this concept is easy to grasp for students, a more detailed consideration is possible that will allow students to understand the role of atmospheric stability. Atmospheric scientists typically employ a slightly modified form of the ideal gas law:

$$P = \rho R_M T$$

In addition to the familiar pressure (P) and temperature (T), a density is defined (ρ): mass per unit volume. Because the more familiar ideal gas law is based on moles and volume, the ideal gas law constant R is divided by the average molecular weight of air to produce R_M. Examining this equation, students will understand that when pressure decreases, density and/or temperature should also decrease. Relying on their understanding of balloon flights, they will understand that density does decrease with altitude. Students may then wonder whether temperature changes at all.

In fact, advanced undergraduate students can start with the ideal gas law, the equation of hydrostatic equilibrium and the first law of thermodynamics to derive the dry adiabatic lapse rate. Although working through the math is not essential, students should understand the adiabatic concept. This simply means that no heat is added or removed from air when it rises in the atmosphere. Students can picture a balloon that not only encloses the helium, but also serves as an insulator. If the air is dry, the adiabatic lapse rate is constant: 9.8 °C/km. A rising balloon should cool off at this rate. (Actually, the rate will be different by a factor of 5, because the dry adiabatic lapse rate depends on the specific heat at constant volume of the gas.)

The next concept necessary to analyze the temperature of the balloon data is potential temperature. Using the adiabatic assumption, there is an equation that relates the temperature and pressure of air to the temperature it would have if it is compressed to standard pressure P_0:

$$\theta = T\left(\frac{P_0}{P}\right)^{R_M/C_P}$$

Here C_P is the specific heat capacity of air. If the air at a certain altitude had risen to this altitude from the surface of Earth following only adiabatic processes (e.g., no cloud formation), its potential temperature (θ) will be a constant, namely the temperature it had while at the surface. Note that the temperature must be given in Kelvin and the ratio of R_M/C_p is a constant for dry air (0.286).

The final piece of the puzzle is how the variation of potential temperature with height affects atmospheric stability. Again going back to their balloon knowledge, students will understand that a balloon rises in the atmosphere because it is lighter. Although this is because helium is lighter than air, students should also be able to understand why a hot air balloon rises. Examining the ideal gas law given above, a hot air balloon and the surrounding air have virtually the same pressure (the balloon itself introduces only a negligible pressure differential). If the temperature is greater, then the density must be lower. Analysis of atmospheric stability is based on this same principle. If potential temperature is increasing with height, then the atmosphere is stable. This is because if air near the ground rises, its potential temperature does not change. When air with a lower potential temperature than the air above it rises, it will have a lower actual temperature than the surrounding air when it reaches a higher altitude. As a result it will sink back down. On the other hand, if potential temperature is decreasing with height, the air is unstable. When air rises, it will be warmer than the surrounding air, and continue to rise. There is also neutral stability, when the potential temperature does not vary with height. If air rises it will stay at that level because it has the same temperature as the surrounding air.

Using these principles, we can examine data from 4 balloon flights conducted during 2010 and 2011 by students and faculty from DePaul University. Figure 1 shows the actual temperature data for the entire flights. First, the data clearly show the break between the troposphere and stratosphere. Second, there is an obvious problem with the air temperature sensor built into the Stratostar command pod. Temperatures at the same altitude are higher during the ascent compared to the descent. We attribute this to the thermal mass of sensor and command pod and a corresponding time lag in response to temperature change. Although this means are temperature profiles have a systematic error, we will continue our analyses.

Figure 2 shows the variation of potential temperature with height in the lower part of the troposphere. In each case, the potential temperature decreases with height during the ascent, and therefore the air is stable. There are some missing data during the Jul 14 ascent, so that part of the analysis is inconclusive. During the descent, there is more interesting structure. During the Jul 22 and May 21 flights, the lower atmosphere also appears to be stable. On the other hand, during the Jul 14 flight, there is a large zone of neutral stability (500–1400 m) and a zone of instability (ground to 500 m). On May 20, there is a broad zone of neutral or near-neutral stability (ground to 1500 m).

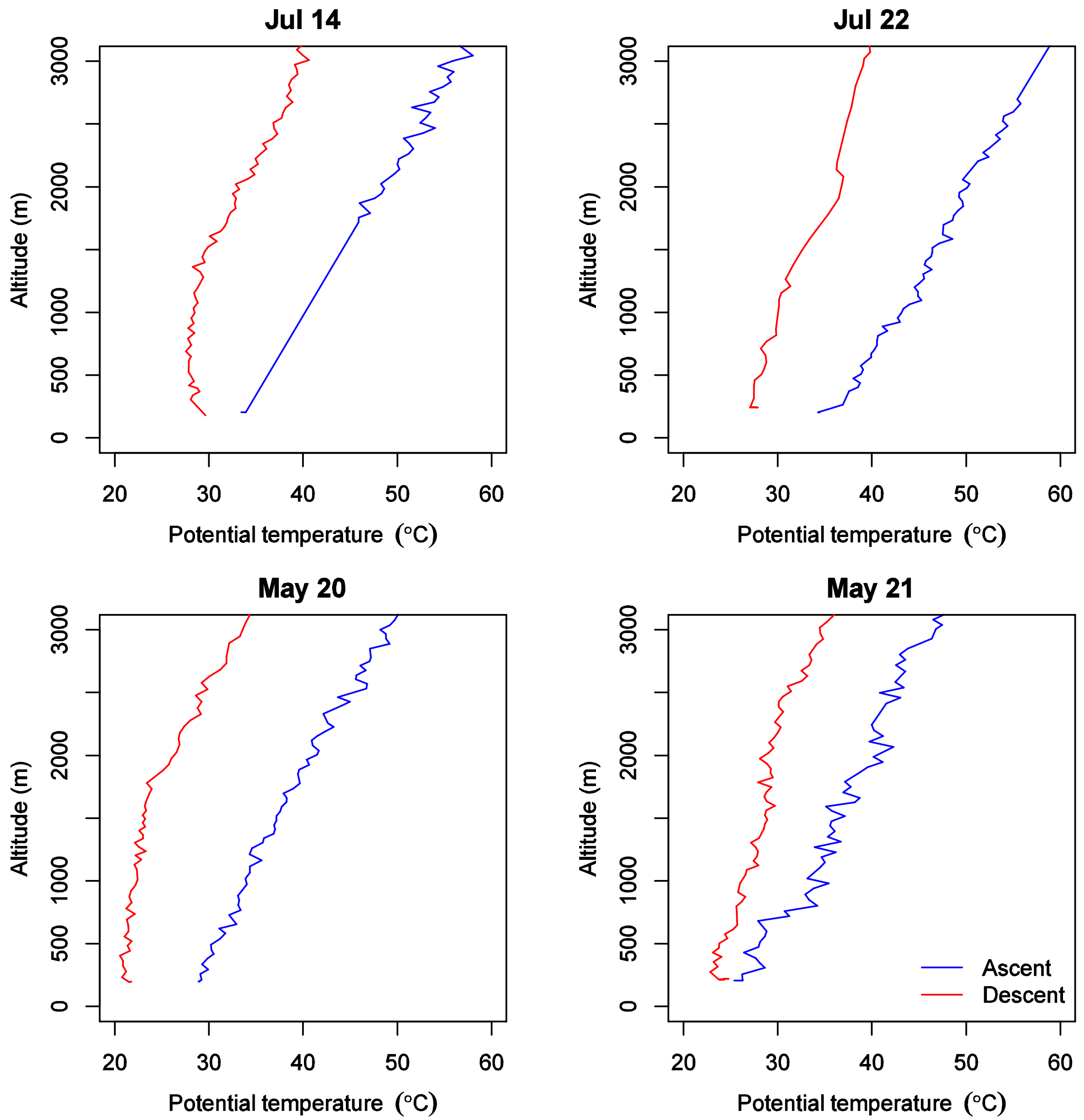

Figure 2 Profiles of potential temperature for the lower portion of the atmosphere. During the July 14 flight, there is missing data from just after the launch until nearly 1700 m.

Figure 3 relates the same vertical profiles of potential temperature during the descent to relative humidity. For the two days with zones of instability or neutral stability, there is constant relationship with relative humidity. Relative humidity increases from the surface to the top of the zone of instability, and then rapidly decreases above that level. Taken together, these observations indicate that the atmosphere was undergoing convection. Solar radiation was heating the Earth's surface, leading to hot air rising. This rising air led to a zone of constant potential temperature. Students could further refine this analysis by computing the mole fraction of water vapor in the air. Relative humidity depends on both the amount of water vapor in air and the air temperature, so it is not a conserved quantity.

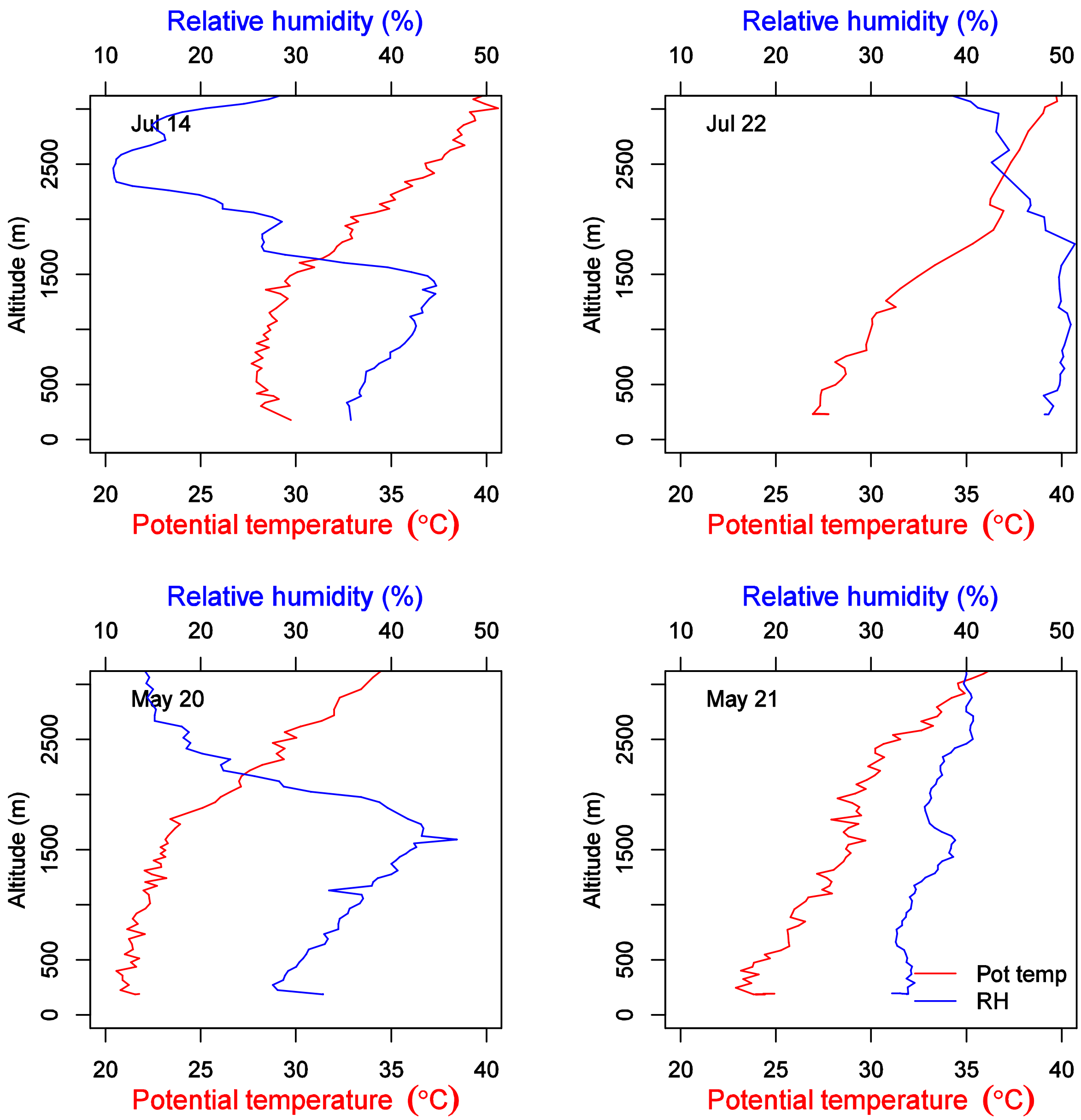

Figure 3 The potential temperature profiles are the same as given in Figure 2 for the descent. The relative humidity profiles are also from the descent.

This simple analysis demonstrates how students could use basic meteorological data and physical principles to understand the process of convection in the lower atmosphere. The explanation above is simplified for undergraduates with some understanding in physics but with little prior exposure to atmospheric science. More advanced students studying meteorology would want to take this further: for example, by considering the wet adiabatic lapse rate and cloud formation. Also, students could compare images taken with digital cameras to these analyses. For example, if students deduce the presence of convection, is there visual evidence of cumulus clouds, which are characteristic of convective situations?

III. Geographic Coordinates and GPS

For many students the most exiting parts of high-latitude ballooning missions are the launch, chase and recovery. Even if they have never participated in any balloon flights we normally put the students in charge of these activities, with faculty only acting as backup in case problems occur. We use a Stratostar command pod with two mobile antennas, allowing up to four tracking teams in two vehicles, as well as an APRS transmitter that students track on their smart phones and tablet PCs via the aprs.fi web site. Before the flight the students predict the landing zone by entering the latitude and longitude of the launch site into trajectory prediction software. During the flight the location of the balloon is measured by GPS receivers attached to the balloon and transmitted to the chase vehicle or the HAM radio network. Students direct the chase vehicle by comparing the measured coordinates, which are shown on maps in Microsoft MapPoint and the aprs.fi web site, with their prediction. After some landings (e.g., mid-summer landings in high corn) they enter the final transmitted latitude and longitude into a hand-held GPS receiver or car navigation system to help them locate the payload.

Especially students without a lot of science background are often only vaguely familiar with computer-based maps, geographic coordinates, and GPS. To maximize the probability of a successful recovery, the students work through a variety of in-class activities intended to familiarize them with these concepts. There are a variety of web-based tools that can be used for this purpose. For example, Google's "Map Labs" can be used to determine latitude and longitude points on a map, and to measure distances between them. The GPS Visualizer web site has a variety of calculators that allows students to convert geographic coordinates between different formats, measure great circle distances between pairs of coordinates, find the geographic coordinates of a point at given distance and bearing, and draw range rings around multiple points for trilateration. An application of these tools that many students enjoy is a GPS scavenger hunt. Figure 4 shows an example created with GPS Visualizer, which is based on the following instructions: Start at waypoint 1 (WP 1) located at latitude 41.92366, longitude -87.65643. Continue to WP 2, which is 181.5 m from WP 1 and 162 m from the entrance of the DePaul University Welcome Center. If multiple points meet these criteria go to the one furthest north. WP 3 is located 305 m from WP 2, bearing 132.819°. The scavenger hunt ends at WP 4, which is located on Kenmore Ave and has the same distance from WP 3 as the starting point. If multiple points meet these criteria go to the one with the lowest latitude.

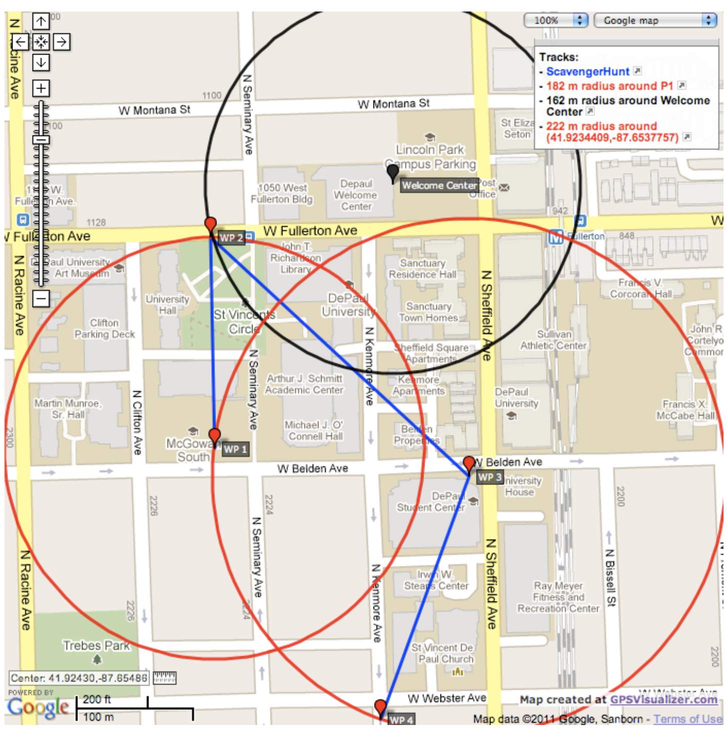

Figure 4: Example of a GPS scavenger hunt created with the GPS Visualizer web site.

Another simple yet fascinating activity that helps students become more familiar with geographic coordinates and GPS is the determination of Earth's circumference with handheld GPS receivers or car navigations systems. It uses a method first developed by Eratosthenes over 2200 years ago. By observing the lengths of shadows cast by the sun in Alexandria and Syene, Eratosthenes determined that the latitude difference is 7.2°. He concluded that the distance he measured between Alexandria and Syene must therefore be 7.2/360 (=1/50) of the circumference of Earth. Because of the high-accuracy of handheld GPS receivers, students can repeat this experiment by measuring the latitude difference between locations that are only a few hundred meters apart, and still get a result that is within a few percent of the correct value. For example, the latitude difference between the intersection of Sheffield Ave and Fullerton Ave, and the intersection of Sheffield Ave and Webster Ave on the DePaul Campus is 0.00369°, and the distance between them is 410 m (see figure 5). Following Eratosthenes's reasoning, the circumference of Earth is 360°/0.00369°×0.410 km = 40,000 km. An interesting extension of this activity is to use two locations that are at the same latitude and measure their longitude difference. The students should be able to explain why this measurement yields a smaller circumference, and how the result would change if the measurement was made at a location that is further north or south.

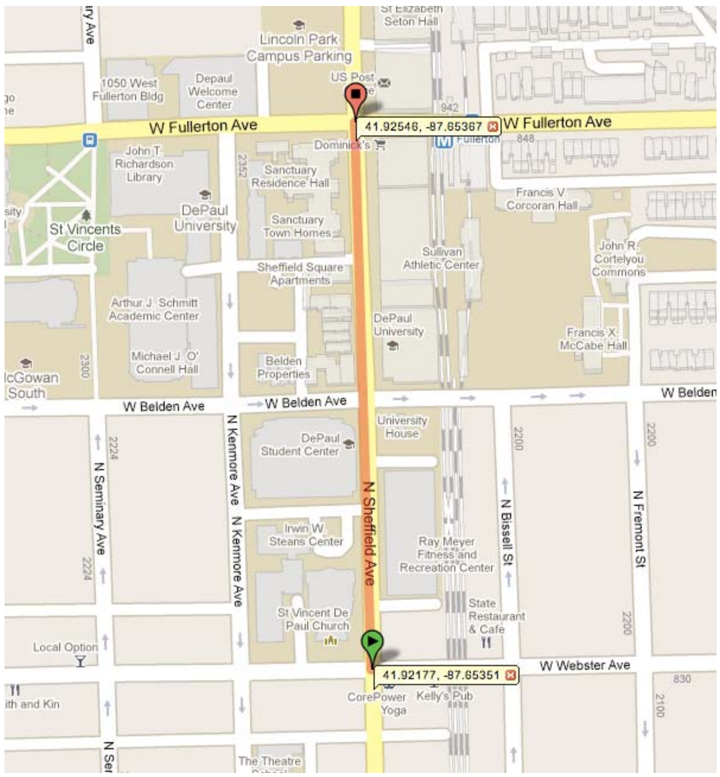

Figure 6: Measuring the circumference of Earth using Eratosthenes's method

Celestial navigation used by navigators at sea long before the advent of GPS technology is an interesting historical connection to the use of GPS technology in ballooning. Navigators take advantage of the fact that the orientation of the Earth's rotation axis and its rotation and orbital periods remain nearly constant as Earth orbits the sun. High-precision measurements are difficult and require sophisticated instruments. But even students without any prior experience who are using crude instruments such as sticks, protractors, and plumb-bobs can typically determine their position to within about 30 miles by measuring the altitude of the sun and time when it passes the north-south meridian. (The north-south meridian is an imaginary line that starts on the horizon directly south of the observer, passes overhead, and ends on the horizon directly north). For example, the shadow cast by a vertical stick will show that in Ames, Iowa on June 22 the sun passes the north-south meridian at approximately 1:16 PM CDT (12:16 PM CST), at an altitude of 71.5° above the horizon. On the central meridian of the central time zone (longitude W90°) the meridian passage on this date occurs at 12:01 PM Central Standard time. Earth rotation rate is approximately 0.25° per minute, so the fact that the meridian passage occurred 15 minutes later tells us that Ames is 15/0.25°= 3.75° west of the central meridian, at a longitude of approximately -93.75°. The latitude of Ames can be determined from the altitude of the sun at the time of the meridian passage. The declination of the sun on June 22 is

23.4°, so latitude of Ames is approximately 90°-71.5°+23°= 41.5°. Sadler and Night have written a nice article for the March 2010 articled of The Physics Teacher provides with more details about this method.

IV. Microcontrollers

Another aspect of ballooning which is ideally suited to creating rich and valuable learning experiences for students is embedded microcontrollers. Ballooning provides an ideal platform where students can learn how microcontrollers work, how to program them themselves, and even can learn about careers in engineering with which they may not be familiar. And, from our experience working with students, what is so exceptional with the ballooning platform that students, through the process of formulating their own questions and seeking the answers, are internally motivated to learn about these technologies and methodologies. The motivation to learn genuinely comes from the students themselves.

In the case of embedded microcontrollers, students soon learn that these small, versatile computers with input/output connections are used in the tracking system and one usually connects temperature, humidity, and pressure sensors to the main tracking system. However, in designing their own projects, the students quickly come up with projects that require control (such as triggering a camera a fixed interval or turning on a motor at a specific time or altitude) or datalogging (analog signals from sensors or counts from Geiger counters or scintillation counters). They become highly motivated to learn about microcontrollers and how to program them for their own use. We developed a series of labs of gently increasing complexity, which introduce students to the concept of microcontrollers and culminate in the construction of a simple datalogging system with an analog sensor. For microcontrollers, we have used BasicX (www.basicx.com) and Arduino (http://www.arduino.cc). In our recent work with students we are using the Arduino microcontrollers because they are open source and inexpensive and because there is excellent community support in terms of software libraries for common tasks. Arduino microcontrollers also have a clever design by which one easily attach additional hardware to them; these attachments are called “shields,” and there are now dozens of hardware shields available, containing hardware ranging from memory, motor control, Ethernet, BlueTooth, ZigBee as well as blank ones so you can build own. An alternative microcontroller designed specifically for ballooning is Paul Verhage’s BalloonSat Easy, Mini, and Extreme (http://nearsys.com/). These microcontrollers use the PicAxe microcontroller and programming environment; they are easy to program and hardware interfaces to commonly used sensors is built in. Another microcontroller used by students in ballooning are the Basic Stamp (http://www.parallax.com/) but we have found them of limited use for ballooning.

The series of labs starts with simple input and output (e.g. turning an LED on and off at fixed intervals). Even the first lab has application in ballooning: students have used a microcontroller to send signals to a digital camera to take photographs at fixed intervals using this method. The key concepts of variables and loops are introduced as they learn about various forms of input, in particular analog inputs. There are opportunities to learn about analog to digital conversion and in turn the converting the analog voltage data into meaningful units. The series concludes with working with memory: students learn how to store data on the microcontroller’s EEPROM and retrieve it. They construct a working datalogging system using a very simple sensor (a photoresistor). At this point students are enabled to adapt the microcontrollers to their own projects. Further labs could investigate controlling motors, however the sequence is an appropriate length. They continue to learn more about microcontrollers and embedded programming as they proceed on their projects.

With electrical engineering students, a ballooning course gives the opportunity for the students to develop more advance projects using multiple processors and field programmable gate arrays.