USC Wide Angle Navigational Kinetic Eclipse Photography

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Abstract

The University of Southern California Astronautical Engineering department, with generous funding from the wider Viterbi School of Engineering, set a goal of photographing the US solar eclipse in April 2024 from a payload flown on a helium high-altitude balloon. A USC team consisting of students across several academic levels successfully completed this objective. Several GoPro models and a Sony RX0II were configured to photograph the eclipse from a range of angles, as well as the wider high altitude environment. Monte Carlo methods were employed to predict and characterise the trajectory undertaken by the flight. Atmospheric conditions such as historic wind and humidity data were utilised to predict ascent rates, bursting altitude, crossing of totality, parachute-aided descent rates and subsequent sigma distributions for likely landing sites. In keeping with local laws and Federal Aviation Administration (FAA) regulations, subsequent analysis concluded that a launch from near San Antonio, Texas provided the most optimal and safe flight path that fulfills the mission requirements. The landing zone was calculated to be within the greater Fredericksburg, Texas area. Despite complications during the launch, owing to especially strong winds and thus overinflation of the balloon, the final landing site lay within the three-sigma landing predictions, demonstrating a successful analysis.

Eclipse Photography | High-Altitude Ballooning | USC | Monte Carlo Simulations | Atmospheric Conditions | Prediction Software | 2024 Solar Eclipse | USC Eclipse Ballooning

Introduction

In late 2023, The University of Southern California Astronautical Engineering department and the wider USC Viterbi School of Engineering began making preparations to assemble a team which would track the Total Solar Eclipse taking place on April 8th, 2024, the last opportunity to track an eclipse in the continental United States until the mid-2040s. The following sections contained in this paper describe USC's 2024 eclipse ballooning efforts, from project conception to launch day activities and results.

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Mission Planning

Site selection for this project consisted of two major components: low-fidelity simulations using historical winds to identify a general launch/recovery region several months in advance and high-fidelity simulations in the week prior to the eclipse to identify a specific optimal launch site and corresponding dispersion area. The 2024 Total Solar Eclipse passed through the United States, starting in South Texas heading northeast towards Maine, and with a path of totality over 100 miles wide, a plethora of potential launch sites had to be considered. Texas was immediately selected as the launch location for its proximity to Los Angeles, reducing transportation time and costs. To select a launch site within Texas, historical weather conditions were investigated to determine the probability of rain and cloudiness during the balloon launch. Fifteen years of hourly historical weather observations (METARs, or Meteorological Aerodrome Report) recorded at six airports throughout Texas in the Dallas (AFW, DFW, and DAL), Austin (AUS), San Antonio (SAT), and Del Rio (DRT) metropolitan areas for the month of April were analyzed.

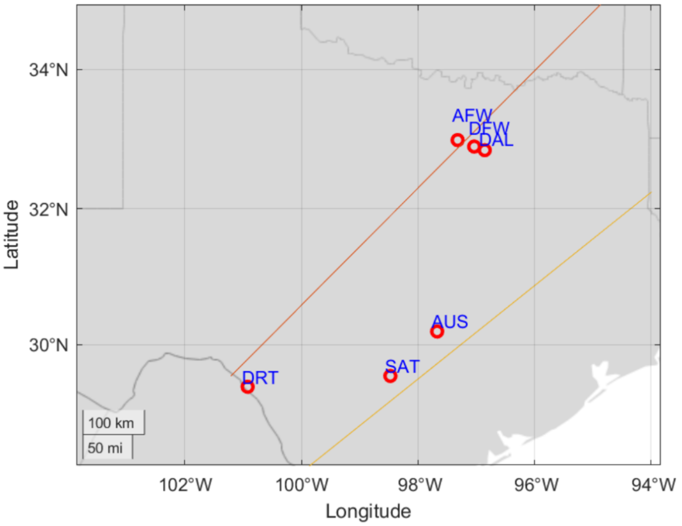

Fig. 1. The airports from which historical weather data was obtained

The chance of rain was computed as the probability that any amount of measurable precipitation was recorded in a given hour of data. The chance of "cloudiness" is the probability that 3/8ths or more of the sky was recorded as obscured by clouds (eighths is the convention used in aviation for cloud coverage, with 3/8 or greater coverage corresponding to “scattered,” “broken,” or “overcast” conditions being reported).

Both rain and "cloudiness" were the primary determining factors for launch site selection. Rain could pose a risk to electronics (less likely) or add additional weight to balloon stacks (more likely), therefore compromising a launch. Cloudiness, while likely not a cause to scrub a launch itself, can obscure the sun from observers on the ground and thus reduce their chances of getting a good view of the eclipse. Less cloudy areas are also generally less likely to have rainfall. Clouds with convective activity can also unpredictably affect the ascent rate of the balloon (e.g. updrafts and downdrafts). Therefore, Del Rio was identified as the best potential launch site due to the dry climate and lowest probability of cloud cover.

Site	Probability of Rain	Probability of Cloudiness
AFW (Alliance-Fort Worth)	0.057	0.52
DFW (Dallas-Fort Worth)	0.060	0.50
DAL (Dallas Love Field)	0.050	0.49
AUS (Austin)	0.046	0.54
SAT (San Antonio)	0.052	0.55
DRT (Del Rio)	0.021	0.30

Table 1. Probability of rain and cloudiness at selected sites in Texas

With the Del Rio region selected as the launch area, historical dispersion analysis was conducted. With these lower-fidelity simulations, the flight was modeled with two stages: the balloon ascent stage and the parachute descent stage. For the ascent stage, a constant 5 m/s (1,000 fpm) ascent rate for the balloon was used from launch until it burst at about 30,000 meters (98,500 ft), approximating performance values for balloons at the scale of this project. The parachute stage assumed a parachute sized such that the payload (of arbitrary mass and dimensions) would land at 5 m/s with the payload descending at the terminal velocity at every altitude during its descent. Four years (2020-2023) of historic winds for the month of April (120 days total) were downloaded from the NASA Merra-2 database, a global historical weather archive of 4-dimensional (across latitude, longitude, altitude, and time) wind and atmospheric properties. For each day, the historic winds were found from this database for the Del Rio, Texas region at 1200 CDT (approximate launch time of the balloon). A nominal flight using the assumptions above was then simulated for each day and the landing area recorded. These dispersions cover an extensive range because historic winds have significant variability. However, these dispersions informed potential landing areas for recovery planning and launch site selection, suggesting that a launch site south of Del Rio was optimal, though a range of potential launch sites had to be identified to account for other various wind conditions and to avoid landing in potentially inaccessible areas, such as in the hills south of Interstate 10.

A higher-fidelity, physics based simulation software was developed in Python for launch-day trajectory analysis. This software computes the net force on the balloon at each timestep, and integrates using Scipy's RK45 integrator to find the time series state vector representing the motion of the balloon. The flight is modeled with two stages: a balloon ascent which terminates when the balloon radius exceeds the specified burst radius, and a parachute descent stage which terminates when the payload hits the ground. The physics-based approach allows easy implementation of Monte Carlo simulations by varying the payload mass, helium mass, balloon burst radius, parachute drag, and balloon drag, which were used to generate the dispersion area of the balloon. During the ascent stage, three forces acting on the balloon are modeled. Note that all are given in vector notation in the NED (north, east, down) frame. The buoyancy force is given as a function of position and time by:

$$\vec{F}_{buoy} = -\frac{4}{3}\pi r^3 \rho_{amb}\vec{g}$$

where r is the radius of the balloon, ρ_{amb} is the density of the ambient air, and $\vec{g}$ is the local gravity vector. The net aerodynamic (drag) force on the balloon is given by:

$$\vec{F}_{aero} = \frac{1}{2}C_D \rho_{amb} S_{ref}\vec{v}|\vec{v}|$$

where C_D is the drag coefficient of the balloon, S_{ref} is the cross-sectional reference area (assumed to be the circular cross-section for a spherical balloon), and v is the relative wind to the balloon (defined as the difference of the wind and balloon velocities). Finally, the net gravitational force is given by:

$$\vec{F}_g = m\vec{g}$$

where m is the mass of the balloon material, helium, and payload. The motion of the balloon is then determined from Newton's Second Law using the sum of these forces as the net force acting on the balloon. During the parachute descent stage, the buoyancy force is zero, while the aerodynamic and gravitational forces are computed by the same equations above with appropriate corresponding values of S_{ref}, C_D, and m. For each stage, the atmospheric conditions were found at the given altitude assuming International Standard Atmosphere (ISA) conditions. Wind is found as a function of altitude by interpolating the input wind profile. The results of these higher-fidelity simulations using launch day and time forecast winds from the National Oceanic and Atmospheric Administration (NOAA) High-Resolution Rapid Refresh (HRRR) model are plotted with 3-sigma dispersions in Figures 3 and 4.

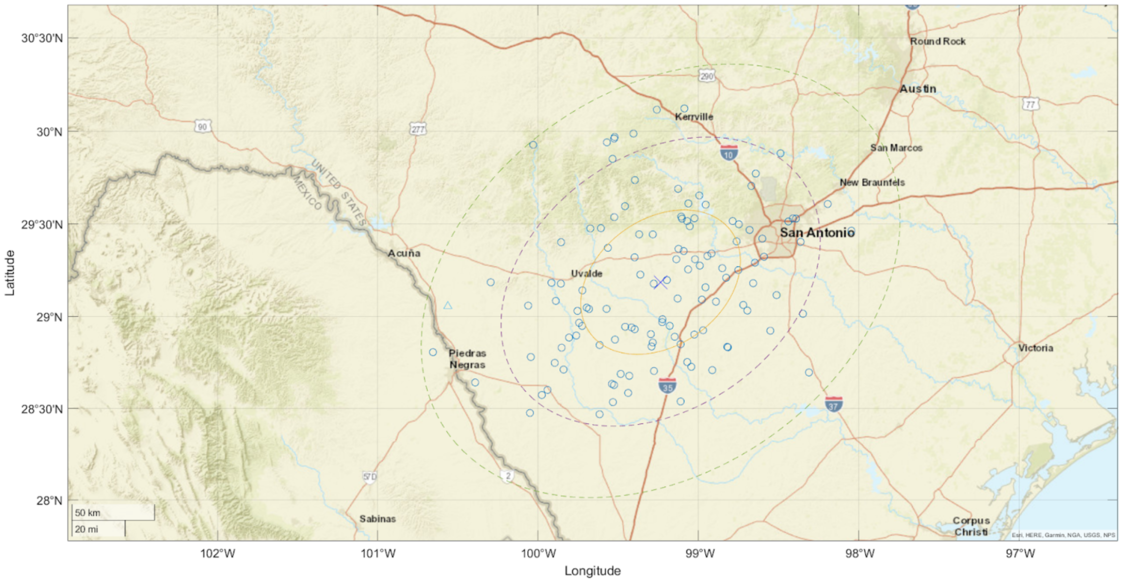

Fig. 2. Historic wind dispersions for Del Rio, Texas

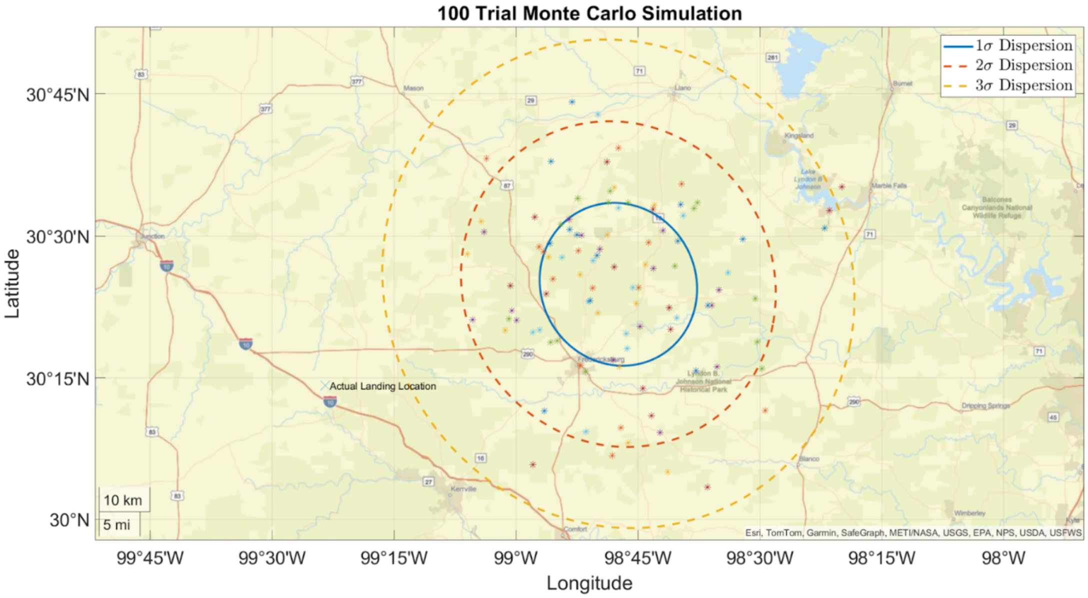

Fig. 3. Higher-fidelity launch day simulation results with 3-sigma dispersions

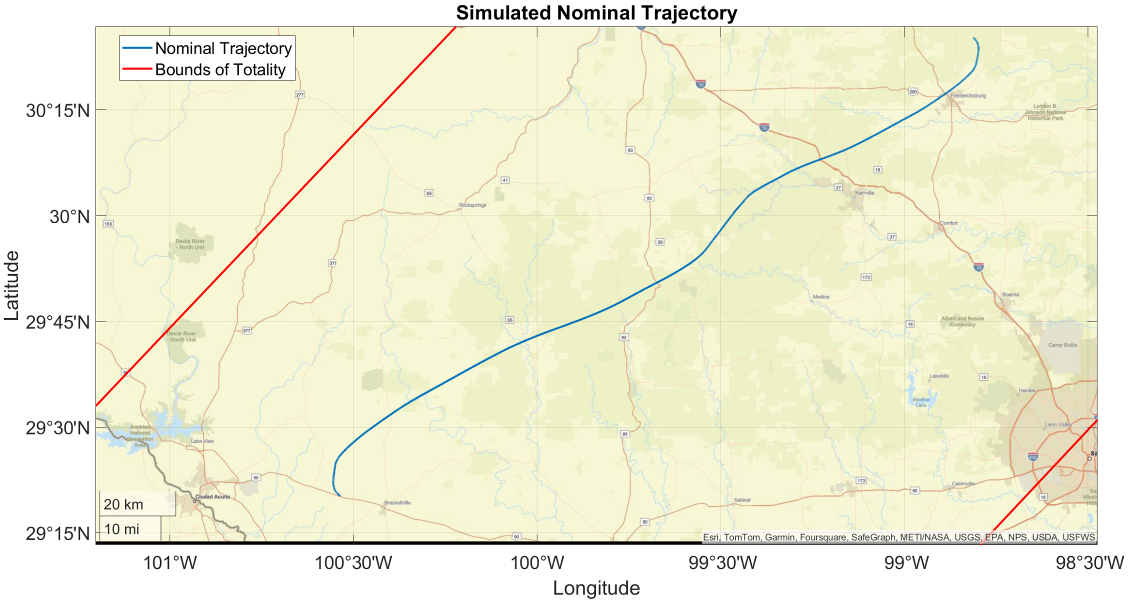

Fig. 4. Higher-fidelity launch day trajectory simulation from the actual launch site

Ultimately, a launch site east of Del Rio (different from the one used for historical dispersions in figure 2) was selected due to a more north-easterly jet stream at the time of the eclipse, necessitating a more easterly launch site to ensure landing in an accessible location for recovery. This launch site also allowed the balloon to travel parallel the path of totality. The actual launch site used is reflected in the dispersions shown in Figures 3 and 4.

Post-Flight Trajectory Analysis

The actual ascent time measured by onboard footage was 100.6 minutes (consistent with the predicted ascent time) and the descent time was 42.3 minutes. Since the parachute tangled during descent, the descent rate was about 17% faster than predicted (with a nominal descent time predicted as 50.9 minutes). This meant that the payload landed short of the predicted landing area, and even the 3-sigma dispersion could not capture the anomalous flight path. However, the nominal dispersions are not representative of the actual flight dynamics because the parachute produced less drag during descent in its tangled state. We can estimate the effective drag coefficient of the balloon by matching the simulated and actual descent times (assuming that the balloon burst at its predicted apogee), which suggests an effective drag coefficient of approximately 0.68. With this assumption, the dispersions assuming a tangled parachute are as such:

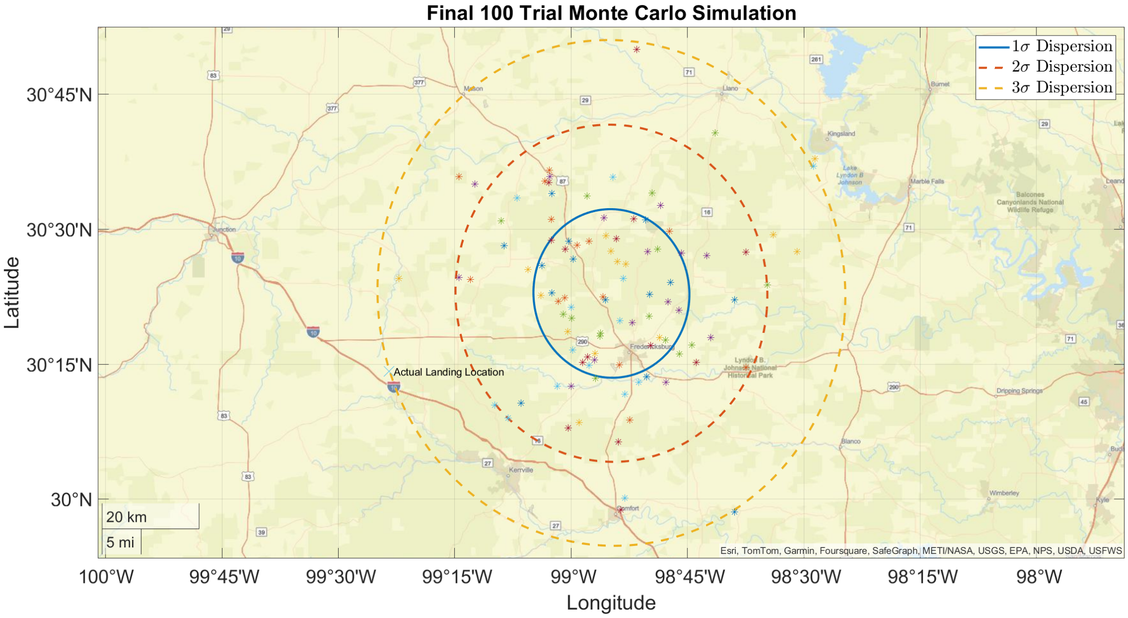

Fig. 5. Dispersion analysis taking the tangled parachute into account

Based on these final dispersions for the balloon assuming a tangled parachute, the payload landed within the 3-sigma dispersion about 35 miles southwest of the predicted landing location. Because no telemetry was received during flight, it is not possible to determine what other factors may have contributed to a southwesterly landing location. It is possible that true winds differed from wind forecasts, the balloon was overfilled due to strong surface winds impeding our lift measurements, or that the Monte Carlo parameters were too liberally assumed and should be varied to increase the dispersion area.

System Design

Several different options were considered when initially designing the flight system, including a venting and termination subsystem to provide a wider variety of possible mission profiles, but ultimately a relatively simple one-balloon design without a venting system was chosen to reduce complexity, uncertainty, and risk, particularly with the relatively short development timeline and the limited time available for test flights to essentially certify the system. For many of the same reasons, a decision was made to not include video telemetry from the payload. The following section describes, in detail, the finalized USC HAB Payload Architecture, providing a systems-level description of the ballooning payload.

The primary goal of the mission was to acquire footage and images of the eclipse, hence the camera selection was one of the first and more important design considerations when making payload design decisions. The balloon's primary camera system consisted of a single Sony RX0 II compact camera. With its 1-inch sensor and 24mm lens, the RX0 II was the highest quality compact camera available and it was mounted on one of the two identical carbon-fiber camera booms to provide a view of the balloon along with the sun and eclipse in frame. The RX0 was to be mounted on a gimbal system to make sure that the eclipse remained in frame regardless of balloon motion, but due to last-minute technical issues, the gimbal was removed from the design and the RX0 II was mounted statically on the boom during the actual eclipse. This still worked well since the footage obtained included not just the eclipse but the balloon in-frame at the same time as the eclipse.

The three backup cameras provided a redundant method of capturing the eclipse had the primary camera failed and also provided secondary views during flight. The backup cameras consisted of two GoPro Hero 11 Minis and a GoPro Hero 10, which were selected for their relatively high-quality video and wide field of view. The Hero 10 was mounted statically on the second carbon fiber camera boom, opposite the Sony RX0, angled so that it captured the "selfie-style" view of the payload and balloon in front of the eclipse. The GoPro's wide FOV enabled it to relatively easily keep the sun in view without a gimbal system, regardless of the payload motion. This camera was chosen for its removable battery which helped to prevent overheating in-flight. The GoPro Hero 11 Mini's were mounted on the payload's exterior at an approximate 45-degree angle toward the ground, both mounted opposite each other. These cameras captured footage of the eclipse's shadow moving across the ground as well as additional footage of the balloon's ascent and descent phases.

APRS and SPOT Trackers were used to track the balloon stack, with a QRP Labs LightAPRS tracker being the primary tracking system. This fully integrated tracker is capable of transmitting GPS coordinates, altitude, and basic atmospheric data on both the 2m and 20m amateur radio bands in 30-second intervals at an output power of 144.39MHz. The goal was to have these packets be received directly by the base station, but with the optionality of still being able to be received and relayed by publicly available receivers on the APRS.fi network for added redundancy. On the 20m amateur radio band, the LightAPRS was set to transmit WSPR packets consisting of a maidenhead locator; the packets would be received by the nationwide WSPRNet network and serve as a redundant tracking method.

The transmitting antenna utilized by the LightAPRS consisted of a $\frac{1}{4}$ wavelength monopole antenna with 4 radials. The antenna was mounted to the bottom of the payload box with the radiating element of the antenna pointing vertically downwards toward the ground and measuring 49.3 centimeters in length. The radials were 55.3cm long and extended perpendicularly to the radiating element until meeting the edges of the payload box, where they bent at a 45-degree angle upwards. All antenna elements consisted of 2mm brass tubing for weight savings.

The base station receiver on the ground consisted of a similar $\frac{1}{4}$ wavelength monopole antenna with 4 radials, constructed much the same as the payload antenna. The antenna was mounted to an 8-foot PVC pipe which was then inserted into and supported by the stake pocket near the back of our rented pickup truck when tracking (else, when driving, this was taken down and the antenna was then removed from the PVC pipe and pointed through the sunroof if tracking in the car). The radio receiver used was a Kenwood handheld radio and its audio output was connected to a laptop computer running Direwolf Model Software to decode our balloon's APRS packets.

The backup tracking system consisted of a single SPOT Trace satellite tracker. The SPOT Trace was fully independent from the balloon's other systems, containing its own battery, GPS receiver, transmitter, and antennas. The SPOT was programmed to report the payload's GPS position and altitude through the globalstar satellite network at 5-minute intervals. As a backup redundancy, packets with GPS coordinates were guaranteed at least once every 24 hours if the primary system failed (a feature which was ultimately crucial for this specific mission). Both position reports were made available through SPOT's app.

In the case of the actual eclipse flight, the APRS system failed but the 24-hour SPOT Trace sent a ping the next morning nearly 24 hours later, which resulted in prolonged but ultimately successful recovery efforts of the balloon. Another USC student group re-flew the same APRS antenna shortly after and it also failed, so efforts will be made to utilize a different APRS system and additional backup redundancy in future flights.

Power for the main payload was provided by a 24 amp-hour USB Battery Pack. This battery provided power to the balloon's camera and tracking systems throughout the duration of the flight. Payload systems were connected through standard USB Type-A cables, since vibration and cable strain weren't a concern for the flight.

Three of the four cameras (the Sony RX0, the GoPro Hero 10, and one of the two GoPro 11 Mini cameras) were powered by the main battery bank, with the fourth, the second GoPro Hero 11 Mini, still running on its internal battery (which ultimately overheated less than 30 minutes into the flight). The Sony RX0 has a limited internal battery life, so external power was a good workaround for this and it also limited the risk of camera failure due to the internal battery either overheating or getting too cold. The GoPros were connected to the battery bank via a USB power splitter while the RX0 used a port directly on the power bank. In order to mitigate an overheating issue experienced with the GoPro Hero 11 minis during testing, caused by an unremovable internal battery when connected to an external battery source, one Hero 11 was run solely on internal battery power. Additionally, the LightAPRS was also powered by the main battery via a USB breakout board.

The payload box primarily consisted of a styrofoam cooler measuring approximately 10 inches on each side. This was the main structure on which the booms and antenna were mounted with the electronics and battery being housed inside the main payload box for insulation. As mentioned earlier, two carbon fiber booms extended down at 45-degree angles from opposite sides of the payload box to provide the primary vertical and “selfie stick” views of the payload, balloon, and eclipse in the same frame for the primary Sony Camera and the GoPro Hero 10, respectively. A combination of Kevlar Twine, Bungee Cords, and Braided Mason Twine was used to connect four corners of the payload box to the 2000g Kaymont Balloon Neck. Key Rings from “Michaels,” which have demonstrated much better performance in stratospheric conditions compared to key rings from vendors such as Home Depot, were used to hold the rigging together, and “indoor-outdoor” Zipties were used to secure the payload rigging to the balloon neck using techniques demonstrated by Dr. James Flaten of the University of Minnesota.

Operations

High-Altitude Ballooning missions are extremely complex, requiring a large number of steps to be executed correctly in order to be successful. Mission operations were primarily broken down into three different phases: pre-flight, pre-launch, and post-launch & recovery operations. This section isn’t an exhaustive look at our equipment or operations procedures but is instead intended to be a high-level overview since the focus of the paper is to discuss the eclipse methods and results.

While USC has had some ballooning experience in the past, such as with the 2017 Solar Eclipse, there was no full-time ballooning lab on campus prior to the 2024 Solar Eclipse Project, so the operations procedures had to be developed mostly from scratch. To develop these procedures, a large amount of time was spent researching publicly available data and resources from several other ballooning teams (including references 7-10 and several other sources), often reaching out if there were any specific questions regarding either the procedures or the specific equipment used for a certain step. Detailed online resources provided by NASA’s Minnesota Space Grant Consortium and articles from previous AHAC Conferences were particularly valuable in this regard.

Ultimately, procedures were made for pre-launch and launch day operations, and either concurrently or once the procedures were established, a thorough and comprehensive equipment list was also made. Pre-Launch, arrangements were made to rent helium tanks from a local vendor (Airgas) in San Antonio and as mentioned in the mission planning section, the final launch site determination was narrowed down in the days leading up to the actual launch depending largely on factors such as weather, cloud cover (so that team members could see the eclipse), wind patterns, the possible landing site, and other factors. The team also implemented procedures that meticulously ensured that all necessary equipment was accounted for and was brought to the launch site since there was a narrow launch window (30 minutes maximum) in which we could launch to successfully track the eclipse. While there was not time for a full test-flight in the Mojave Desert of Southern California as originally planned, a full rehearsal for launch operations (assembling the entire flight stack, inflating the balloon with helium, etc.) was also conducted on-campus 2 weeks prior to the Eclipse in Texas in order to practice and refine the procedures before the actual mission. Although not a full test flight as originally planned due to certain time constraints, the tethered test launch was still very valuable and proved to be instrumental in the success of the eventual eclipse flight.

Launch procedures included arriving at the launch site early, preparing the payloads (discussed in more detail in the previous section) and ensuring that they're in working order, activating the APRS and SPOT Trackers, and assembling the balloon stack before lastly (carefully) unboxing and inflating the Kaymont 2000g Balloons with the proper amount of helium from the canisters. At the launch site, the team was careful not to set up close to any trees, power lines, high fences, or any other object which could potentially entangle or collide with the balloon stack during or after launching. This was particularly important since there were relatively strong surface winds the day of the launch, although had it been worse, there were contingencies for launching in high-wind conditions. The final launch site was situated approximately 2 hours west of San Antonio and about 30 minutes east of Del Rio, Texas. With the eclipse flight, there was only a small launch window (~20 minutes) if we wanted to obtain images around our target altitude of ~80,000-100,000 feet. Without a vented configuration, if the balloon was launched too soon, it would likely naturally burst around ~100,000-105,000+ feet and while images at relatively lower altitudes such as 65,000 or 70,000 feet would be approximately the same as those from ~80,000-100,000 feet, giving an additional 10-15 extra minutes if needed, the launch window was still extremely tight at ~20-30 minutes. Once the flight stack was successfully released, the team began monitoring for telemetry from the balloon's APRS antenna and then remained at the launch site for approximately 2 hours to view the eclipse.

With safety of the team members being the top priority when viewing the eclipse, and with there being many vendors selling inauthentic (and thus potentially dangerous) eclipse glasses, approximately 25 pairs of eclipse viewing glasses with a ISO-1232-1 certification were purchased from a reputable vendor in order to safely view the eclipse. After the launch, the exact period of totality was also precisely re-calculated for the exact launch site which was chosen in order to ensure that the eclipse was directly viewed without glasses only during this time period. It should be noted that on the day of the Eclipse, conditions throughout Texas were cloudy, but the location of the launch site, as predicted, had much less cloud cover and the clouds there had dispersed and luckily gave way to mostly clear skies shortly before the eclipse. Upon the conclusion of the eclipse, the team initiated recovery operations, eventually recovering the balloon and payload near the predicted landing site of Fredericksburg, Texas nearly 3 hours away. Thereafter, we began post-processing and analyzing the flight data.

Results

The team ultimately achieved its goal of imaging the Eclipse from a high-altitude balloon around ~90,000-100,000 feet as shown in Figures 6 and 7 below.

During launch, the windy conditions made it extremely difficult to get an exact lift measurement, so for future missions it may be worthwhile to come up with a method to counteract or create a workaround for this effect if possible. While contingencies were made for successfully releasing the balloon in the event of windy conditions, this situation wasn't accounted for and resulted in a possible net lift measurement roughly between 9.5-11.5 pounds (~2+ lbs error).

While the APRS Transmitter was non-operational throughout the flight, it appears that the flight went as expected, assuming a relatively typical ascent rate of 5 m/s and the balloon naturally bursting around roughly 100,000 feet plus or minus a few thousand feet. Even though the APRS failed and there was no onboard GPS logger, this can be deduced based both on the camera data and also based on the landing site, which was within 3-sigma, or approximately 35 miles southwest of the center of the final predicted dispersion of possible landing sites near Fredericksburg, Texas despite the likely over-inflation of the balloon due to windy conditions resulting in faulty measurements. After not being able to precisely locate the payload on April 8th due to the tracking not working as expected, the Payload was successfully recovered the next morning after the SPOT Trace sent its "once-a-day" status report packet nearly 24 hours after launch.

Finally, after recovering the payload, the team proceeded to downtown Fredericksburg to both analyze the data and enjoy some much-needed downtime. Immediately upon arrival, all SD Cards were carefully removed from the cameras and data was immediately backed up to several team members' computers and google drive in order to ensure that the footage was secure. Additional highlights from the flight and the trip are all given below.

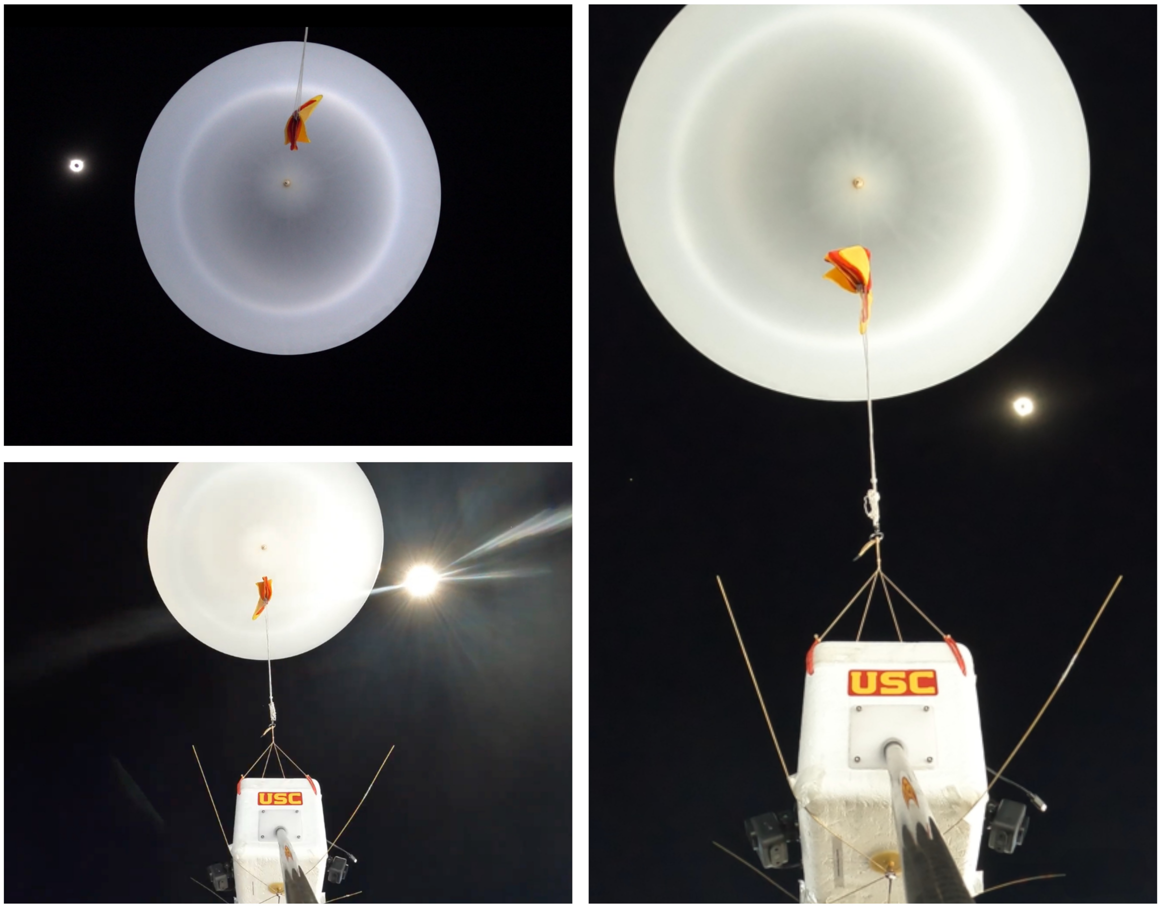

Fig. 6. Two images taken during the eclipse (upper left and right) compared to a non-eclipse image (bottom left)

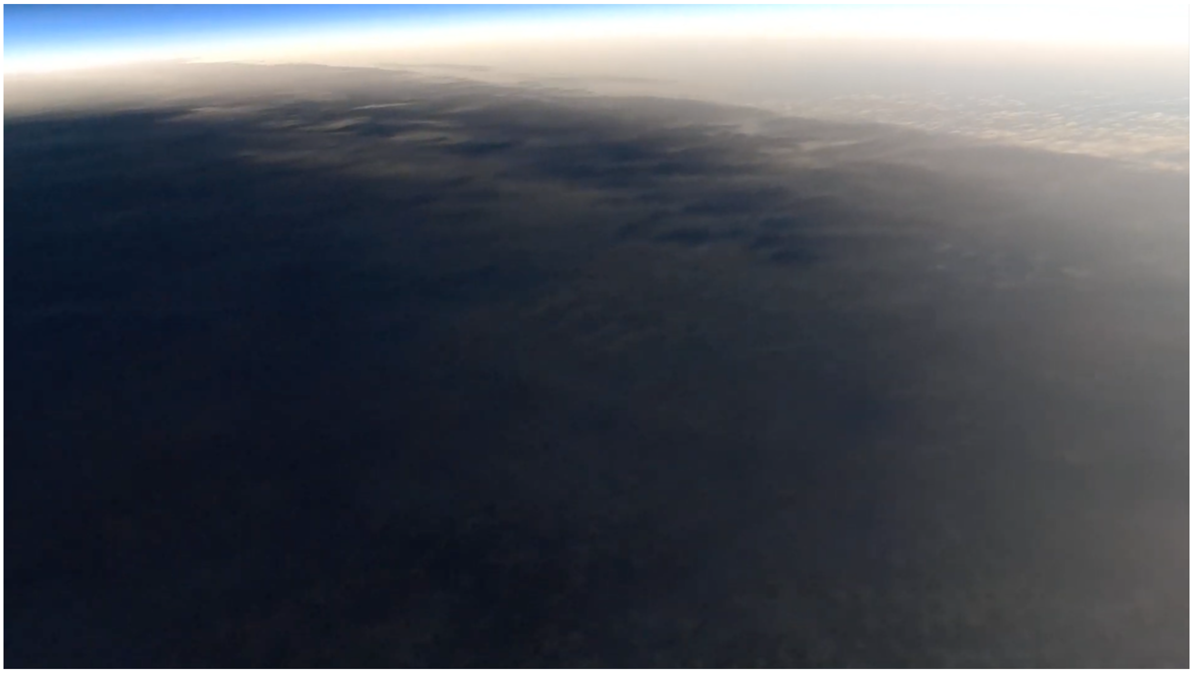

Fig. 7. The eclipse's shadow as seen from the balloon

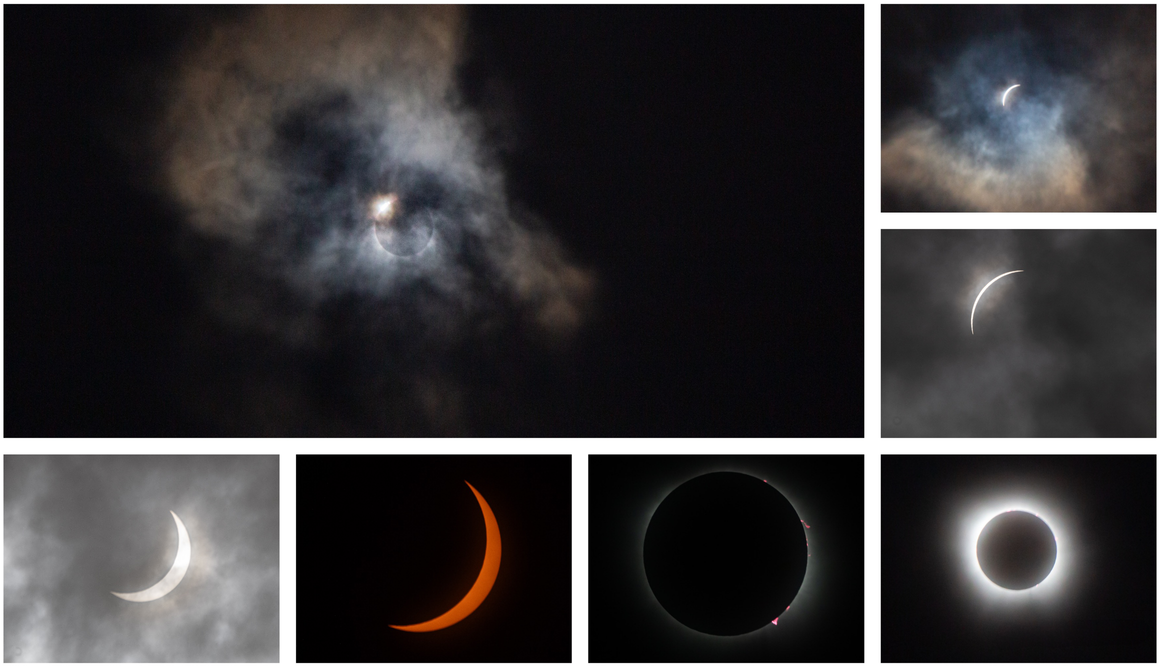

Fig. 8. Photos of the eclipse taken by team members at the launch site

Fig. 9. Aerial views of the launch site and surrounding area

Fig. 10. Parachute deployment, Recovery, Post-Recovery, and Various Team Photos

Conclusions & Future Work

The Eclipse Ballooning Project has had a profound and lasting impact on high-altitude balloon activities at the University of Southern California. Due to the success of the project and the advocacy of our team leads, the Ballooning Team at USC will now be a full-time extracurricular lab for undergraduate and graduate students, providing a number of educational high-altitude ballooning opportunities for years to come. In the short term, the team aims to continue building on the systems developed for the eclipse and improving them for similar missions in the future, possibly including but not limited to the August 2026 Eclipse taking place in Greenland and Western Europe in addition to other ambitious ballooning missions. All of the lessons learned throughout the 2024 eclipse project will be invaluable in these efforts moving forward.

Acknowledgments

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