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Solar Eclipse Ballooning with a Multiband Tracking Subsystem for Undergraduate Research Experience

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Abstract

This paper discusses an on-going research project that offers an undergraduate research platform in electrical and computer engineering (ECE), especially for high-altitude ballooning in near space, that attracts and engages students in undergraduate research early on, and improves their overall learning experience at college. We first briefly describe an existing ballooning system designed for the 2017 solar eclipse project, and then provide details of the subsystems of our own payload that integrates three different modes of communication technologies to enhance tracking capability of the balloon system. Combined with the Iridium-based balloon tracking, our multiband tracking system can be a useful tool for tracking of high-altitude ballooning systems and provide a platform of undergraduate research for further enhancements or modifications, ultimately contributing to improving the student learning experience.

1. Overview of the Project

The Eclipse Ballooning Project 2017 [1] is a nationwide effort to facilitate and coordinate high-altitude balloon flights across the August 21, 2017 total eclipse path, sending live video and images from near space to a designated website. While video and images of a total solar eclipse (SE) from near space are fascinating and rare, collection of them has never been done live in a network of coverage across a continent [2]. For the facilitation of high-altitude ballooning by university/ college teams with varying levels of experience, a baseline system developed by the national project office has been provided to all teams in July 2016 but also with opportunities of further enhancing/ complementing the baseline system [3]. The baseline system consists of a ground station and four standard payloads for still image, video, Iridium-based tracking, and cut-down, respectively.

As one of the teams from the commonwealth of Pennsylvania, an undergraduate project team at the University will launch a high-altitude ballooning system (HABS) for the August 21, 2017 solar eclipse from a pre-selected location in Kentucky as part of the nationwide coordination of colleges and universities to capture the entirety of the eclipses across the United States. In addition to the baseline system, our team has been developing an additional tracking system that utilizes three different modes of communication technologies, hereafter referred to as the multiband tracking subsystem (MTS), to ensure recovery of the HABS in Kentucky's mountainous terrain. The three communication technologies that comprise the MTS include a 900 MHz RF system, an Automatic Packet Reporting System (APRS) operating at ~150 MHz, and a cellphone-based tracking system operating at ~2 GHz. The MTS also utilizes a Global Positioning System (GPS) receiver and a micro-controller unit (MCU). The payload's real-time position will be acquired by the GPS receiver, and the MCU will convert the raw GPS data into a set of formatted strings of positioning information. These strings will then be transmitted to the ground where each subsystem's receiving end will map and track the payload with real-time location-mapping software developed by the team utilizing Google Maps.

The project team consists of eight undergraduate students, mostly ECE majors but including a science major, and two faculty advisors from the ECE and Physics departments. All students participate in this project as an extracurricular activity and do not receive any course credit toward completion of the ECE or science curriculum.

For the remainder of this paper, we 1) present a brief description of the baseline system, as well as detailed descriptions of the MTS of our SE ballooning system, 2) identify key technical knowledge required for a successful design of the subsystems in reference to specific ECE course content, 3) present how the extracurricular research activities are administered to keep students motivated and engaged in the project, and 4) present and discuss assessment results on how these extracurricular project activities contribute to improving the student learning experience and thus student learning outcomes defined by ABET.

2. High-Altitude Ballooning System for Solar Eclipse

2.1. Brief Description of the Baseline System

Figure 1 shows the functional diagram of the entire solar eclipse ballooning system. It consists of a balloon system, a baseline ground station, and an MTS mobile station. The balloon system consists of five payloads which include four baseline payloads for still image, video, Iridium, and cut-down of the baseline system. The fifth payload, MTS-Tx is an additional payload for a 3-mode tracking subsystem which will be further described along with its counterpart in the MTS mobile station in the subsequent sections. Although the balloon payloads operate on batteries, the ground station requires AC power. As such, a portable generator may be required to supply power to all components of the baseline ground station if the ground station is placed far from any source of AC power. On the other hand, the AC power to the MTS mobile station will be supplied from a

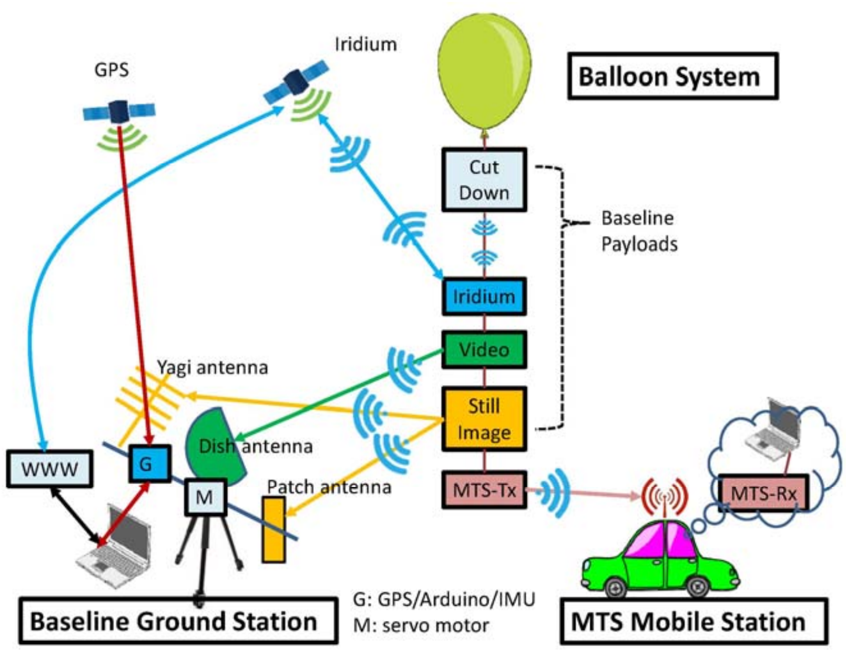

Figure 1. Functional diagram of the solar eclipse ballooning system

standard automotive power converter that generates 120 VAC output from the standard 12 VDC automotive power socket.

As the baseline system was provided to all participating teams by the national project office and its descriptions for the payloads and the ground station are available online [3], in this paper we focus on the MTS as well as the steps necessary for our students to successfully operate the baseline system to capture images and streaming video of the solar eclipse on August 21, 2017.

Learning about and testing of the baseline system – In order to be prepared for proper operation on the day of the eclipse, our students have learned and tested the functionality of each and every payload, and its ground station counterpart, in the lab and also outdoors. Since fall 2016, multiple simulations for the balloon launch procedure have been conducted as well as a tethered test flight in a nearby convention center building with high ceiling. More simulations and tethered test flights are scheduled on a monthly basis until the team leaves for the eclipse day.

The still image payload uses a Raspberry Pi with a camera module to acquire pictures in flight at a rate of one per minute. These images are then transmitted from the payload to a patch antenna and a Yagi antenna on the ground station, as depicted in Figure 1, using a RFDesign RFD900+ modem operating at ~900 MHz. Its counterpart RFD900+ modem on the ground station is connected, via USB, to a Windows 10-based laptop running custom software operating in a virtual Linux operating environment to download, store, and display these images in near real time. The software can also be used to send commands to the still image payload. Operation of the payload requires providing power to the Raspberry Pi and modem on the balloon system, connecting the ground RF receiver, connected to a patch and Yagi antenna, to the laptop via USB, and running a Python code.

The video payload uses a second Raspberry Pi with camera module to capture high-definition video during flight. A 5.8 GHz Ubiquiti modem, the Rocketfish M5, is used on the balloon system to transmit the video to another M5 modem on the ground station, receiving the 5.8 GHz signal through a dish antenna. The M5 modem on the ground station is connected to the same laptop used for still images. Transmission of the video is initiated via remote login with the Raspberry Pi, defining the output filename (the video is also recorded to disk), and beginning streaming of the video using the Real-time Transport Protocol (RTP). The ground station uses VLC Media Player to display the video stream.

Tracking of the balloon system location is accomplished using the Iridium payload (depicted in Figure 1) which is built around an NAL Iridium Satellite Tracking Modem to generate GPS packets of GPS coordinates of the balloon system. The GPS coordinates are transmitted to a server at the solar eclipse project headquarters in Montana via the Iridium satellite network, and the laptop on the ground station retrieves these GPS coordinates from the server via the Internet. This allows for accurate payload position determination even if line-of-sight communication is lost between the balloon system and the ground station. The Iridium payload is also used to receive the command to cut-down the payload, and it communicates with the cut-down payload via an XBee wireless module. In the event that a malfunction prevents proper transmission of the cut down command, both the Iridium payload and cut-down payload have backup timers. These timers must be reset before launch to prevent pre-mature termination.

The cut-down payload consists of a custom electronics board, developed by a team at the SE project office in Montana, that turns on a motor with a cutting wheel attachment. The motor turns on when it receives a command from the Iridium tracking payload via a XBee module, as described above, and cuts the line between the balloon and parachute to release the balloon and drop the payloads to the ground if/when needed in an emergency or unexpected situation during flight. In a normal flight, the balloon bursts when it reaches an intended altitude, such as ~110,000 ft, and then payloads parachute safely to the ground.

Prior to balloon launch, all teams are required to run a flight prediction to ensure the balloon will not traverse restricted airspace. Balloon prediction can also aid in the chase and recovery process, allowing a chase vehicle to be positioned near the predicted landing location. There are a multitude of options for producing these flight predictions. An example can be found on the SE project website, from the NOAA Ozone and Water Vapor Group [4]. Our team has also used the Cambridge University Spaceflight Landing Predictor (CUSF) [5]. Given the mountainous terrain in Kentucky (and several controlled airspaces near the eclipse path), flight prediction is very important.

One important factor in balloon flight prediction is the ascent rate, which in turn is a function of payload weight and balloon lift. For this project, the target ascent rate is about 1,000 ft/min. To achieve this rate, the empirical formula derived from experienced ballooning teams is that the lift force should be 1.28 times the weight of the payload. Balloon lift can be determined using either a hand-held spring scale or filling the balloon until it is able to lift the correct amount of ballast (which is disconnected prior to flight).

2.2. Key Technical Knowledge and Learning

Although not as challenging as designing a complete ballooning system of a complexity similar to the baseline system described above, quite a bit of effort and understanding is required for typical ECE undergraduate students to properly operate the baseline system and be ready for the eclipse day. At the beginning of the project, three students from our team along with a faculty advisor attended a 3-day workshop in July 2016, organized by the SE project headquarters for each team to construct a complete baseline system from individual parts and components and perform a preliminary test for functional verification of each payload and the overall integrated system. The information from the workshop was disseminated to all participating team members after the workshop. Review of these materials allowed further learning to take place on the following aspects of the project:

- Because all team members from the ECE department are on the electrical engineering track as opposed to computer engineering track, configuring the Raspberry Pi via a remote SSH login to the Linux environment required a significant amount of learning. Working in a Linux environment was fairly new to all of them and required learning basic commands and recognizing major differences between Windows-based and Linux-based operating systems, including such fundamental aspects as clicking with a mouse to perform certain tasks on a Windows system versus precisely typing commands in a command line. Even properly using upper- and lowercase letters as well as special characters (e.g., underscore and space) in the Linux environment were part of the new learning. Also, learning basics of computer networking was required to properly configure the GUI (e.g., communication ports) on the laptop for the modems on the ground station and also to configure the Pi remotely via a wireless connection between the laptop and the payloads.

- Reviewing the datasheets and manuals of the modems used, i.e., RFD900+ at 900 MHz, M5 at 5.8 GHz and Iridium, lead to basic knowledge of communications. ECE students in our curriculum do not get into communications until taking a technical elective in introduction to communications either in their junior or senior year. None of the team members had basic knowledge in communications from their coursework yet.
- Students were required to develop a basic understanding of directional antennas and beam patterns, relevant to the dish, Yagi, and patch antennas used. Once again, antennas are only touched later in the semester, as part of an electrical engineering core course, Electromagnetic Fields, in the junior year on the electrical engineering track, and none of them had completed the course yet until the end of fall 2016.

2.3. Multiband Tracking Subsystem

The multiband tracking subsystem consists of a payload, MTS-Tx, and an MTS mobile station as shown in Figure 1 above. For further details, a functional block diagram of the MTS-Tx is shown in Figure 2 below. The APRS transmitter operating at 150 MHz and the RF modem operating at 900 MHz utilize commercial off-the-shelf (COTS) devices to deliver positioning information from a high-altitude-purpose GPS module processed in an on-board microprocessor. In the MTS mobile station, the position coordinates are extracted by their respective receiver units and displayed using an in-house Google map-based mapping software. As such, the operation of these two subsystems does not require any Internet connection while on the balloon-recovery mission. However, the RF modem does require line-of-sight communication with the payload.

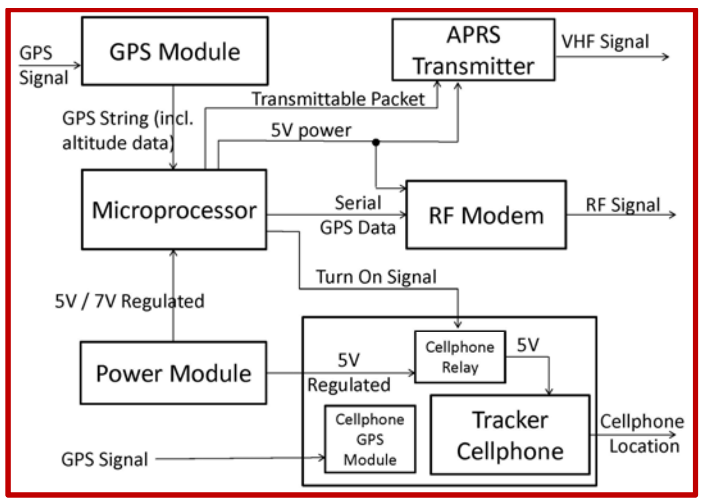

Figure 2. Functional block diagram of the MTS-Tx payload

The third subsystem, a tracker cellphone, uses a cheap COTS smartphone that delivers positioning information from its own GPS module to an online software site to map the position. To access the online mapping software in the MTS mobile station, an Internet connection is required. Further details of these MTS subsystems will be discussed in the subsequent sections.

3. RF-based Tracking

3.1. Integration of COTS Components for RF-based Tracking

Communication between the balloon system and MTS mobile station is facilitated using XTend 900 MHz RF modems as shown in Figure 3. The modem on the balloon is connected to a ChipKit MAX32 microcontroller. The microcontroller reads the GPS string from a GPS receiver via a 4800-baud serial connection. Since most GPS receivers are not designed to function above an altitude of 60,000 ft, an Inventek Systems ISM300X GPS receiver was selected that did not suffer from this limitation. The microcontroller parses the National Marine Electronics Association (NMEA) GPS string to determine the GPS coordinates, and transmits the coordinates in a formatted data string through the RF modem.

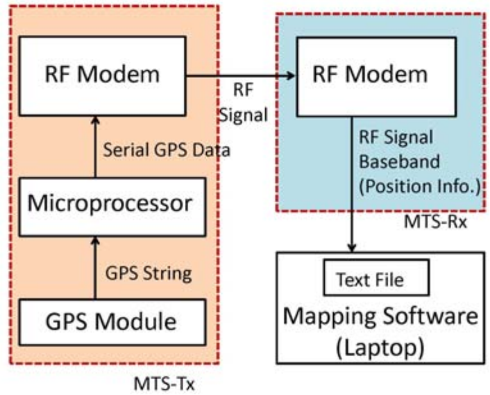

Figure 3. Functional diagram of the RF-based tracking

GPS data strings are formatted in a number of different ways. For this project, we used the GGA string which provides the current Fix data. The algorithm used to parse the GPS string for the GGA substring is shown below. Similar algorithms are used to extract the important data fields from the string, including UTC time, latitude, longitude, and altitude.

```
//////////////////////////////////////////////////////////////////////////////////
// This function parses the GPS data string.
// Will return ref_char, which is the location of the comma after the string $GPGGA
int GGA_Finder(int gps_record_size) {

    for (int c = 0; c<gps_size-5; c++) {

        if ((raw_GPS[c+0] == '$') && (raw_GPS[c+1] == 'G') && (raw_GPS[c+2] == 'P') &&
        (raw_GPS[c+3] == 'G') && (raw_GPS[c+4] == 'G') && (raw_GPS[c+5] == 'A') &&
        (raw_GPS[c+6] == ','))  {

             int ref_char = c + 6;
             return ref_char;
        }

  return 0;
}
```

The formatted data string from the balloon is then received by the XTend RF modem connected to the MTS mobile station, which includes a laptop for data processing. This laptop is running custom C# code to read the position string and then plot the current balloon position using Google Maps. This software does not require an Internet connection, provided that the maps have already been stored locally on the laptop.

3.2. Key Technical Knowledge and Learning

As the main components of the RF tracker use serial communication (GPS to microcontroller, microcontroller to RF modem, RF modem to laptop), learning to code the microcontroller to read and write to a serial line was crucial to achieving project success. The ChipKit microcontrollers were programmed using MPIDE, which uses the same syntax as the popular Arduino IDE. This language makes serial communication fairly straightforward (although still challenging for a first or second year student).

Perhaps the most significant hurdle was helping the students find a way to efficiently parse the GPS string. Since these strings are not fixed length, students had to write code to find commas and select the data fields inside. Again, this was a good task for novice programmers to begin learning the basics. Since some code existed from previous projects, students also had to learn to read existing code, understand it, and modify it to suit their needs.

4. APRS-based Tracking

4.1. Integration of COTS Components for APRS-based Tracking

The APRS system uses the 144 MHz amateur radio band to broadcast data packets. Each data packet is transmitted by an APRS transmitter and received by all available APRS receivers in the area. There is no mechanism for acknowledgement and retransmission, but most APRS receivers act as repeaters ("digipeaters") for the data packets they receive. A packet is repeated amongst all local digipeaters through the number of "hops" specified by the creator of the packet. Some receiver stations also function as APRS Internet Gateways (IGates) and upload the APRS packets they receive to a server, which can be accessed to plot positions on a map. A website already exists to display the GPS positions reported by APRS packets all over the world (http://aprs.fi/).

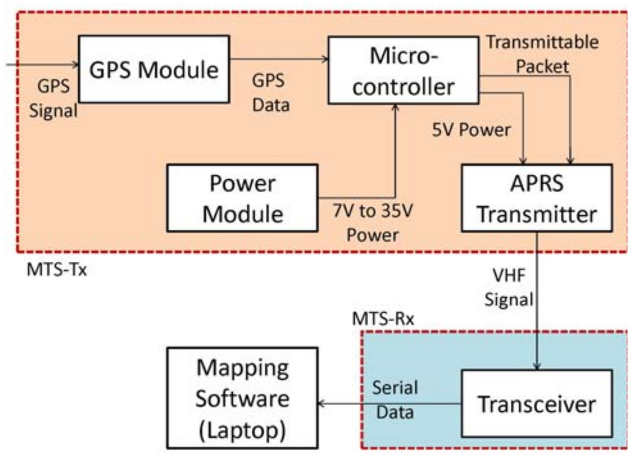

Figure 4. Block diagram of the APRS-based tracking

Our balloon will employ a TinyTrak3+ APRS position encoder, which accepts a serial GPS string and encodes a properly formatted APRS packet. It is then connected to an SRB MX145 radio from Argent Data Systems, which is used to transmit the packet. Although there are a number of digipeaters present in the launch area, we are also using an Alinco DR-135T VHF FM transceiver to receive APRS packet. This receiver will be connected to a laptop, which will run custom code to extract the GPS position from the APRS packet and display it using the mapping software described above. If the MTS mobile station is unable to remain within communication range of the balloon, other APRS digipeaters in the area should be able to receive the balloons position, and the web interface can be used to track it.

4.2. Key Technical Knowledge and Learning

In order to use this system, students needed to learn about the APRS system, select the appropriate hardware, and obtain amateur HAM radio licenses. Since the TinyTrak3 receives serial GPS strings, the same GPS will be employed for both the RF and APRS submodules, with the microcontroller forwarding the GPS string to the APRS encoder. In addition to the microcontroller code to receive and parse the GPS data string, separate code will be used to retransmit the original data string to the APRS encoder via a second serial line.

5. Cellphone-based Tracking

5.1. Integration of COTS Components for Cellphone-based Tracking

A GPS enabled smartphone is a very attractive, low-cost tracking option. Many phone applications exist to display the location of the phone on a variety of platforms, and the phone can report its position from anywhere it receives cell service. For the purposes of this project, an LG L33L phone running the Android operating system was selected because it was inexpensive and had an easily accessible battery.

However, using a cellphone to track a balloon payload is somewhat complicated by FCC regulation 22.925 [6], which prohibits the use of cellular communication in aircraft or balloons that are not touching the ground. (Cell phones are allowed to remain in “airplane mode” while in the air.) In order to circumvent this restriction, we use a power relay, depicted in Figure 5, as an ON/OFF switch that keeps the cell phone off during flight. A relay was chosen to open/close the circuit between the phone and the power module instead of supplying the DC power to the cellphone directly from the microcontroller since cellphones may require a higher current than a DC output from a microcontroller could supply. Once the balloon has landed, the GPS coordinates will stop changing, and altitude can provide a useful cross check to ensure compliance with FCC regulations. When the microcontroller detects that the payload has landed, it will switch the power relay to turn on the phone. The phone will be configured to automatically start *AccuTracking*, a cellphone application software, which will transmit the GPS coordinates of the phone to its server and mapping software maintained by the software vendor. This mapping software runs on the laptop in the MTS mobile station. While this will not record the entire flight path of the phone, it is a useful backup option for recovery.

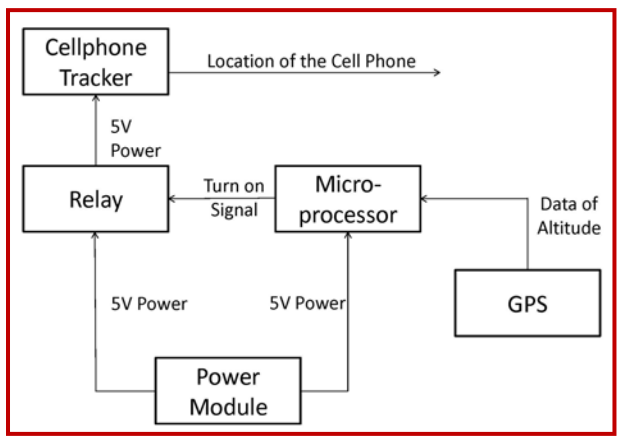

Figure 5. Block diagram of the cellphone-based tracking

5.2. Key Technical Knowledge and Learning

Students learned about several apps in the Android ecosystem, as well as interfacing a power relay with a microcontroller. To control the relay, students apply their knowledge on electronics to design circuitry that will process and execute the turn on signal from the microcontroller. The students also program the microcontroller to properly generate the turn on signal considering all possible scenarios during the landing. Fortunately, the same microcontroller and GPS unit can be used for all subsystems (RF, APRS, and cellphone) and the students working on different modes of tracking could collaborate and share their knowledge and experiences.

6. Mapping Software

6.1. Design of Mapping Software

Our in-house mapping software is based on Google Earth which can be downloaded and installed on any computer. To display a location, Google Earth reads in location coordinates from a Keyhole Markup Language (KML) file. Our in-house mapping software is developed such that, when the RF modem and/or APRS transceiver is connected to the computer via a USB port, it parses and periodically saves the incoming geographic data to a CSV file. This CSV file is read in by another routine to create a KML file that Google Earth uses to display the geographic data on it. The processing flow for the code development is depicted in Figure 6. By appending all incoming geographic data to a CSV file during a balloon flight, an entire trajectory of the balloon flight can be displayed as well as the most recent location.

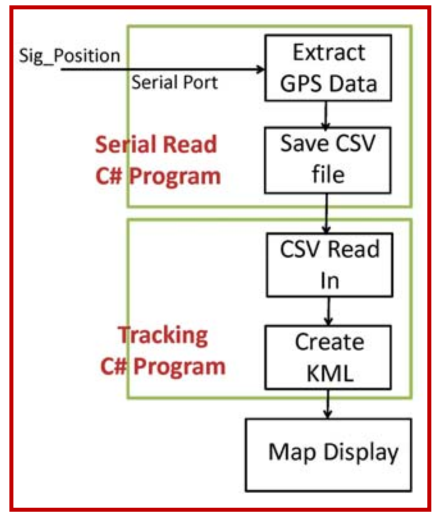

Figure 6. Block diagram of the mapping software

6.2. Key Technical Knowledge and Learning

The project team revised a preliminary Google Earth-based mapping software that was partially developed in house for the mapping purposes in a high-altitude ballooning experiment conducted a few years ago. A critical component to add to the preliminary mapping software this time was to read geographic data from the USB port(s) to which the RF modem and APRS transceiver is connected. The software development was in C#, which is yet a new programming language to ECE students – unlike computer science majors, ECE students in our curriculum learn programming with C++. However, rather than simply developing C# codes, students get to integrate them with actual hardware devices and verify the entire operation between the MTS-Tx on the balloon system and MTX-Rx on the mobile station to successfully track and recover the balloon payloads.

7. Assessment of Learning Experience and Discussion

7.1. Facilitation of Project Activities

Our project activities on the solar eclipse payload began in early fall 2015, prior to receiving the baseline system described in Section 2 or any technical details about it. We began developing our own tracking system based on previous experience in high-altitude ballooning and chose the three tracking modes presented in this paper. With 8 students on the team at that time (all of them still actively participate), two students were assigned to each subsystem, i.e., RF-based tracking, APRS-based tracking, cellphone-based tracking, and in-house mapping software. Each student volunteered and committed a minimum of 5 hours per week for team's laboratory activities. To accommodate student's schedules while ensuring sufficient time to make progress, the 5 hours per week are split into two 2 ½ hour sessions such that students could come to the lab twice a week for teamwork-based lab activities.

The authors of this paper have served on the role of faculty advisor, to motivate students as often as needed, facilitate learning, help them overcome challenges and make progress. Equally importantly, students learn to deliver. Having started this project in fall 2015 with then-freshmen and sophomores, we have been able to retain all of them over a period of more than 3 semesters, i.e., fall 2015, spring and fall 2016, and this spring 2017. We believe that close interaction between students and the faculty advisors and maintaining regularly scheduled lab hours, throughout a semester and over several semesters, have been crucial to keeping them on the project and helping them improve learning experience outside of the classroom. Also, we believe that injecting even a small token of appreciation always helps to keep the students motivated; for that, we have incorporated small-amount scholarships into the project budget that have been awarded to those eligible to receive a scholarship in each semester. Furthermore, although 5 hours per week was set as a minimum to volunteer and commit, students who are able and wish to commit a total of 10 hours/week are put on payroll as student research assistants for the entire 10 hours per week.

7.2. Assessment by Survey

We have adopted ABET's student outcomes "(a) through (k)" as metrics to quantitatively assess the effectiveness of the balloon program through student surveys. The survey consists of 22 questions developed in line with the 11 "(a) through (k)" student learning outcomes defined by ABET/EAC. For each student outcome, we asked two questions: i) if the project provided opportunities for the student to improve on the learning outcome and ii) if the student actually did improve that learning outcome by participating in the project. For instance, for the student outcome (a): an ability to apply knowledge of mathematics, science, and engineering, the survey questions for Q-a(i) and Q-a(ii) are, respectively, Q-a(i):

Table 1. Average Ratings for (a) through (k)

Q#	**Opportunity Provisioning / Perceived Improvements**					
	Oct. 2013 (9 participants)		***May 2015 (8 participants)***		***Jan. 2017 (7 participants)***	
a	5.00	4.78	4.88	4.63	4.71	4.57
b	4.89	4.67	4.38	4.00	4.14	4.14
c	4.67	5.00	4.00	4.13	4.14	4.43
d	4.67	4.56	4.38	4.25	4.29	4.29
e	4.78	4.89	4.63	4.63	4.43	4.29
f	4.44	4.33	3.88	3.50	3.86	4.24
g	4.89	4.78	4.25	4.25	4.14	4.14
h	3.78	3.78	4.50	4.38	3.86	3.86
i	4.33	4.33	4.00	4.38	4.14	4.14
j	3.44	3.44	3.88	4.25	4.00	3.71
k	4.44	4.44	4.50	4.63	4.43	4.29

"The project activities provided me with an opportunity to improve my ability to apply knowledge of mathematics, science, and engineering;" and Q-a(ii): "Participating in the project activities, I have improved my ability to apply knowledge of mathematics, science, and engineering." For more details and specific texts for all survey questions, refer to Table 2 in [7].

Table 1 summarizes the average scores obtained from the results of the surveys conducted in January 2017, where '5' indicates that students strongly agree, and '1' indicates that students strongly disagree. We also compared the results from the surveys on our previous undergraduate research projects conducted in 2013 and 2015, respectively. It is noted that these survey results demonstrate that all student groups in 2013, 2015, and 2017 agreed that our projects provided great opportunities to improve their learning experience, but also that these projects helped them actually improve in most of the ABET (a)~(k) student outcomes.

8. Concluding Remarks

We have presented an undergraduate research project that is intended to enhance balloon tracking capabilities. Built as an additional payload to a baseline ballooning platform for solar eclipse ballooning, the project proved to be an effective tool to attract and maintain student interest in extracurricular undergraduate research activities. From our assessment results, these extracurricular project activities contributed to improving the student learning experience and thus student learning outcomes defined by ABET.

Acknowledgement

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