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# Engineering Experiences and Lessons Learned from 2023 Annular Eclipse Ballooning

**Zachary Owen Dickinson, Gannon University**

Zachary Dickinson is a Cyber engineering student at Gannon University, Erie, PA, and expected to graduate in May 2024. His areas of research interests include embedded systems and hardware security.

**Hannah Paige Jacobs, Gannon University**
**Sara Jones, Gannon University**
**Damien Thiên Ân Chu, Gannon University**
**Hunter Dawson Yaple, Gannon University**
**Mr. Andrew Donald Snowdy**
**Zoey McClain, Gannon University**
**Dr. Nicholas B Conklin, Gannon University**

Nicholas B. Conklin received a B.S. in applied physics from Grove City College in 2001, and a Ph.D. in physics from Penn State University in 2009. He is currently an associate professor and chair of the Physics Department at Gannon University, Erie, PA.

**Dr. Wookwon Lee, Gannon University**

Wookwon Lee, P.E. received the B.S. degree in electronic engineering from Inha University, Korea, in 1985, and the M.S. and D.Sc. degrees in electrical engineering from the George Washington University, Washington, DC, in 1992 and 1995, respectively. He is currently a full professor in the Department of Electrical and Cyber Engineering at Gannon University, Erie, PA. Prior to joining Gannon in 2007, he had been involved in various research and development projects in industry and academia for more than 15 years.

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*Zachary O. Dickinson, Hannah P. Jacobs, Sara M. Jones, Damien T. Chu,*
*Hunter D. Yaple, Andrew D. Snowdy, Zoey McClain,*
*Nicholas B. Conklin*, and Wookwon Lee*

*Department of Electrical and Cyber Engineering*
**Department of Physics*
*Gannon University*
*Erie, PA 16541*
*Email: lee023@gannon.edu*

## 1. Background and Learning Objectives

For more than fifteen years, high-altitude ballooning has been an attractive framework to promote technical and non-technical knowledge and skills to college students in STEM disciplines. Since 2009 in our institution, we have been actively accumulating experience and expertise in constructing various science and engineering payloads for high-altitude ballooning. Having successfully participated in the 2017 total solar eclipse nationwide ballooning campaign, we continued revising our ballooning framework for our ballooning program and for the upcoming solar eclipse events in October 2023 and April 2024. In late 2022, we were selected as one of the 53 teams for Nationwide Eclipse Ballooning Project (NEBP)[1] and in Oct. 2023, participated in a nationwide balloon flight campaign during the annular solar eclipse.

At the time of NEBP team selection, our ballooning framework consisted of several balloon payloads and ground stations. On the balloon side, our payloads were for multiple Pi cam-based video streaming[2], 900 MHz RF-based balloon tracking, 144 MHz APRS-based balloon tracking, 1.6 GHz Iridium-based balloon tracking, 2 GHz cellphone-based balloon tracking[3], and 2.8/5.8 GHz microwave downlinks for real-time video transmission. On the ground side, our equipment included a fixed ground station for receiving video streams and other sensor data and two mobile stations for tracking and recovery of the balloon payloads. For the balloon tracking, our mapping software included a local copy of Microsoft MapPoint for 900 MHz RF-based tracking and several on-line position-mapping software tools that are specifically associated with the Iridium-based tracking, cellphone-based tracking, and APRS-based tracking, respectively.

As one of the NEBP engineering teams, in early 2023, we had received a new set of balloon payloads and two ground stations from the NEBP leadership teams and this set of new equipment broadened our choices of technology for the 2023 annular solar eclipse and 2024 total solar eclipse. For the 2023 annular solar eclipse, among the various technology choices we had, we adopted the new set of NEBP equipment as the primary platform and worked on additional payloads. This paper describes our engineering experiences and lessons learned from preparing for and conducting the annular solar eclipse ballooning on Oct. 14, 2023 in San Antonio, Texas.

The goal of this solar eclipse ballooning project was in general to improve the quality of students' learning experience in an extracurricular setting at our institution. Toward achieving this goal, the SMART objectives of the project were:

1. (Specific) To engage students in high-altitude ballooning and design of payloads for live video streaming, balloon tracking, and science research
2. (Measurable) To provide research and engineering opportunities to at least five undergraduate students per year on average
3. (Achievable) To improve and sustain a framework for NASA mission-related laboratory experiments and project formulation for undergraduate student research
4. (Realistic) To complete the proposed projects within the project budget, with funds already secured from an external sponsor and other internal funds available to the team
5. (Time-bound) To demonstrate project outcomes by the end of AY 2023-2024

Our project team consisted of student members from freshmen through junior as of spring 2023. Students participated in project lab activities regularly for 5~10 hours/week, depending on their time availability. Students' activities were facilitated under close in-lab supervision of the two faculty members.

## 2. Payload Configuration and Integration

Figure 1 shows a functional block diagram of the NEBP ballooning system with additional functionality we added for APRS-based tracking and muon detection. The NEBP balloon system includes a cutdown and vent module, Iridium payload, RFD900 payload, Pterodactyl, and video payload. The ground system includes a balloon-tracking module, a 5.8 GHz dish antenna, a 900 MHz grid antenna, and a ruggedized laptop. The muon detector was prepared by a Physics faculty member from a partner institution for the balloon launch site and was for their experiment needing our balloon flight and thus its description is omitted in this paper. Having worked on developing these subsystems for a few years, the NEBP leadership teams provided detailed technical

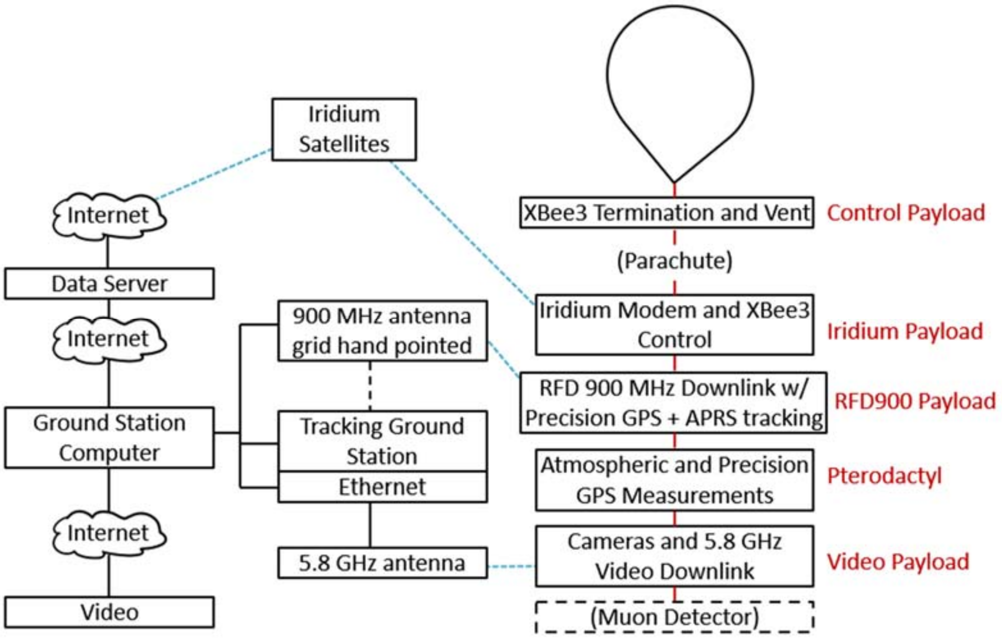

Figure 1. NEBP engineering system[5]

documentation of these subsystems[4] to assist new NEBP engineering teams that were tasked to assemble, configure, and integrate them, as applicable, into a complete ballooning system in a relatively short time-period of about 8 months in 2023. Our student members were assigned to a payload of their technical interest to assume the primary responsibility for its flight readiness. Collaboration was encouraged as needed among the students. The following subsections present our student members' work and experience, as well as lessons learned.

### 2.1. Iridium Payload and Control Commands for Vent and Cutdown

The Iridium Payload uses a Model 9602 LP Iridium satellite tracker[6]. This device is a pocket-size, low-cost, satellite tracker designed to operate with the Low Earth Orbit (LEO) Iridium satellite network. It is a lightweight, low-power solution to use GPS to track an unmanned balloon flight. As this device has capabilities for 2-way communication over the Iridium satellite network, it is also used for the remote execution of control commands during flight, most notably, the activation of the Vent module and the activation of the Cutdown module. Figure 2 shows a block diagram for the internal communication within the Iridium payload for these operations. When a command is received over the Iridium satellite network, it is communicated over the integrated serial port to the Optimized Command and Control Aerial Management System (OCCAMS). OCCAMS is a module developed by one of the institutions in the NEBP leadership teams.

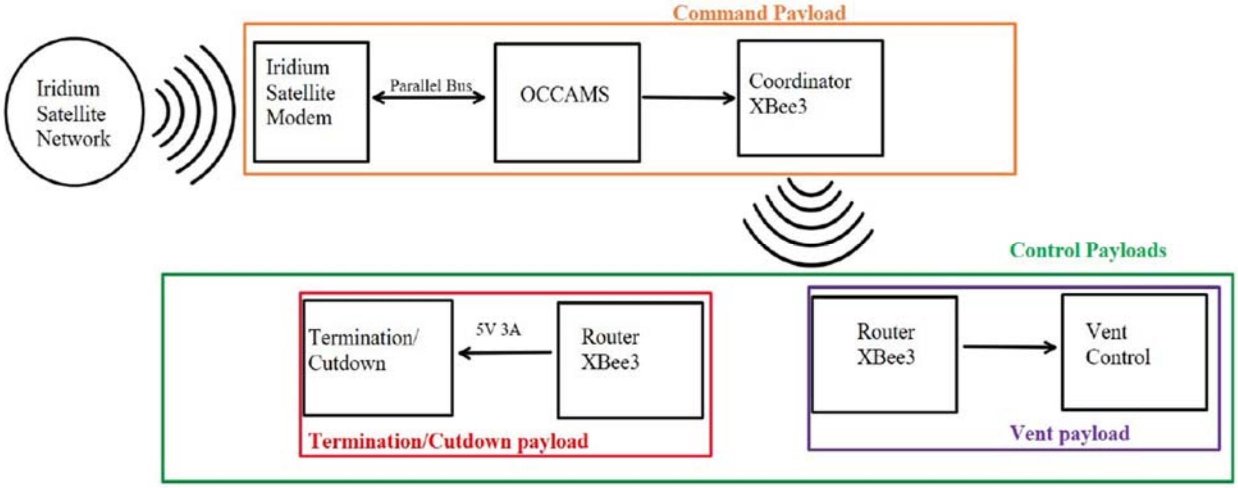

Figure 2. Iridium (Command) Payload communication with the Control Payload[7]

When a command is received by OCCAMS, it is interpreted and forwarded to the Vent and Cutdown modules using a Coordinator XBee3. The command is broadcast as 3 characters to both Router XBee3s in the Vent and Cutdown modules. When the modules receive the command for a defined action, the modules execute it. Only 4 Commands were used as shown in Table 1.

Table 1. Iridium Commands

| Command | Bits | Description |
|---|---|---|
| Idle | 000 | Used to reset the ability for cutdown. |
| Vent Open | 011 | Opens the vent to release Helium. |
| Vent Close | 100 | Closes the vent to stop releasing Helium. |
| Cut Down | 001 | Terminates flight; can only be used once. |

To verify the functionality of the supplied modules, the student members extensively tested the performance of each module. This included the verification of the configuration of all XBee3 modules to ensure reliable wireless communication among them. The Iridium modem was tested to verify that it could communicate with the satellite network and report location information. Subsequently, all modules in the Iridium and Control payloads were tested together to verify that commands are received and execute the expected operation.

In our testing, XBee3 communication among the modules worked seamlessly. The Iridium module, however, proved to be unreliable when tested at ground level. The modem would be turned on a clear cloudless day with the antenna pointed to the sky for upwards of 15 minutes before a location was recorded. The Iridium module had its configuration verified and compared to the Iridium module used on a previous flight in 2017 to ensure that it was not an issue with the module. Using online tools to check when satellites were in an optimal position above the testing site and moving to a higher elevation led to more reliable communication. All commands were verified to work and execute the expected action. A notable and unexpected outcome of the testing was that control commands could be received by the Iridium module even when it failed to transmit and report its location. This is important to note because, in the event where the cutdown, vent open, or vent close command is issued, there may not be information coming back to confirm that it was received.

There were a few anxieties regarding the Iridium tracking, but the consensus was that it should be reliable at altitude during flight. Ultimately, during the balloon flight we had a solid Iridium connection that allowed for near constant tracking once the balloon reached a high enough altitude. We were able to monitor location, altitude, and speed data on a website, hosted by one of the institutions in the NEBP leadership teams, that included flight information for all NEBP teams. This website hosted both real time flight data as well as logs of all previous flights. As the flight continued, we focused on the real time coordinates of the balloon as well as the recorded altitude.

For the annular eclipse flight, it was decided to not use the Vent after its failure in the first launch attempt. Due to this, the functionality of venting Helium or using the cutdown system was not usable during the flight. This left the Iridium payload to be used largely as a real time tracking system. At first, there was no Iridium satellite connection to the Iridium payload, but after a few minutes of flight, a strong connection was maintained. This connection lasted until the balloon was in its descent and it had dropped in altitude too much. This poor tracking ability near ground level was supplemented with a SPOT GPS tracker that was mounted to the top of the video streaming payload. Figure 3 shows our balloon flight path and Figure 4 shows balloon altitudes over time.

Another system that was heavily influenced by the Iridium payload and its tracking capabilities is the Ground Station. The Ground Station is a tripod mounted tracking system used to point a dish antenna to the Video payload as the balloon is in flight. This system used two servo motors, controlled by an Arduino Uno and a Python program running on a laptop, to set the angles that the antenna is pointed horizontally and vertically. The Ground Station is calibrated by setting it level in the field and pointing the antenna at the sun. Using the current GPS coordinates of the Ground Station and the position of the sun in the sky, it can automatically point the antenna to the last known location of the balloon as reported by the Iridium payload. This system includes a smart predictive tracking system that tries to predict the current position of the balloon based on its

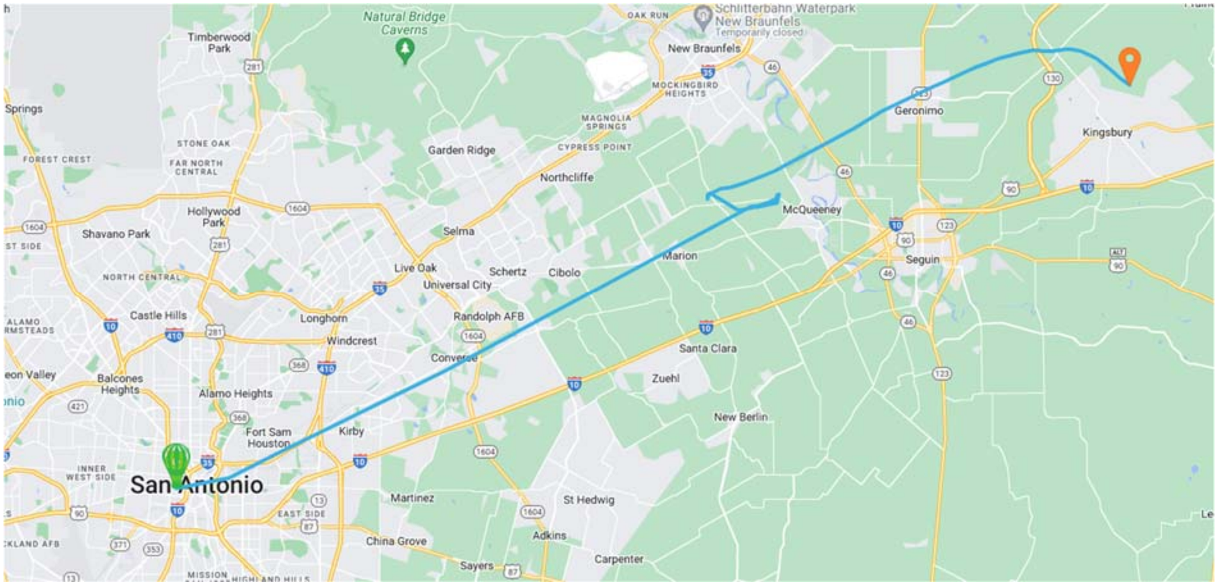

Figure 3. Balloon flight path

Figure 4. Balloon altitude over time

movements over time. Because the Iridium tracking system was unreliable for the first few minutes of flight, the Ground Station was unable to automatically track the balloon until it was a few minutes into flight. This issue was compounded by issues in receiving the video transmission and resulted in poor reliability for the video stream.

Lessons learned -- In this experience, the students gained a lot of working knowledge on satellite communication, GPS tracking, and wireless communication. This opportunity shined a new light on the strengths and weaknesses of the system. More work will be needed to ensure the full reliability of the system. On this payload, the team has identified multiple points of focus for their work to prepare for the April 2024 total eclipse.

### 2.2. APRS and RFD900 Payload

The RFD900x is a telemetry radio modem used for long-range data transmission, utilizing the unlicensed 902-928 MHz frequency band[8]. This modem was integrated with a data-collection board containing an Arduino Uno, sensors, and data loggers into a payload referred to herein as the RFD900 payload. Developed by one of the teams in the NEBP leadership, the RFD900 payload enables the transmission of data containing various information such as GPS coordinates, altitude, time, battery status, supply voltage, internal and external temperature, acceleration, pitch, roll, and yaw. The setup of the payload is shown in Figure 5. The radio modem and board were placed inside the payload with a pair of omnidirectional antennas attached to the modem via cables. The battery, RFD900 modem, and board were secured on the metal plate. This plate was housed inside of a payload enclosure. It is important to note that the antennas were connected to the RFD900 through to the underside of the metal plate and were kept inside of the payload. At the ground station for the RFD900 payload, another RFD900 modem was connected to a grid parabolic antenna known as "Griddy" and a laptop computer that was used to monitor in real time the incoming data as well as exporting them to a .csv file.


Figure 5. RFD900 payload set-up

The RFD900 payload performed well during ground testing. The data packets were received as intended and the accurate data appended to an output file in .csv format. During a tethered balloon-launch practice in San Antonio a day before the annular eclipse, the RF signal was transmitted and received successfully by the modems; however, inaccuracies in the data were observed. Notably, the GPS location received was about a mile off its actual coordinates. During the flight on the day of the annular eclipse, the telemetry between the RFD900 transmitter and receiver only lasted about 30min. The main challenge was orienting the "Griddy" antenna correctly toward the payload in flight, which became increasingly difficult as the balloon ascended and disappeared from sight. The loss of signal may be attributed to the loss of line-of-sight communication with the balloon. To ensure more reliable telemetry in future missions, a better solution for sustaining communication between the RFD900 payload and ground station receiver needs to be explored, along with further testing and optimization. Despite the limited data obtained, a MATLAB code was created to import and analyze the data in the .csv file. This gave the students valuable experience in using MATLAB as a tool for analyzing large sets of data in order to interpret experimental results.

Lessons learned -- Through the use of the RFD900 modem used as a method of long-range data transmission in the application of high-altitude ballooning, students gained experience in telemetry and data transmission. They learned about the intricacies of wireless communication, different frequency bands, and antenna designs and positioning to optimize the signal. Additionally, the students learned about data processing and analysis through using MATLAB to create a code that imports, processes, and analyzes the information collected. This experience is valuable for data-driven research that the students may go on to pursue.

Our RFD900 payload also housed an open-source Automatic Packet Reporting System (APRS) tracker called Tracksoar[9] shown in Figure 6. This device was not something that was provided by the NEBP leadership teams, but was included in the payload for our team to incorporate redundancy into the tracking of the high-altitude balloon. Tracksoar allows real-time transmission of data packets over the 144.390 MHz amateur radio band, providing tracking information and telemetry data such as altitude, temperature, and battery status via the APRS radio band. These

Figure 6. Tracksoar, an open-source APRS Tracker

packets are received by Digipeaters and then passed on to Internet gateways (iGates) which upload the information from the data packets online. The information can then be seen on various websites, including aprs.fi  through which the device can be tracked. The Tracksoar device is shown in . The configuration code for the Tracksoar is open-source and is aided by user-friendly instructions through Tracksoar's website. The only piece of the code for any change, in general, would for updating the default call sign with one for the actual HAM user. In our case, however, for a different purpose of using this device, in our previous experiments we had further edited the code to be able to use the location information from the device in either GNSS-based NMEA format or legacy GPS-based NMEA format. Either format can locate this tracker on the apri.fi map.

Ground testing prior to leaving for San Antonio was successful as the position of the device was properly tracked on aprs.fi. However, during the tethered launch practice in San Antonio, the device failed - the packets were not transmitted at all. Upon checking the supply voltage pins, it was found that the voltage provided to the input was significantly lower than the required 3 volts. This problem was fixed by, instead of using a 3.7V 5600mAh (or 10050mAh) battery connected to the battery connector on the board, using a small USB power bank connected to the configuration/serial USB port on the board to power the device. Upon fixing this problem, the device was again successfully tracked on aprs.fi as seen in Figure 7 which shows the trail of the device on Saint Mary's University campus in San Antonio during testing prior to the eclipse launch.

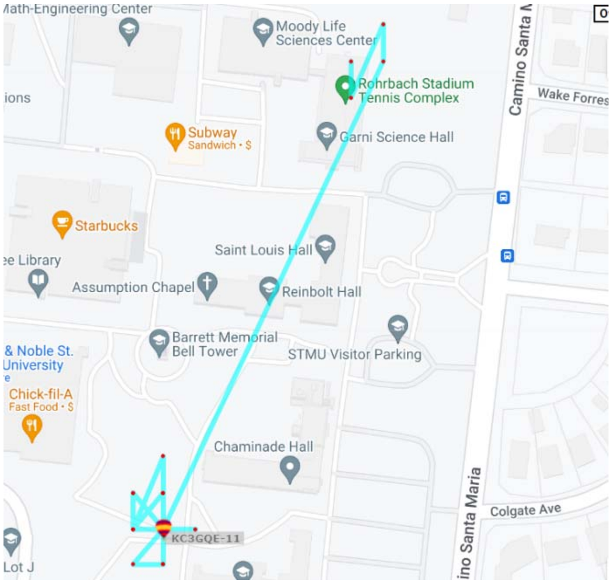

Figure 7. Map on aprs.fi showing the position of the Tracksoar during testing in San Antonio

Before the eclipse balloon launch, the antennas of the Tracksoar were repositioned to point outwards, out of the payload, and horizontal to the ground in order to achieve optimal performance for transmitting and receiving signals. Orienting the antennas this way allows for better ground level coverage because it prevents the signal from being emitted towards the sky or directly downward. This was noted during the tethered test launch when the team was investigating the initial failure of the device. During the solar eclipse launch, the signal from the Tracksoar was received; however, its GPS location was not available, i.e., invalid data, and thus, the device could not be tracked. From the post-analysis of the failure conducted by the team, it was concluded that the likely reason for invalid location information was that we placed the Tracksoar underneath the metal plate of the RFD900 shown in

Figure 5 and thus, the GPS receiver on the Tracksoar board could not see the satellites which subsequently resulted in a failure to report its location. This problem is expected to be an easy fix by placing the Tracksoar above the metal plate and likely on the payload enclosure's lid.

Lessons learned -- Through using the Tracksoar, the students' skills in tracking high-altitude balloons were improved. An understanding of APRS and amateur radio was gained through configuring the device and learning how the signals are transmitted to ensure that the data packets can be received optimally. The team also developed problem-solving capabilities when the Tracksoar failed during the test launch and alternative solutions had to be made on the spot.

### 2.3. Arducam-based Video Streaming Payload

As one of the NEBP-supplied payloads, this video payload was constructed during a workshop held during the summer 2023 in Hartford, CT. Two students and a faculty advisor attended this workshop. Returning from the workshop and working on configuring it in our lab on campus, we ran into a few issues with the video streaming payload. On hardware issues, the main problem was the Arducam multiplexer board which was for multiplexing two camera outputs into a single video stream. It seemed to operate on its own without any recognizable pattern or connection. In addition to that, the multiplexer board which sat on top of the Raspberry Pi4 and was very troublesome to disassemble when needed. It was important that the Raspberry Pi was properly configured and that the scripts were written correctly. After configuration settings and the scripts were confirmed correct, the team began working on the construction of the payload. When the team was working to mount the equipment inside a payload enclosure, it was quickly discovered that the cameras needed to be moved to get an optimal angle for the video feeds. The team decided to look into replacing the ribbon cables with longer ones so that the cameras could be dismounted from the metal plate and attached directly into the wall of the payload enclosure. This presented a challenge, however, because the ribbon cables between the camera and the Arducam board were a Pi zero-to-standard ribbon adapter and it was difficult to find the proper cables on the market. After procuring them with some effort, the cameras were finally placed on the foam payload enclosure for the lenses to poke out of the holes carved. Although this change in placing the cameras presented another difficulty in navigating around the payload components when any work was needed on them, the video footage was finally seen on the ground station receiver and the payload was ready for a ballon flight on the eclipse day.

While all functionality of this payload was verified the day before the eclipse day, on the eclipse day during the preparation for a balloon launch, the team ran into another issue. That is, the team was not being able to access the video-streaming Raspberry Pi from the ruggedized NEBP laptop which was dedicated to video reception and forwarding to our YouTube channel set up for broadcasting of the launch and flight video. In a panic mode as the timed launch was in a matter of minutes and things were getting down to the wire, the team was ultimately able to determine the cause of it and resolve the issue which turned out to be that, among three laptops connected to a new Wi-Fi router the team procured the day before to better facilitate the balloon launch operation, one of them was using the same static IP address as the one already assigned to the NEBP laptop.

Lessons learned -- Overall, the students learned a lot about electronics and the engineering process through hands-on experiments and critical thinking. Also, it has been a great way to learn about working with other people and how people can react differently under pressure. The knowledge and experience the students acquired from this project can only be found outside of the classroom and from hands-on experiments with details. Not only is this a way for students to engage in something outside of class, but it also teaches them valuable life lessons that they can employ in their future.

### 2.4. Pterodactyl Payload

Developed by one of the teams in the NEBP leadership, Pterodactyl stands for Payload To Enable Recording Of Data and Communication Telemetry Y(While) Lofted. The purpose of the Pterodactyl flight computer is to record data from the balloon launch onto an onboard SD card so that it can be reviewed after the payload is recovered. The sensors on Pterodactyl capture a variety of data types including time/date (down to the second), coordinates, altitude, internal and external temperatures, pressure, velocity/acceleration, and orientation/angular velocity. The electronic components used in the pterodactyl are ublox M9N GPS, MS5611 Pressure Sensor, Sparkfun OLED Screen, 10k Ohm Thermistor, and BNO055 Internal Measurement Unit.

When the project was introduced to our team in the spring of 2023, the computer was already assembled; however, there were some issues that came up. First, the onboard OLED screen was broken, making setup without the use of an external computer impossible. This was an easy fix as a new screen was ordered and it worked without problems. After that the thermistor broke which caused multiple components of the device to not function properly. Once a new thermistor was ordered and installed the device was once again functional. One of the biggest reoccurring issues with the device was the length of time it took to acquire a signal from satellites. It could take several minutes to acquire a signal; however, the M9N GPS that was being used should be able to pick up a signal in a fraction of the time. It turned out that one of the components on the pterodactyl was causing interference to the GPS. To fix this, the GPS was moved off the board and connected with wires instead of plugging directly into the pterodactyl. Once this fix was implemented the GPS performance improved drastically. Over the course of several months, the pterodactyl code was updated by the creators to work better and some slight modifications were made by our team to better cater to our needs, such as more specific coordinate values and easier on device setup.

During our testing in San Antonio, the Pterodactyl worked as intended as we obtained a data file post launch from the onboard microSD card with the recorded information. According to the file, the pterodactyl recorded data for 46 minutes and reached an altitude of over 59,000 feet before it stopped recording. The file had a very large amount of data, so in the future it may be beneficial to record data every couple of seconds instead of multiple logs per second in order to make the data easier to navigate. This should be able to be done fairly easily by modifying the code.

### 2.5. Webcam-based Video Streaming

This video payload was not part of the ballooning payloads provided by the NEBP leadership teams, but was implemented and tested as an optional payload for our team to incorporate redundancy in real-time video streaming. This video streaming payload operates by recording video from the Raspberry Pi Cameras and sending that data to a ground station via Rocket M5 radios. This process is facilitated through Linux-based script files, which manage video streaming during the flight. A primary challenge in operating the video payload revolved around acquiring the skills necessary in using Linux on the Raspberry Pi. This was essential for navigating the

Raspberry Pi file system, analyzing the system, and creating and editing script files for video streaming. It also involved configuring the correct IP address on the Pi to ensure that the ground station received video from the intended source. Understanding how the Raspberry Pi recognized the cameras was another crucial aspect. We had encountered a few issues in how the Pi Cameras were being recognized, which meant our script files applied to a different video port than the one being assigned to the camera. Rectifying these issues allowed for our students to become more skilled in navigating Linux and operating the Raspberry Pi effectively.

Properly configuring the M5 radios was essential to stream video from the video payload to the ground station. The access point M5 was connected to the video payload to go with the balloon during a ballon flight. The data from the video payload was then transmitted to the second M5 attached to the ground station. The M5s needed to be configured so that they were able to properly communicate and transmit data. The video scripts on the Raspberry Pi took the video from the Pi Cameras and created a VLC video to be streamed to OBS on the ground station computer. It was necessary to understand how to operate VLC and configure the application to receive video from the desired destination.

One of the main objectives in our use of the video payload was to stream video from more than two Raspberry Pi Cameras in order to capture more angles of the solar eclipse during the flight. However, we faced some challenges in reducing the amount of data being transmitted in a certain period of time. If the video scripts used too much data to transmit the video, the resulting video on OBS would be pixelated and laggy. Therefore, there was much fine tuning in determining how many Raspberry Pi Cameras could be placed on a single Raspberry Pi without sacrificing the quality of video. We have been combatting these issues by editing the script files to make the videos take up less data. The effect of the changes was analyzed on both the Raspberry Pi, the M5s, and the ground station computer. The lag and pixelation were viewed directly on OBS in comparison to the amount of data being transmitted from the access point M5 to the ground station M5. These results were tested based on how many cameras were being run, resolution of the video being transmitted, and the video streaming script being used.

Another issue involved the amount of power being used by the payload overall on the flight. The Raspberry Pi and M5 needed to be able to operate for the desired amount of time with the battery power able to be supplied. The effect of the video streaming set up on the CPU usage was analyzed using Linux in order to optimize the amount of power being consumed by the payload within a given time frame. Since we wanted to stream from multiple cameras, it was necessary to limit the amount of weight created by the payload. Using Fusion 360, the base for the payload was designed to maintain the required amount of strength so as to not break with 10Gs of force applied while being as light as possible. Our design was then laser cut and tested by applying ten times the expected weight to the base on standoffs.

### 2.6. 3D-Printed Vent Unit

The Vent unit is a 3D-printed module that connects all the payloads to the balloon. It also houses the actual venting apparatus for the helium and the cutdown system for the balloon itself. This allows commands to be sent from the ground to the balloon to control the altitude of the balloon and drop altitude. The vent and the cutdown systems utilize the Iridium satellite system to receive commands from the ground.

The entire housing was 3D printed. The files were sent by one of the NEBP leadership teams to all the NEBP teams to utilize. The parts were printed using PETG plastic and were put together using various metric screws, nuts, washers, eye bolts, and standoffs. The openness of the design made it easier to take apart, albeit very meticulously. This made it easy to install the servo motor and the servo control board. The cutdown board, on the other hand, had its own housing to protect it from the elements. The vent mechanism is a door connected to the servo motor with a sturdy metal wire, shown in Figure 8 as (1). The wire itself is bendable enough to shape, but sturdy enough to keep straight when opening the door.

Most of the assembly was done in our lab. However, some of the setups had to be done on the launch site. During testing and launch, the balloon neck was attached to the neck of the unit and fastened with two zip ties. The first zip tie was solely to fasten the balloon to the neck. The second zip tie was to further fasten the balloon to the neck, as well as anchor for another two zip ties to function as loops for a tether line that ran from the ground to the nozzle and back to the ground. The loop zip ties and the tether line are displayed in Figure 8 as (3) and (4). The neck of the unit was then attached to the body using a set of three identical clamps. Two zip ties were used to connect them together, displayed in Figure 8 as (2). The final holes for the clamps were used for the cutdown string. Another zip tie was used to secure the clamps to the main body of the vent, also displayed in Figure 8 as (2). This allows the clamps to drop down and hang from the vent instead of falling completely off, negating the need to print more. The cutdown string was weaved through the holes in the housing and through the cutdown board. The slack end of the cutdown string was then tied to an eye bolt at the bottom of the unit. Now the unit is ready to be sent up with the balloon payloads.

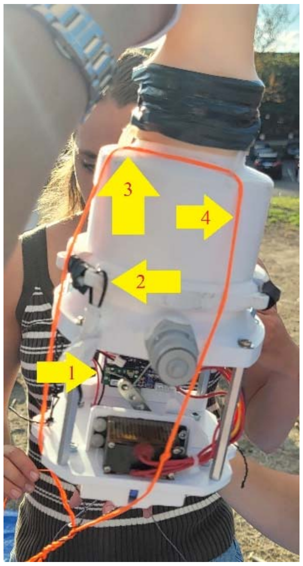

Figure 8. Test vent unit

The entire unit relies heavily on the Iridium payload. This is how it communicates with the ground. For the vent/cutdown specifically, emails are sent with commands to the Iridium satellite from the ground. From there, the satellite communicates with our Iridium payload. After that, the payload communicates with one of the two XBee3 radio modules on the unit. If venting, the Iridium communicates with the XBee3 on the servo controller board to open/close the vent door. If cutting down, the Iridium communicates with the XBee3 on the cutdown board. Once either XBee3 receives the command, the vent opens/closes or the string for the cutdown system is burned.

Lessons learned -- Problems occurred during the launch of the payloads in San Antonio, Texas. During initial testing, the procedure was to string the clamps together, run it through the cutdown board and the housing, and tie it to an eye bolt. The next step was to fully tighten the zip ties that were holding the clamps to each other. This made sure tension was kept on the cutdown string, ensuring that it would keep contact with the nichrome wire on the cutdown board. During tests, no issues occurred so it seemed that the procedure was safe to do during the launch. However, during the actual launch, the cutdown string snapped. This caused the clamps to let loose and disconnecting the balloon/nozzle and the payloads. Another point of failure was the tether line loops on the nozzle. The loop zip ties for the tether line were small and this caused problems when pulling the balloon back to the ground. For the launch, the zip tie loops were made larger to fix the issue of the tether line knotting itself while holding and pulling. The loops snapped and the tether line was disconnected from the balloon/nozzle. During future launches, a third zip tie will be added specifically to anchor the loop zip ties. The loops will also be made a bit smaller to minimize the force that is acting on them, as well as maximize the area to allow the tether line to freely move without knotting itself.

## 3. Balloon Launch and Payload Recovery

### 3.1. Lessons Learned from Balloon Launch

Many challenges were faced during the 2023 annular eclipse balloon launch. Despite this, it amounted to a successful launch and a multitude of lessons learned. There were two launch attempts, one aligned for the eclipse, and an attempt hours later. The initial launch proceeded nominally up until a moment of catastrophic failure. The following attempt implemented a last-minute correction, fostering a successful launch. For the duration of the initial launch, almost everything went well. From setting up to releasing the balloon, there was plenty of time to test and correct. The only payload that struggled was the Iridium, and this was due to low elevation; therefore, nothing could be done until it gained altitude, and a connection was made. Strings were meticulously set up to hold the payload down during inflation. The inflation was speculated to have been slightly too much - after calculations the balloon was determined to hover a 19 lbs bag at a foot (labeled 2 in Figure 9) to obtain proper altitude. It was difficult to tell due to wind and potential human error.

Other lessons from the first launch include paying attention to the minute details. For instance, zip tie direction, string loop sizes, sharp edges, over tensioning and releasing order. The main point of failure for the first launch was the cutdown string. It is hard to say why, maybe there was too much tension, sharp edges, or too large a thrust force unaccounted for. The zip ties for the secondary string (labeled 1 in Figure 9) also snapped causing the balloon to fly off with nothing but a 3D printed cutdown part. This led to the rest of the payloads to fall from roughly 50 ft and resulted in some slight damages. After the fall of the initial launch, there were issues with the video payload. One of the cameras stopped functioning, and with little time to correct, the payload was launched with only one camera sending its video. After further inspection, it seems to have been an issue with the cable.

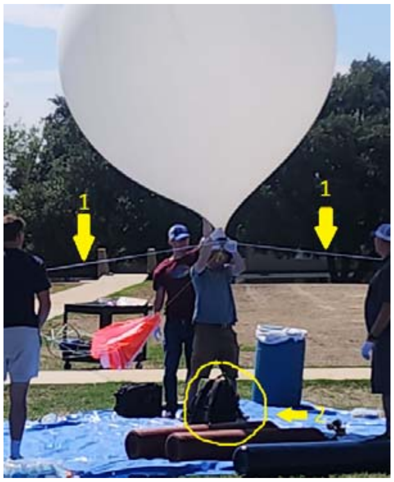

Figure 9. Balloon tethers

The main adjustment for the second attempt was using a traditional balloon seal. It was used on previous launches and involves inserting a PVC pipe inside the balloon neck as support and then zip-tied to hold in place. Next, folding the balloon neck back onto itself with more zip ties to seal. Another modification for this launch was that zip ties for the hold-down string were doubled making no chance of breaking. Lastly, the Insta360 camera was moved under the parachute due to foreseen issues on the first launch attempt. All of these corrective actions amounted to a successful launch.

### 3.2. Payload Recovery

The payload recovery was not ideal, yet it could have been much worse. The balloon landed on a private farm. Luckily, there was a car passing by who knew the owners, eventually allowing us to get on the property. When walking roughly a mile to the last location the payloads transmitted, it was noticed that they were stuck in trees out of reach. There were many different tactics utilized to obtain the payloads. It is evident from Figure 10 that the distance to the payloads was our issues in recovery. The highest payload was roughly 30-40 feet in the air. The main solution used to get the payloads down was a telescoping pole. This pole, along with various items attached to the end such as carabiners, a grappling hook, string, and various tape helped to grab the payload and surrounding strings to rip them down. It was not the best way to recover, but it was the best tool at our disposal. In the end, the team managed to recover every payload just before dusk. The payloads did not seem to take significant impact damage; however, there may have been some slight damages while pulling them down from the tree. It is hard to say for sure where some of the payload damage came from. There were broken antennas, bent metal plates inside some payloads, and some split wires. Overall, the damage was not severe.

Figure 10. Recovery attempt

Lessons learned -- Some improvements that could be added for future recoveries include new attachments for the telescoping pole. The grappling hook was a useful design but weighed too much, deeming it nearly useless. Something light with a hook on the end would be ideal for getting payloads out of trees. The grappling hook attached to a rope was not utilized due to the potential risk involved and inaccuracies.

## 4. Concluding Remarks

We have presented a comprehensive overview of our annular eclipse ballooning project, outlining the objectives, the technological advancements, and team's approach to integrating several payloads and ground stations into the ballooning framework. From various stages of success and failures during design as well as balloon launch, tracking, and recovery, student’s learning experience was substantially improved beyond what would be covered in classroom settings. Further improvements are due for the upcoming total solar eclipse ballooning in 2024, but students are well positioned to apply lessons learned to make the upcoming event more successful.

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