HIGH-ALTITUDE BALLOON TRAJECTORY OPTIMIZATION

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Recently, attention has turned to missions with satellite constellations or other distributed systems to accomplish higher resolution science, communications and lower the overall cost, such as NASA's Venus Flagship Mission. The missions require multi-vehicle multi-platform optimization and evaluation to design the system for the objective. Tools, such as DISCO-Tech, have been developed to optimize these disaggregated and nontraditional space systems. Currently, however, DISCO-Tech is limited to satellite and ground station platforms. This work on high-altitude balloon trajectory algorithms aims to expand DISCO-Tech's capabilities for multi-balloon and multi-platform applications and also address the current absence of high-altitude trajectory programs designed for optimization. This paper presents the background and methodology for a high-altitude balloon trajectory predictor designed for incorporation into a mission optimization tool. The predictor generates trajectories from launch to landing and introduces generating trajectories based on achieving an in-flight location objective. Initial results for trajectory algorithm verification with actual flight data for a latex balloon are presented. Additionally, this paper presents new results for an initial application of trajectories based on an in-flight objective to NASA Space Grant's Nationwide Eclipse Ballooning Project, also with latex balloons.

1. Introduction

From satellite constellation missions, we now know that multi-vehicle missions for science have the potential for cost reductions through disaggregating space systems and rideshare opportunities [11]. Currently, NASA is developing a flagship mission to Venus that includes small satellites, and orbiter, a lander, and a high-altitude balloon component for higher resolution and longer duration atmospheric, cloud, and seismic activity sensing [3]. Attention has turned towards these distributed systems to accomplish higher resolution science, communications, and lower the overall mission cost. However, for all of these cross-platform and constellation missions, planning the mission, sometimes years in advance, is critical for success. Tools such as DISCO-Tech, Disaggregated Integral Systems Concept Optimization Technology, were developed to optimize such disaggregated and nontraditional space systems and evaluate the system's effectiveness [11]. The tool primarily uses a variable-length genetic algorithm to simultaneously optimize orbital parameters, payload parameters, and payload distribution for space systems with multiple objectives [11]. Currently, however, DISCO-Tech is limited to satellite and ground station platforms. This work on high-altitude balloon trajectory algorithms aims to expand DISCO-Tech's capabilities for multi-balloon and multi-platform applications and also address the current absence of high-altitude trajectory programs designed for optimization.

Research does exist for limited balloon constellation planning, however most HAB trajectory prediction research focuses on single balloon launches by either forward or backward propagating the trajectory given specific launch or landing coordinates [1][9][10][1]. There is also limited published research for HAB predictions that optimizes flight parameters for specific mission goals such as reaching a desired altitude over a desired location[1][5]. While the underlying physics for the trajectory predictors is well understood and current methods have been proven, the existing publicly available tools for trajectories are not in a form for balloon mission optimization or flight planning with special considerations. A trajectory planner with new capabilities would allow for coordinated atmospheric sensing, targeted land coverage, and extended flight in specific atmospheric conditions for analog planetary technology testing.

This paper presents the background and methodology for a high-altitude balloon trajectory predictor designed for incorporation into a multi-vehicle multi-platform mission optimization tool (Sections 1 and 2). The predictor generates trajectories from launch to landing and introduces generating trajectories based on achieving an in-flight location objective. Initial results for trajectory algorithm verification with actual flight data for a latex balloon are presented (Section 3). Additionally, this paper presents new results for an initial application of trajectories based on an in-flight objective to NASA Space Grant's Nationwide Eclipse Ballooning Project, also with latex balloons (Section 4). Finally, the paper will discuss optimization considerations, additional considerations for trajectory predictions, and next steps for the trajectory planning software (Section 5).

1.1. High-Altitude Ballooning Basics

The term "High-Altitude Balloon" (HAB) or stratospheric balloon typically refers to unmanned free-flying latex weather balloons, zero-pressure balloons, or super-pressure balloons. Private and public entities like NASA have used HABs for many decades, but recently their potential has become more apparent with the improvement and miniaturization of technology. Balloon platforms commonly support payloads for atmospheric science, astronomy, surveillance, satellite system prototypes, and more. HABs bring payloads to "the edge of space" with flight altitudes up to 130,000ft (~40km), an ideal environment for atmospheric science and testing novel space technology at a significantly lower cost, recovery capability, and shorter development time than alternative platforms.

Figure 1: Examples of Free-Flying High-Altitude Balloons (Left: Latex [8], Middle: Zero-Pressure[19], Right: Super-Pressure [18])

Weather balloons have the smallest volume and therefore lift only light payloads. They are sealed latex balloons that ascend until the balloon bursts and then the flight string descends under a parachute; flights typically last about 3.5 hours. Zero-pressure and super-pressure balloons are large balloons manufactured out of plastic where the largest balloon can lift payloads up to 3 tons [13]. Unlike super-pressure balloons that are completely sealed, zero-pressure balloons have open ducts to allow lifting gas to escape for equalization of the pressure differential during ascent to "float" at a particular altitude [13]. Zero-pressure balloons can stay aloft for a few days to a week, whereas super-pressure balloons are capable of staying aloft for over a month [13].

One of the defining features of a free-flying high-altitude balloon mission is the uncontrolled ascent and descent of the balloon or parachute and payload(s). Therefore, one of the most important aspects for a HAB mission is predicting the balloon's trajectory to protect the public and the payload. Publicly available tools for HAB trajectory predictions are primarily for free-flying small latex weather balloons. Habhub by Cambridge University or the ASTRA High Altitude Balloon Flight Planner are the most recognized and regarded tools due to the high accuracy of their prediction compared to the actual flight and their ease of use [10][9]. Zero-pressure and super-pressure balloon predictors are typically developed at an organization for their use only. However, because balloons have been around for decades, their underlying physics are well known and current research is actively refining proven benchmark models [1][2][4][5][10].

1.2. Latex Balloon Equations of Motion

The governing equations for a latex balloon in this trajectory software are the same first-order equations as the Habhub API [6]. Balloon motion is separated into a vertical component (altitude) and horizontal component (latitude and longitude). The vertical component (z axis) of a balloon for a standard flight profile has three stages: ascent, balloon burst, and descent. The vertical component of a float flight profile, where the balloon remains at approximately the same altitude for an amount of time before the flight string separates, also has three stages: ascent, float, and descent. The ascent and decent motion models for both a standard and float flight profile are identical. Motion during the ascent is assumed to be a constant ascent rate (equation 1). Descent motion (equation 2) is modeled with a "descent- under parachute model" where the descent rate at a specific altitude is determined by a NASA Earth atmosphere model and estimated descent rate at sea level [7] [16]. If the trajectory is a float profile, the altitude is assumed to be constant once the desired altitude is achieved for a specified amount of time.

$$Altitude\ (m):\ \ z = \frac{dz}{dt}\Delta t \tag{1}$$

$$Ascent\ (m/s):\ \ \frac{dz}{dt} = constant \tag{2}$$

$$Descent\ \left(\frac{m}{s}\right):\ \ \frac{dz}{dt} = -\frac{\frac{dz}{dt}_{sea\ level} * 1.1045}{\sqrt{\rho(z)}} \tag{3}$$

$$\text{where}\ \ \rho(z) = \frac{p(z)}{0.2869 * T(z)}$$

$$Float\ (m/s): \frac{dz}{dt} = 0 \tag{4}$$

The horizontal component assumes that the balloon's motion is the same as the surrounding air [7][9]. Therefore, the change in latitude and longitude (equation 4) can be estimated assuming a spherical Earth and using NOAA's GFS models, which provide u-wind (+ to the east) and v-wind (+ to the north) in meters per second.

$$Latitude\ (deg):\ \ lat = \frac{dlat}{dt}\Delta t$$
$$Longitude\ (\text{deg}):\ \ lon = \frac{dlon}{dt}\Delta t \tag{5}$$

$$R = R_{Earth} + z(t) \tag{6}$$

$$Change\ in\ Latitude\ (deg/s):\quad \frac{dlat}{dt} = \left(\frac{180}{\pi}\right)\frac{vwind}{R} \tag{7}$$

$$Change\ in\ longitude\ (deg/s):\quad \frac{dlat}{dt} = \left(\frac{180}{\pi}\right)\frac{uwind}{R * \cos\left(lat(t) * \frac{\pi}{180}\right)} \tag{8}$$

2. Methodology

This methodology generates latex balloon predictions from a launch location and from an in-flight objective latitude, longitude, altitude, and time for both standard and float flight profiles. To translate this methodology to zero-pressure and super-pressure balloons, the primary changes would be the equations of motion and a float function based on constant pressure, not altitude. Both zero-pressure and super-pressure balloons fly a float flight profile where the float duration is hours to weeks. Some can even station keep, remain above the same general area by traversing the wind layers, but that is not within the scope of this preliminary work. The general functions for the motion models, termination, and flight profiles would still be applicable to the larger balloons for trajectory predictions.

2.1. Basic Structure

The structure of the code follows Habhub's callable model approach with separate functions for motion models, motion termination, and flight profiles [6].
The motion models return the change in latitude, longitude, and altitude at a time and are designed generally as the

following pseudocode [6]:
Motion Model Function:

```
def f(lat, lon, alt, time, wind_data, dzdt):
    lat_dot, lon_dot = horiz_motion(lat,lon,alt,time, wind_data)
    alt_dot = dzdt
    return lat_dot, lon_dot, alt_dot
```

where the wind_data is the GFS weather data, dzdt is altitude rate of change with time, and horiz_motion() calculates the change in latitude and longitude from the GFS provided u-wind and v-wind (equations 7 and 8).

Motion termination functions are conditions that determine whether the prediction stage should stop [6]. An example of this function for stopping the ascent stage at a burst altitude is as the following pseudocode [6]:

Termination Function:

```
def termination_func(lat, lon, alt, time, burst_alt):
    return alt >= burst_alt
```

Both the motion models and termination functions are written such that they can be integrated into the flight profile models in stages. A single stage solves the first-order motion equations (equations 1 and 5) and generally is written as the following pseudocode [6]:
Stage Pseudocode:

```
while not term_func(lat, lon, alt, time):
    lat_dot, lon_dot, alt_dot = f(lat, lon, alt, time)
    lat += lat_dot * dt
    lon += lon_dot * dt
    alt += alt_dot * dt
    time += dt
```

Each stage will continue processing the motion model, f, with time step, dt, until the termination function, term_func, stops the stage.

2.2. Trajectory Generation from Launch Location

2.2.1. Standard Flight Profile

A standard flight profile has two stages: ascent and descent. The prediction starts at a specified inputs of launch coordinates, altitude and time. Assuming a constant ascent model (equation 2) and drag descent model (equation 3), the constant ascent rate, burst altitude, and sea level descent rate are also specified as inputs. The standard flight profile function takes the inputs, processes and records each time step, and outputs a list containing each step of the prediction as the following pseudocode:

```
def standard_flight_profile(inputs):
    lat, lon, alt, time = launch inputs
    dt = 60 #[s] minute time step
    #ascent stage
    < constant ascent stage with burst alt. termination>
    #descent stage
    < drag descent stage with topographic altitude
        termination>
    return [lat, lon, alt, time]
```

2.2.2. Float Flight Profile

A float flight profile has three stages: ascent, float, and descent. The prediction starts at a specified inputs of launch coordinates, altitude and time. Assuming a constant ascent model (equation 2), constant altitude float (equation 4), and drag descent model (equation 3), the constant ascent rate, float altitude, float duration, and sea level descent rate are also specified as inputs. The standard flight profile function takes the inputs, processes and records each time step, and outputs a list containing each step of the prediction as the following pseudocode:

```
def float_flight_profile(inputs):
    lat, lon, alt, time = launch inputs
    dt = 60 #[s] minute time step
    #ascent stage
    < constant ascent stage with float alt. termination >
    #float stage
    < constant alt. float stage with float duration
        termination >
    #descent stage
    < drag descent stage code with topographic altitude
        termination >
return [lat, lon, alt, time]
```

2.3. Trajectory Generation from an In-Flight Objective

In order to generate predictions that have an in-flight location objective, the flight profile has an added component at the beginning. This component determines the launch location that, when propagated, will have the smallest distance at the objective altitude to the objective latitude and longitude. The process starts by back propagating from the location and time objective. If the in-flight objective occurs during ascent, a negative ascent model is used to approximate the trajectory from that objective. If the objective occurs in float, the algorithm assumes the objective occurs half way through the float duration and back propagates though half of the float and the negative ascent model for the approximate trajectory. The trajectory is approximate because the winds that calculate the location at t-1 are those at time t. The directions of the winds cannot just be reversed for an accurate backpropagated trajectory in time, but because that is the data we have access to, the back propagated trajectory can only be approximate, not accurate. Once the negative ascent model has terminated, a grid of 9 launch locations is generated around the approximated launch latitude and longitude at $\pm$ 0.01 degrees. Each of those locations are then propagated forward with a constant ascent model until the altitude is above the objective altitude. The latitudes and longitudes of the final two timesteps, one above and one below the objective altitude, are then linearly interpolated with respect to the objective altitude to determine what the trajectories' latitudes and longitudes are at the objective altitude. The Euclidean distance is calculated to determine the trajectory closest to the objective location. Once selected, the closest trajectory is propagated forward to landing and that is the final trajectory prediction output from the algorithm.

2.3.1. Standard Flight Profile

To generate a trajectory from the in-flight objective, the flight profile has 4 stages: back propagation, possible trajectories propagation and distance check, finish ascent, and descent. The prediction starts at specified in-flight objective coordinates, altitude and time. Assuming a constant ascent model (equation 2) and drag descent model (equation 3), the constant ascent rate, burst altitude, and sea level descent rate are also specified as inputs. The standard flight profile function takes the inputs, processes and records each time step, and outputs a list containing each step of the closest trajectory prediction as the following pseudocode:

```
def standard_flight_profile(inputs):
    lat, lon, alt, time = objective inputs
    dt = 60 #[s] minute time step
    #back propagation
    < negative constant ascent stage with
        topographic altitude termination >
    #possible trajectories propagation and distance eval
    < constant ascent stage code with objective altitude
        termination >
    < closest trajectory selection >
    #finish ascent stage for closest trajectory
    < constant ascent stage with burst altitude
        termination >
    #descent stage
    < drag descent stage code with topographic altitude
        termination >
      return [lat, lon, alt, time]
```

2.3.2. Float Flight Profile

With an in-flight objective, a float flight profile has five stages: back propagation from float, possible trajectories propagation and distance check, finish float, and descent. The prediction starts at specified in-flight objective coordinates, altitude and time. Assuming a constant ascent model (equation 2), constant altitude float, and drag descent model (equation 3), the constant ascent rate, float duration, and sea level descent rate are also specified as inputs. Float altitude is not included for this profile due to the objective and float altitude being the same. The standard flight profile function takes the inputs, processes and records each time step, and outputs a list containing each step of the closest prediction as the following pseudocode:

```
def float_flight_profile(inputs):
    lat, lon, alt, time = objective inputs
    dt = 60 #[s] minute time step
    #back propagation
    < negative constant altitude float stage with
        0.5*float duration termination >
    < negative constant ascent stage with
        topographic altitude termination >
    #possible trajectories propagation and distance
        check
    < constant ascent stage with objective altitude
        termination >
    < constant altitude float stage with objective
        time termination >
    < closest trajectory selection >
    #finish float stage for closest trajectory
    < constant altitude float stage with 0.5*float
        duration termination >
    #descent stage
    < drag descent stage code with topographic altitude
        termination >
    return [lat, lon, alt, time]
```

3. Initial Trajectory Generation Verification for Latex Balloons

The initial verification for this methodology applied to latex balloons compares a standard flight profile prediction to GPS data collected throughout a flight. For the latex model to be completely verified, more than one flight is needed and that data will be collected through the summer of 2023. However, the results for an initial single flight show significant agreement of the predicted trajectory compared to this actual flight path. Virginia Tech conducted the latex balloon flight used for this initial verification on November 8th, 2022. An onboard GPS logger recorded the entire flight path. The balloon was filled to target an ascent rate = ~5.08 m/s (1000 ft/min), which is a typical ascent rate for latex high-altitude balloon flights. To compare the prediction to the flight itself, the wind data ingested for horizontal motion models was the archived GFS forecast generated on launch day. These forecasts were acquired from the Research Data Archive that is maintained by the National Center for Atmospheric Research [14].

The input launch location and time were the same as the actual balloon launch to better compare the predictor models to the flight path. The ascent rate, burst altitude, and descent rate initially assumed that, with no knowledge of the flight fill or parachute size, the inputs were the experienced average performance with ascent rate = 5m/s, burst altitude = 28956m (95kft), and descent rate = 7m/s. The resulting predicted trajectory (aqua) and flight path (red) are shown below in *Figure 2: Nov. 8th, 2022 Flight Path (salmon) vs Initial Predicted Path (aqua) with Average Inputs. Launched at Green Dot, Landed at Red Dot*.Figure 2**Error! Reference source not found.**. Despite the lower burst altitude and slightly faster ascent rate, the predicted trajectory still predicts balloon landing within 6km of the actual landing location.

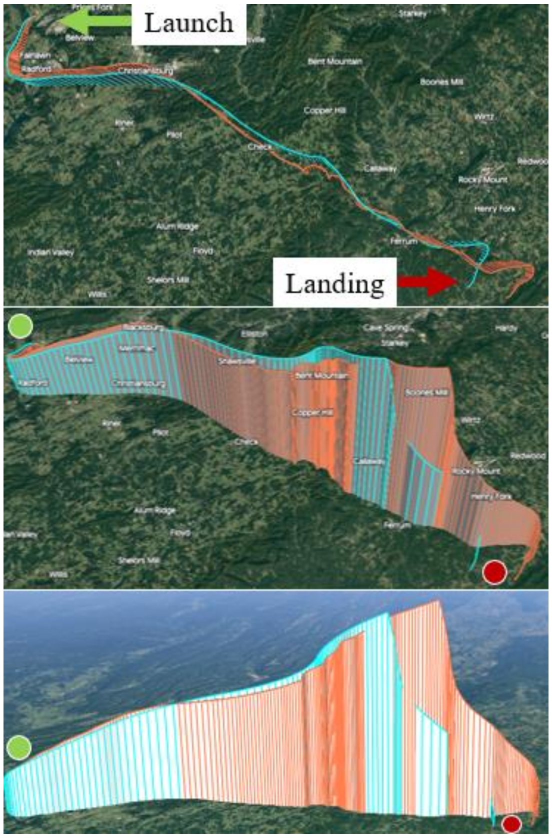

Figure 2: Nov. 8th, 2022 Flight Path (salmon) vs Initial Predicted Path (aqua) with Average Inputs. Launched at Green Dot, Landed at Red Dot.

With some knowledge of the system flown, such as the balloon was slightly underfilled compared to the needed lift to achieve the 5 m/s targeted ascent rate, the parachute was smaller than the originally selected parachute for the flight string weight target descent rate of 7 m/s, and the actual burst altitude from the GPS data, the predictor can generate a flight trajectory with the predicted landing location < 1km to the actual landing location as seen in **Error! Reference source not found.**. For this prediction, the ascent rate = 4.85 m/s, burst altitude = 30700m, and descent rate = 7.5 m/s.

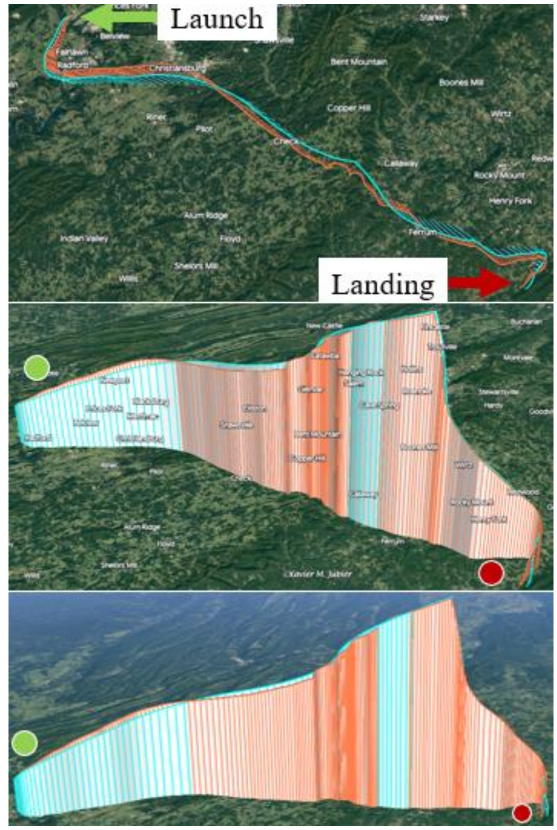

Figure 3: Nov. 8th, 2022 Flight Path (salmon) vs Informed Predicted Path (aqua) Launched at Green Dot, Landed at Red Dot.

The resulting trajectories generated by this methodology, especially with informed inputs, show that the motion models in Section 1.2 are a good approximation for a latex high-altitude balloon. Even with the average inputs, if the starting location and time are relatively accurate, the predicted trajectory was a good enough approximation to generate a landing location within a small region of the true landing location.

4. Case Study: NASA Space Grant's Nationwide Eclipse Ballooning Project

4.1. Case Study Description

On April 8th, 2024, there will be total solar eclipse that crosses the US from Texas to Maine. For this meteorological phenomena, NASA Space Grant is sponsoring a project to live-stream the eclipse from the edge of space. The project is comprised of 30+ university and other student teams across the US that will launch high-altitude balloons along the path of the total solar eclipse carrying video streaming and science payloads. The mission objective for the teams is to live-stream the eclipse while floating around 70kft-80kft. With 30+ teams along the eclipse path, the project aims to stream the eclipse progression across the US. The uniqueness of this scenario is that the total eclipse occurs for only a few minutes in each location as it moves across the US. In order to live-stream those few minutes from 70kt-80kt, the latex high-altitude balloons need to be launched within a specific time window for each launch location. If these balloons fly a float profile, they'll potentially require different launch times and locations if there are high winds the day of the eclipse.

This initial application is for 10 equally spaced in-flight objective points along the central line of the complete totality from southern Missouri to Lake Erie (Figure 4). The objective times for these points are the time of max totality at each location.

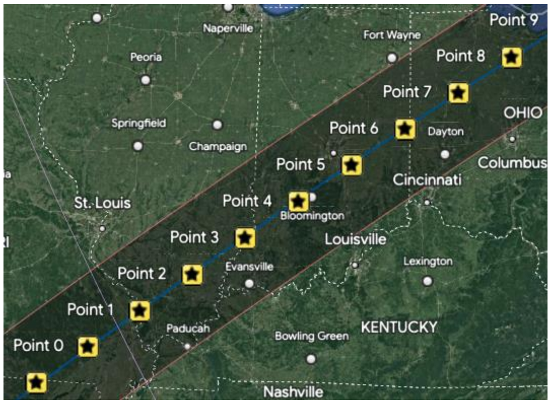

Figure 4: In-Flight Objective Locations Along Central Line of the Total Solar Eclipse

Three separate trajectories were generated for each location: a standard flight profile, a 30-minute float profile, and a 1.5-hour float profile. For this in-flight objective methodology demonstration (Section 2.3), these profiles were generated using GFS archived forecast data from the Research Data Archive for April 8th, 2022 [14]. For a more practical application of this study, alternative weather data and models would be needed to generate the predictions. However, for this demonstration, the forecast data is only supplemental for show the working algorithm and methodology. Each profile is assumed to have a constant ascent rate = 5.08 m/s (1kft/min) and constant descent rate of 7 m/s (~1.38kft/min). For the standard flight profile, the burst altitude is assumed to be 28.956km (95kft). For the float flight profile, the float and objective altitudes are the same at 22.86km (75kft), but the durations are 30 minutes and 1.5 hours.

4.2. Results

The three flight profiles all achieve their in-flight object and the balloon's motion around that point are very similar in path. In Figure 5, the standard flight profiles are purple, the 30-minute float duration profiles are white, and the 1.5-hour float profiles are aqua. However, due to the flight profile chosen, each trajectory starts at a different launch point, especially towards southern Missouri (Figure 6). This was expected for when winds are higher and towards the same direction, the balloon travels further from the launch location (point 0). However, lower winds mean shorter flight paths and therefore the trajectory launch locations for point 10 are closer together even with the extended float duration.

This case study shows the first results of trajectory predictions from an in-flight objective. For all three flight profiles shown, each reached the objective within the trajectory and had similar motion around that point and demonstrates this method to generate trajectories.

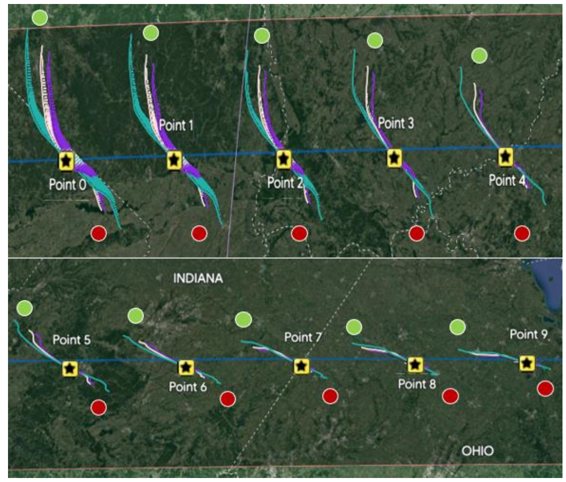

Figure 5: Object Points Along the Total Solar Eclipse Path with a Standard Flight Profile (purple), a 30-minute Float Profile (white), and a 1.5-hour Float Profile (aqua). Image split into two parts to visibility. Launched at Green Dot, Landed at Red Dot.

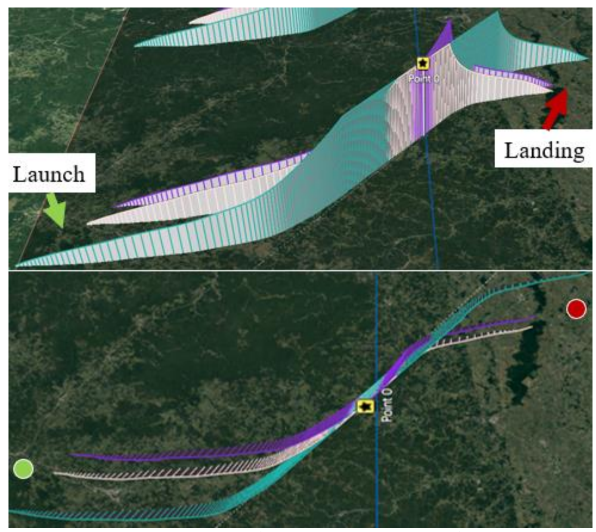

Figure 6: Zoomed in Images of Point 0 with Altitude Profiles (top) and Trajectories from Above (bottom). Standard Flight Profile is Purple, 30-minute Float Profile is White, and the 1.5-hour Float Profile is Aqua. Launched at Green Dot, Landed at Red Dot.

5. Future Work

The next steps for this work include continued verification of the latex motion models, re-writing some functions to be more computationally efficient, and adding and verifying motion models for zero-pressure and super-pressure balloons. Once the overall algorithm is more computationally efficient, the trajectory generators will be integrated into DISCO-Tech, a disaggregated and nontraditional mission systems optimization tool, to design and optimize multi-balloon and cross-platform missions [11]. Additional considerations that might be explored include understanding the effects of using historical data sets for future predictions and optimizing a trajectory for a target area instead of a singular point in flight.

6. Conclusions

This work on high-altitude balloon trajectory algorithms aims to expand DISCO-Tech's capabilities for multi-balloon and multi-platform applications and also address the current absence of high-altitude trajectory programs designed for optimization.

This paper presented the equations of motion for a latex high-altitude balloon, the type of balloon the methodology was applied to. Also presented was the methodology for a high-altitude balloon trajectory predictor designed for incorporation into a mission optimization tool as callable functions. The methodology section generally explained how the functions are designed such that the predictor can generate trajectories from launch to landing and introduces generating trajectories from an in-flight objective location and time objective. Both methods to generate trajectories for a standard flight profile with ascent and descent stages, and for a float flight profile with ascent, float, and descent stages. To generate a trajectory from an in-flight objective, each flight profile adds two additional stages at the beginning: back propagation for an approximate launch location, and generating, forward propagating, and evaluating possible launch locations around the approximate launch location for which trajectory is closest to the objective.

Initial results for the trajectory verification with actual flight data for a latex balloon was presented showing that the latex balloon motion models are a good approximation for predicting flight. Additionally, this paper applied the new in-flight objective trajectory generation methodology to a case study and presented new results for NASA Space Grant's Nationwide Eclipse Ballooning Project targeting a latitude, longitude, and altitude at a specific time to live-stream the 2024 Total Solar Eclipse long the path. These results focus on how the launch location changes based on which flight profile the location flies and that for each flight profile can reach the in-flight objective.

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