Precision Integrated GEOgraphical Navigation Near Space Recovery Technology

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Precision Integrated GEOgraphical Navigation (PIGEION) is a novel payload delivery and retrieval apparatus for use with small, high-altitude balloon payloads. The PIGEION system combines ground tracking, remote control, and autonomous navigation to safely and efficiently transport and recover research and scientific instrumentation weighing up to 3 pounds. After assessing several delivery concepts, the final PIGEION system comprises a steerable parachute guided by a miniature, onboard flight computer. At the mobile ground station, winds-aloft data acquired during the ascent of PIGEION is used to predict a suitable landing location for the system. Following cutaway from ascent balloon and descent to suitable altitude under drogue parachute, the steerable parachute deploys and an autopilot algorithm maneuvers the payload to the desired location, based on GPS and digital compass position data. The use of a PIGEION system can decrease the risk of losing or damaging expensive payloads, increase payload mission lifetimes, decrease costs, and enable research in the near-space environment.

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I. Introduction

The purpose of the High Altitude Balloon (HAB) program is to provide university students with affordable access to space or near-space for purposes of scientific discovery, as well as to inspire interests and offer experiences for aerospace careers. The program has existed since 1998, when the University of North Dakota (UND) launched its first mission balloon. Since then, integration has taken place at UND and now includes both tethered and untethered balloon flights with payloads of varying content, purpose, and, not surprisingly, of varying success rates.

II. Problem Statement and Design Specifications

PIGEON Problem Statement: Design a recovery system that will accompany scientific payloads on high altitude balloons. System must be capable of guiding payloads to a user-designated "safe" landing zone in order to successfully recover payloads intact and prevent damage to people and property.

The purpose of the Near Space Recovery Technology (NSRT) team is to increase the successful return of UND payloads attached to HABs by providing track-ability, maneuverability, and ease of use for interchangeable payloads. This year's NSRT team, who call themselves PIGEON, has taken on the task of creating a canister and controllable landing system to house all future payloads. Winds aloft data acquired via GPS during the ascent of a HAB will be used to predict and control the landing location of a 6 pound HAB payload through the use of a steerable parachute and ground tracking system.

III. Systems Requirements

Realistic design constraints span a large portion of the project. Included in the design constrains are Federal Aviation Regulations (FAR) imposed on all unmanned flights by the Federal Aviation Administration (FAA), which both restrict and place requirements on the design and operation. FAA requirements and restrictions with annotations can be found in Appendix 1**.** Additionally, the mechanical and electrical systems of primary concern will be addressed individual.

A. Mechanical Systems Requirements

Primary mechanical system requirements are as follows:

1) Provide structure and housing for all electrical and mechanical components
2) Provide adequate lift and control with a ram air parachute
3) Choose servos and servo components that effectively control a parachute
4) Insure thermal protection for all electrical and mechanical components

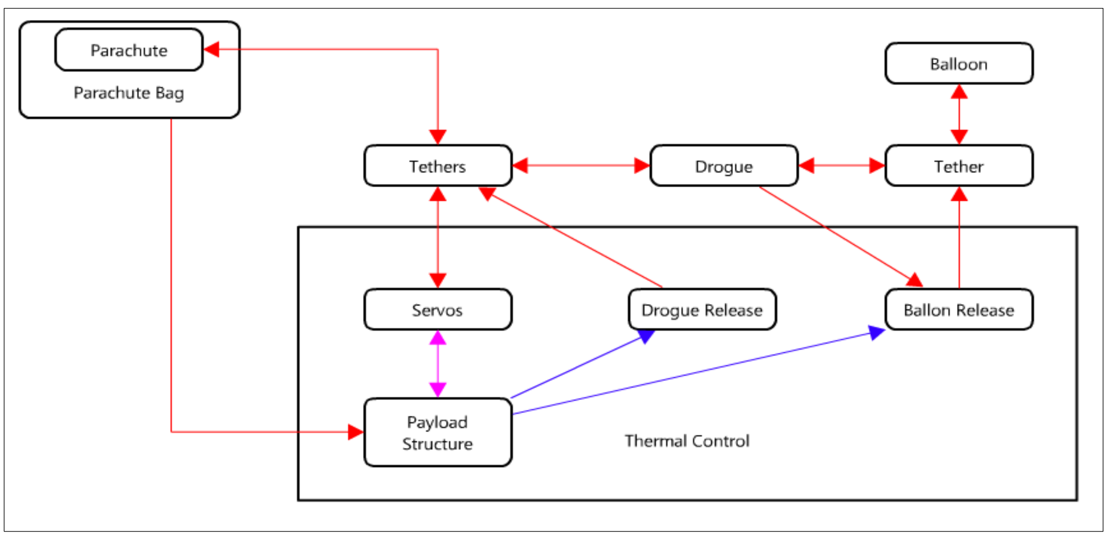

Figure 1. Mechanical Systems Block Diagram

The flow diagram seen in Figure 1 illustrates the major mechanical components required for the PIGEON system. The pink arrows indicate both electrical and mechanical properties influence operations; the blue arrows indicate electrical control; and finally, the red arrows illustrate mechanical properties applied to the component. The balloon will impart buoyancy forces on the payload bus through the balloon tether, which will subsequently imply forces to the balloon. The balloon and drogue release will require thermal control to ensure the electronic cutaway severs the independent tethers; this will be controlled through circuitry within the payload bus structure. Thermal control will also be required to keep the components of the bus structure at operating temperature to ensure proper function of all payload bus mechanisms. For the drogue chute, forces on the tether will create stresses in the bus structure and on the servos. Once released, the drogue will be the primary pulling force for the deployment of the parachute out of the parachute bag. Finally, the main parachute deployment will be effected by the parachute bag opening, this parachute deployment will also place forces on the payload bus structure, though the support wires, which attach to the structure and pass through the parachute bag.

B. Electrical System Requirements

Primary electrical system requirements are as follows:

1) Choose components rated from -40° F to 100° F and 0.01 PSI to 15 PSI.
2) Perform highly efficient power conversion to acquire correct voltages for system components
3) Convert and scale all sensor values to voltage values read by a microcontroller
4) Provide analog-to-digital conversion for needed sensors
5) Provide serial communication for all commands
6) Transmit and receive data between the bus and ground station
7) Control servo arms
8) Control cutaway
9) Monitor software accuracy and insure operation
10) Provide a fail-safe for inoperable critical components
11) Minimize needed equipment and software
12) Monitor software accuracy and insure operation
13) Provide fail-safe for inoperable components or software

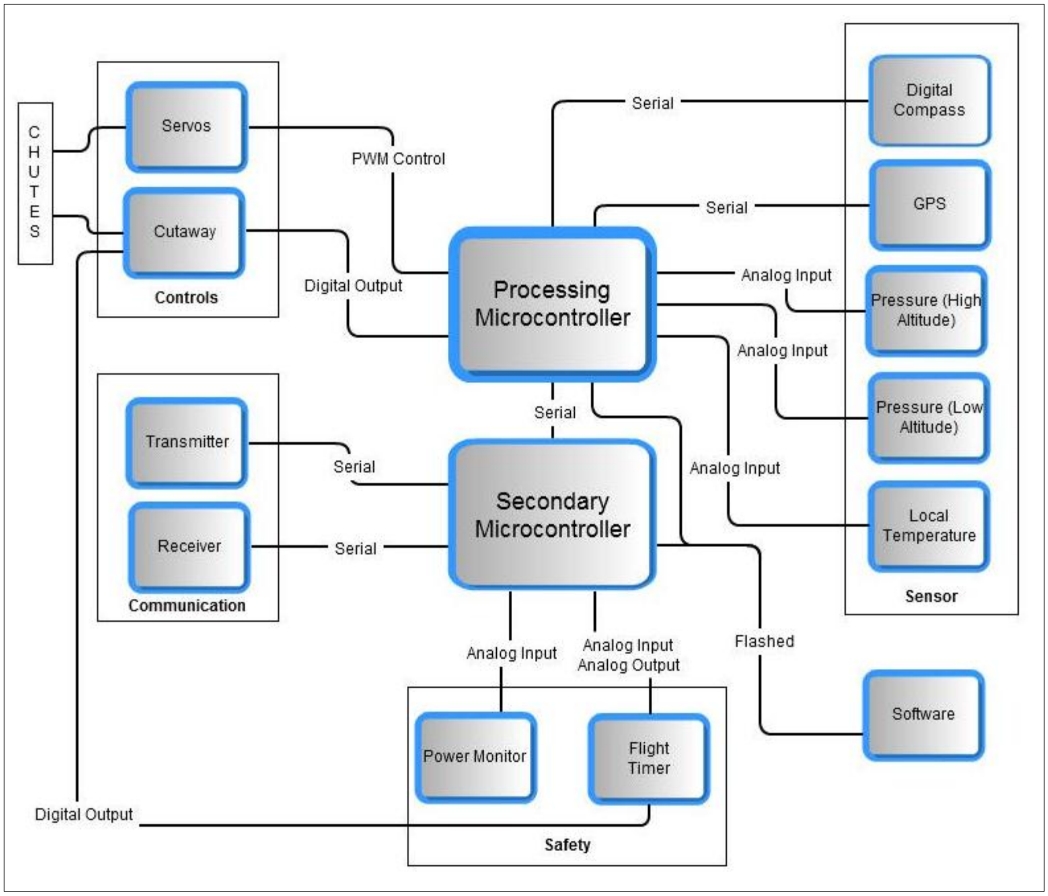

Figure 2. Electrical System Block Diagram.

The payload bus block diagram in Figure 2 shows the overall electrical system and types of data communication between each component. Two parallel microprocessors provide the brains for the payload bus. Every software routine and component communicates with or is processed by one of these two microprocessors. The radio transmitter and receiver allows communication to the ground station. Linear regulators provide an option for monitoring power and will alert the microcontroller if any de-regulation occurs. If, for any reason, the electrical system malfunctions, a flight timer will activate the cutaway mechanism to guarantee parachute deployment. A secondary radio transmitter, which is used as the signal directional radio, is completely separate from this process and is purchased as a complete package.

The ground station, consisting of an antenna and laptop computer, will serve as the tracking and user input data. The antenna will communicate all information received from the payload bus and pass it along to the computer. During ascent, a program will input the received GPS coordinates and sensor information and process them into a tracking and wind profile. This information will then be used to calculate the predicted landing zone of the payload. The user will pick a safe landing zone, and the program will calculate the cut-away elevation required. A smaller landing zone surface area directly corresponds to a lower cut-away elevation. As the payload descends, the ground station will send a set of GPS coordinates that communicate the landing zone and a cut-away elevation.

IV. Engineering Analysis

C. Structural Design

The main structural component of the NSRT Bus system is a Styrofoam box with outside dimensions of 11 inches by 9 inches by 7-1/4 inches and inside dimensions of 8 inches by 6 inches by 4-1/4 inches. The box is intended for insulated shipments and thus provides a well-sealed and insulated structure for the electronic components utilized by the bus system. The foam box is orientated so that its longest dimension of 11inches is in the vertical direction. This allows for the batteries utilized in the payload bus to be located in the bottom of the box maintaining a low center of gravity. Adequate spacing is present inside the box in order to distance the microcontrollers and batteries from the hot wire cutting mechanism, ensuring that they are not adversely affected by the extreme temperatures induced by its operation.

Attached to the underside of the box is a 0.040 inch thick aluminum plate, serving multiple purposes. During tests of extreme loading conditions, it was determined that the ram air parachute should not be attached directly to the top of the Styrofoam. The underside of the box, therefore, became the new attachment point for a supportive metal plate. Offering additional stabilization, the parachute chords for the ram air chute travel through the inside of the box. There they attach to the plate via two eye hooks, which were secured to the center. Further support by the aluminum base plate is obtained by attaching the actual payload with two mounting bolts. The rigid structure provides an ideal mounting surface for any payload designated to fly with the recovery system. The metal plate also has two ends bent up at 90° angles. These bent flanges have holes in them that, again, serve multiple purposes. Through the holes, Daiwa string rigging is used as a deployment bag, which holds the ram air parachute to the box while it is in its stored configuration. Additionally, the cutaway lines run out of the box and down to these holes. This is a prime example of how the components of the bus system serve as many purposes as possible.

Two separate aluminum plates, 0.040 inches thick, are added to the box where the servos attach in order to provide solid attachment points. One plate is located inside the box and one outside. Plate and servo mounting is accomplished using 6-32 machine screws. An additional plate of thickness 0.040 inches is located at the top of the box where the parachute lines enter. This plate's purpose is to prevent the parachute lines from damaging the box when deployed.

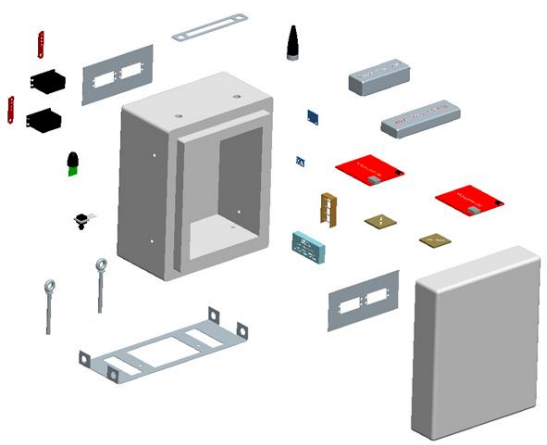

Figure 3. Exploded View with all Components

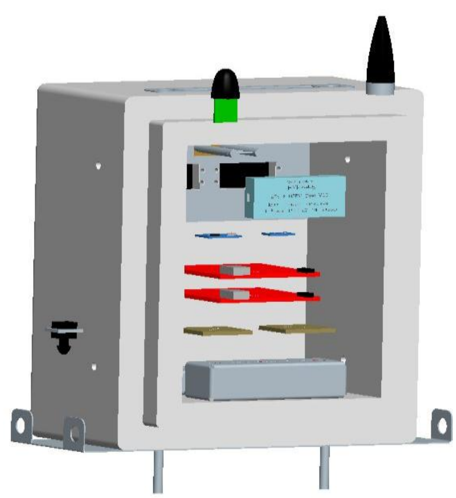

Figure 4. Assembly View of Components Inside

An exploded view of the Styrofoam box and all components can be seen in Figure 3**.** This diagram shows all of the individual components present in the system. Figure 4 displays the system with the lid removed and all components inside. Two batteries are positioned on the bottom level. Located above them are the printed circuit boards (PCBs) for the power control and cutaway mechanism. Above the PCBs are located the two microcontrollers used for command and communication. Directly on top of the microcontrollers are the magnetometer and temperature/pressure sensor. The radio and cutaway mechanism are located on the top level of the box. When placed inside the box components are separated by layers of foam to provide support and additional thermal insulation.

D. Cutaway Design

The cutaway mechanism is a two part system that both releases the balloon from the payload train and deploys the main parachute. Part one of the cutaway is primarily used when the flight is traveling into an undesirable area or moving faster than predicted. It is also utilized after the balloon bursts to release the trailing balloon remnants that may foul the parachute and drogue. The second stage of the cutaway is used to free the main ram-air parachute from its packing and to give control of the payload to the ground station user via servos.

Figure 5. Cutaway Model

The cut down utilizes a small loop of 50 pound test braided Daiwa tensioned with a spring around a set of parallel Nichrome wires as seen in Figure 5**.** The Daiwa is a Teflon product that offers the low coefficient of friction required a melting point of only 300 °F, and desirably low-water absorption qualities. These properties allowed the loop: to slip without snagging out of the securing S-ring, to be severed by the Nichrome wire with less power than alternatives, and to resist water absorption and the expected frost build up.

Two independent outputs are provided for each of the stages of the mechanism, as well as a redundant, cut-down wire to allow for breakage or wire failure and still provide successful balloon separation and main parachute deployment. A 5000 mAh NiCad rechargeable battery is used to power the controller. The battery is capable of high current and voltage output, even at temperatures as low as -50 °F. A 15 Amp power MOSFET switch is used instead of a relay for increased reliability. The circuit is connected with a high-density, space-grade wire to the microcontroller PCB. Most components are rated for operation down to -55 °F, but have been tested successfully to -60 °F.

E. Thermal Design

The thermal design for this project is very important, especially since the payload can experience temperature changes from 90°F all the way down to -90°F. At higher altitudes, convection is significantly reduced due to thinning air density. Radiation from to the sun also becomes a concerning factor. With a smaller amount of atmosphere to filter out the sun's intense radiation and the reduced convection discussed above, much less of the energy that is absorbed by the system can be dissipated. Therefore, an analysis of the important components in the payload bus was performed to determine whether a cooling, heating or no system at all would be required.

For the thermal design of the payload bus four components were specifically considered: the autopilot, the circuit boards, the servos, and, finally, the electronic cutaway mechanism. If a component on the autopilot circuit board becomes too cold or too hot to function, the payload bus would lose its ability to guide itself, possibly resulting in the loss of the payload. Extreme temperature changes could also cause a failure in servo operation. This failure would result in an inability to control the steering lines of the ram air parachute. Without steering control, the payload would still land; however, it would likely come to rest in an "unsafe" zone that would be difficult to recover it from. Finally, for the cutaway mechanism, a failure to release the balloon or parachute could result in a loss of the payload and possibly force the FAA to shut the high altitude program down, thus setting back near space research by at least several months.

F. Mass Analysis

Due to FAA and FAR regulations, which state that a high altitude balloon payload cannot exceed six pounds, the mass of the bus system became very critical. A goal was to make sure the bus system did not exceed three pounds, since in the future a payload would be attached to the bus system and both send up. According to FAA regulations, one payload can exceed six pounds, but the additional mass must be suspended beneath the first six pounds by means of a tethered line. It was determined that this extra tether would create instability in the system as it flies; therefore, the bus and payload were restricted to not exceed this six pound limit. In order to make sure the bus system stayed under three pounds, an Excel spreadsheet of the mass of each component, based off of vendor technical data, was made. After completing this estimate of all components, parts were purchased and, as they arrived, were accurately weighed. The Excel spreadsheet was then updated to show the actual weight of the payload bus. The total mass of the system, only 2.35 pounds, is actually less than our maximum weight goal. This allowed more of the weight budget to be set aside for the scientific payloads which will be attached to the bus.

V. Software

A. Flight Prediction Software

The flight prediction software utilized by PIGEON will operate using two main subsystems. The first system will be commonly used, industry software, called Balloon Track. This software is designed to read input data that sent from high altitude balloons as they ascend and predict their flight path using preset parameters. The program is capable of updating in real time and displaying the systems expected track on mapping software.

When running Balloon Track for real time updates, a Comm Port must be set up that will feed in data use in its predictions. It is important that Balloon track knows the time intervals between each packet it reads as this is what it uses to calculate the velocities between locations and altitudes. Ideally, the time interval between packets should be as small as possible, as this will provide the most accurate set of predictions. It is recommended that the real-time data be saved as it can be used later in example predictions or to complete further analyses of the flight.

Balloon Track relies on mapping software, MapPoint, for plotting the balloon location throughout the flight. While running a real time prediction, Balloon Track will plot an overlay of the balloon flight on the mapping software. The software will then display incoming flight data, wind and altitude information, and, if enabled, alternative tracking information. When running a real time prediction, the system's ascent, burst location, descent, and landing location will also be plotted.

B. Ram Air Prediction Software

The flight prediction software, used to calculate the path profile for the ram air parachute relies MatLab program called Ram Track and Google Earth. Ram Track in its current phase requires user input and only plots data for a deployment at 10,000 feet. Future developments could be made for alternative deployment altitudes. Data that is entered into Ram Track relies on parachute calculations present in an Excel file that details the velocity profile for the ram air parachute selected. An example of the generated Google Earth plot can be seen in Figure 6**.**

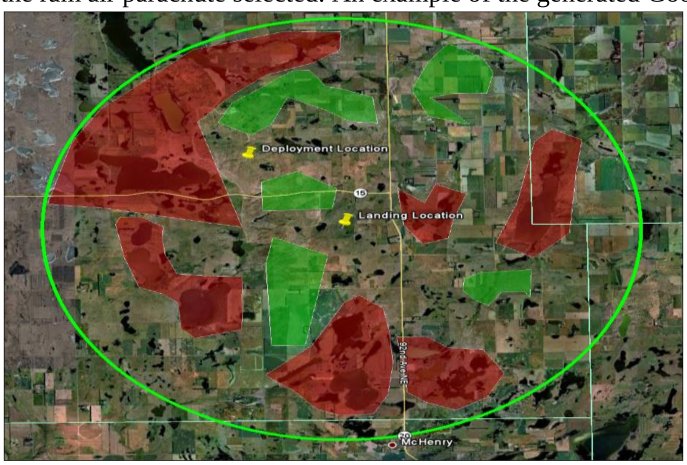

Figure 6. Ram Air Flight Prediction Plot

In order to run the MatLab program, a wind profile must be generated for altitudes ranging from the ground to 10,000 ft. This can be accomplished in two ways. The first method is to pull the wind profile from Balloon Track as the system ascends and generate an average wind vector for the selected altitude range. The second method is to gather winds aloft data from the National Weather Service for the approximate region, and from this data, generating an average wind vector. In each case, the input required for the Ram Track program is the wind velocity in meters per second and the direction the wind is blowing in degrees.

Additional input data that the program requires is the latitude and longitude landing location for the system if it descended to ground level under the drogue parachute. Using this data and the wind profile entered, the MatLab program will generate two .kml files that can be plotted in Google Earth. The first file plots two keypoints that label the latitude and longitude locations for the deployment altitude and the latitude and longitude for the landing location if descent occurred strictly under the drogue parachute. The second file plots a circle representing the area that the ram air parachute could reach if deployed at 10,000 ft. This area is overlaid on the Google Earth base map. Theoretically, anywhere within the plotted region is a possible landing area for the ram air parachute. This allows the user to select a location that is deemed the safest landing zone and direct the system to steer to that location. In Figure 6, green and red areas are plotted that represent safe and unsafe landing locations, respectively. These plots were added for display purposes only and are not plotted by the prediction software. A copy of the Ram Track program is present in Appendix 2

C. Flight Control Software

All flight control is carried out by the use of user entered and software embedded commands. These commands are delivered as telemetry messages to the bus system and are sent at 1200 baud, which means approximately 120 characters per second. This is implemented with interrupt-driven UART ports, so that the power microprocessor can continue its duties without being blocked by transmission and reception. The following is a list of primary commands that can be sent and will be further discussed:

*Cutaway**	*deploy**	*track,xxxxxx**	*manual**	*land,xxxxx**
*cut,xxxxxx**	*depl,xxxxx**	*autooff**	*land**	*powerdown**

1.   Main Routine

The main routine of the onboard software consists of an iterative loop running almost throughout the entire flight. When in the loop, the first duty of the microcontroller is to examine the status of the serial buffer on TX1, checking for received data. If there is a command, it will execute the command and return to its main routine; otherwise, it performs the remaining duties in the main loop. The microcontroller reads GPS position on RX2 and then reads temperature and pressure on the I2C data line from both sensors. After requesting and receiving all sensor data, it packetizes relevant data and then transmits it over RX1 to the radio.

The three main routines differ depending on the flight phase. The main routine for the assent can be seen in .**Error! Reference source not found..** Figure 9 shows the main routine for the drogue fall phase, while the main fall main routine can be seen in Error! Reference source not found..

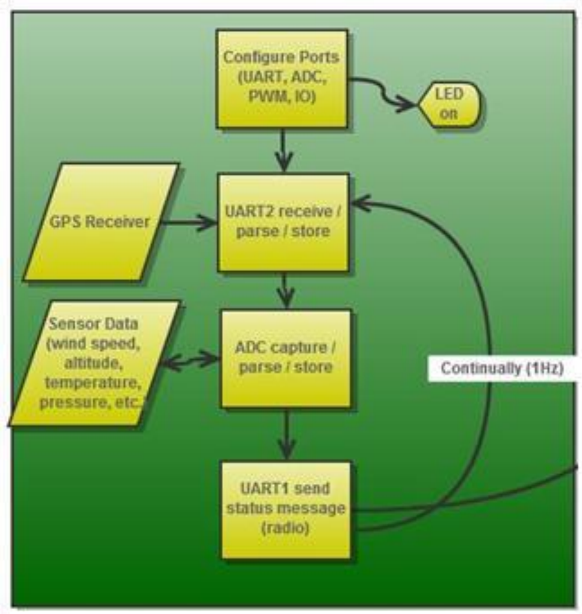

Figure 7. Main Routine - Accent *

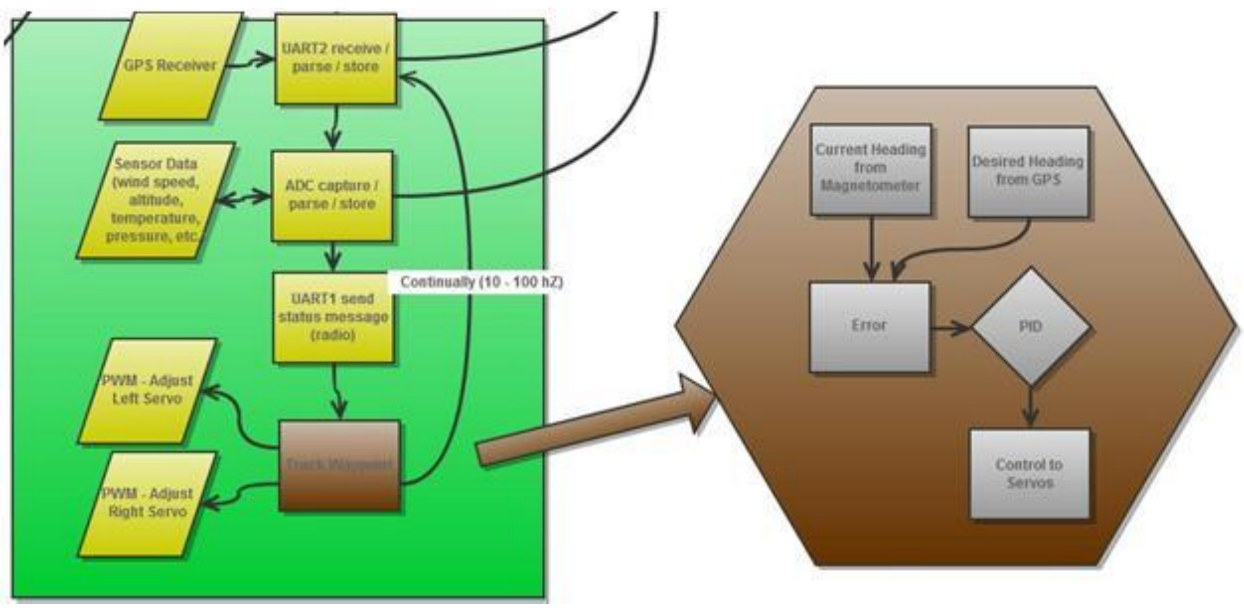

Figure 8. Main Fall Routine

* Footnote input command syntax is denoted with italics

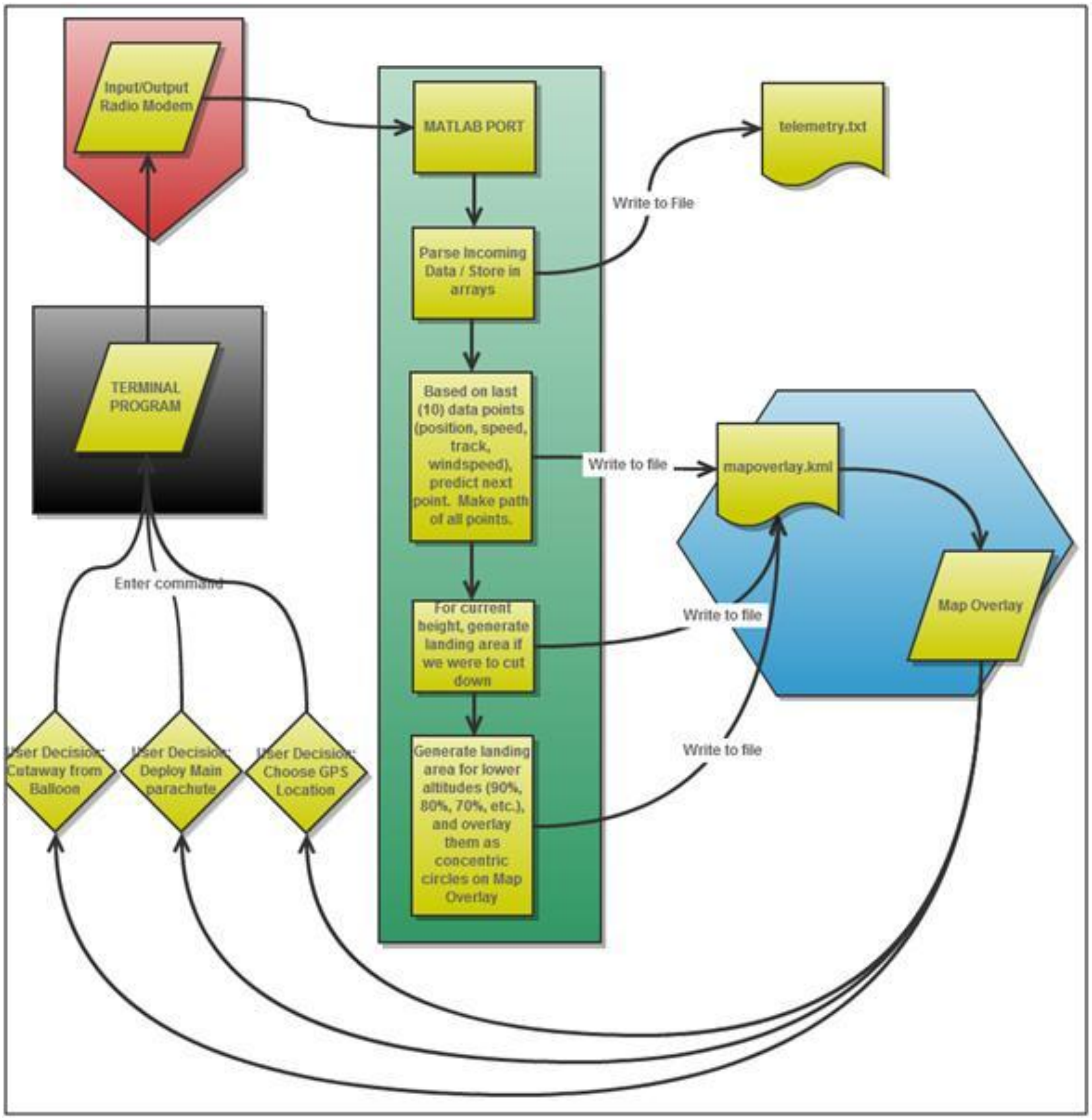

Figure 9. Main Routine – Drogue Fall

2. Cutaway

Upon receiving the “cutaway command,” the software routine sets PIN0 of the available GPIO pins to HIGH for five seconds. Once *cut,xxxxxx* (xxxxxx is altitude in meters) is received, the software routine will set PIN0 of the available GPIO pins to HIGH when the altitude reaches or drops below the altitude specified by *xxxxxx*. The *cutaway* command will immediately initiate the cutaway routine, regardless of whether a cut point was set by the *cut,xxxxxx* command or not. The interrupt routine can be seen in XXXX During the decent of the HAB train, if the altitude reading from the GPS or pressure sensors is below the minimum cutaway altitude, *MIN_CUT_ALTITUDE*, the microcontroller will initiate the cutaway routine. This occurs regardless of whether a command was received and is immediately followed with the deploy routine.

3. Deploy

When the “deploy” command is entered, the software routine sets PIN0 of the available GPIO pins to HIGH for a set amount of time. Upon receiving *depl,xxxxxx*, the software routine will set PIN1 of the available GPIO pins to HIGH once the altitude is equal to or less than the altitude specified by *xxxxxx*. PIN1 will remain high for a specified amount of time whe[6]ther the altitude momentarily climbs above *xxxxxx* again or not. The command

[*] Input command syntax is denoted with italics

deploy will immediately initiate the cutaway routine, this will override a previously entered *depl,xxxxxx* command. Again on decent, if the altitude reading from the GPS or pressure sensors is below the minimum cutaway altitude, *MIN_CUT_ALTITUDE*, the balloon will initiate a cutaway routine and immediately follow it with a deploy routine.

4. *Flight Modes and Auto Steering Flight*

Once there is a successful deployment of the main parachute, the vessel will begin steering toward the location designated by the coordinates saved to memory by the *track, xxxxxx* command.. If no location has yet been sent to the vessel, it will drift freely under the main parachute without powering the servos. If it does have a location saved in memory, an additional routine is added to the main software loop. This additional routine, seen in Figure 10, provides steering control for the ram air parachute with the following sequence: read position, speed, and heading data from the GPS, read and compare heading data from the magnetometer, perform calculations and conversions, and, finally, control steering lines with servo outputs.

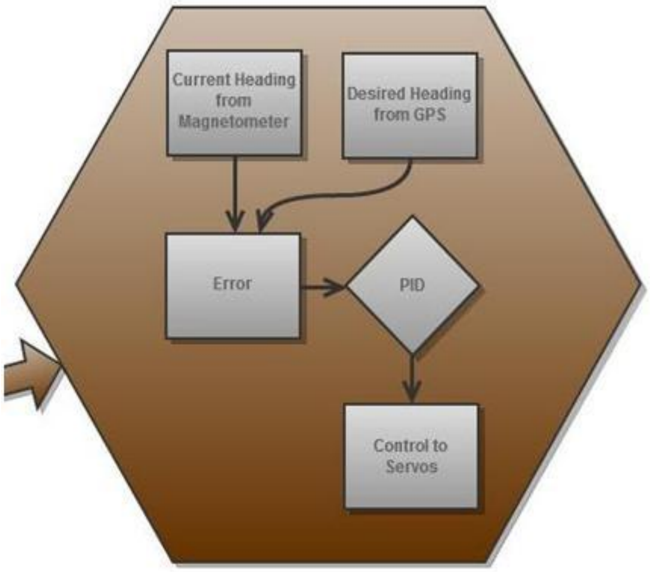

Figure 10. Main Parachute Steering Routine

5. **Two Dimensional Tracking**

The two dimensional tracking is implemented with the *track, xxxxxxx* command, where *xxxxxx* is the coordinate of the point that the vessel is tracking toward. Issuing this command will set PIN2 of the GPIO pins to HIGH, which switches on the MOSFET controlling power to the two servos onboard the craft. This pin will stay HIGH unless the *autooff* command is sent. The tracking algorithm uses the GPS and sensor data, along with the destination coordinates, to generate a value to send each servo. This value is converted into a PWM signal, which locks the servo at a certain setting and does not change until the next iteration of the loop, where this value is recalculated in the tracking algorithm. Currently, the available data used to steer the payload bus is derived from the GPS and magnetometer. This includes: location, calculated heading, and calculated speed.

6. *Rate of Descent and Landing*

Several methods of controlling decent and landing have been analyzed. The methods found most desirable, but not implemented, will now be discussed. Theoretically, actuating both servos at the same time should increase the vessel's descent rate by changing the glide ratio. Similarly, the payload bus could be induced into a controlled, slow spiral down to the ground once it is within a certain range of the landing spot, or when it is a certain height above the average ground altitude of the area. The average ground height of the area the payload bus is designated to land could be viewed by the ground control station operator on a map and sent with the *land, xxxxxx* command. Otherwise, a "land" command could be sent to initiate a landing at the payload's current location.

7. *Power-down*

If a the *powerdown* command is issued, the power microcontroller will turn the main microprocessor, all sensors, servos, and the radio off, as well as, turn on a radio tracking beacon. By leaving the power pick on, control of the GPS and radio transmitters are maintained. The pololu switch, requiring a digital HIGH (5V) signal, guarantees the power-down command is not falsely issued

8. *Autopilot Control*

During the flight, when the microcontroller receives the *track,xxxx*, *land*, or *land,xxxx* command, the servos are powered on by a GPIO controlled MOSFET switch. They receive PWM pulses from the second microcontroller, the AtMega328, on the board (which is solely for PWM capture and generation). This second microcontroller receives the servo position values (a numerical value generated by the tracking algorithm) from the main microcontroller and generates the PWM signal from this value.

9. *Manual Control*

If at some point during the flight, the main microcontroller receives the command manual, then it will send a command to the second microcontroller, specifying that it now operates as a pass-through for the RC receiver on the PCB**.**. The Atmega328 reads the PWM signals from the receiver and replicates them, outputting the signals to the servos and allowing an operator on the ground to remotely steer the vessel.

D. Safety / Failsafe / Redundancy

If the electrical system stops working for any reason, a failsafe “auto-cutaway” command is issued by the 555 timer. This command immediately cuts away balloon and releases the lines on the deployment bag. The ram-air parachute is released because it provides the highest coefficient of lift, allowing the longest amount of time for the microcontrollers to reset the system.

VI. Conclusions

With the current settings, the main parachute, if kept, would allow for soft landings and excellent steer-ability. This would, in turn, result in the likelihood that the payload would be returned without damage. For the drogue chute, a three foot diameter parachute would be used in order to get the proper rate of descent. With the current two foot diameter parachute, the descent rate would likely to be too fast for most payloads, especially in thin air conditions. With a higher descent rate, the payload bus would more likely be get damaged. Plus, when the main parachute is deployed, the impact forces imparted on the payload bus structure and parachute will be much larger, meaning that a failure in one of these critical components would be more likely.

VII. Recommendations

The parachute, acquired through Hobbyking, requires a more detailed profile, which the PIGEON team felt unable to complete with current UND resources. The chute was restrung with a heavier nylon string to prevent the breaking of lines during deployment testing and to reduce the number of control lines. The as-purchased rigging possessed an extremely high number of lines in order to allow the parachute, as designed, to act as a parafoil wing for remote control ultra-lights, not our skydiving-type application. Additionally, the parachute area requires modification. The area of the chute, if reduced, would be more like that of a skydiving parachute. This could be done by cutting off cells of the parachute, therefore increasing the wing loading and improving flight characteristics for the light weight payload. However, in-depth testing would be required in order to ensure that the parachute’s flight characteristics would not be changed in an unfavorable manor for actual operation. This could be accomplished with extensive large wind tunnel testing. If not, the parachute and a dummy payload could also be dropped from an airplane or tethered balloon.

It is further recommend, except in failsafe mode, that the parachute not be deployed at an altitude above twenty thousand feet. This is because the winds and reduced air density above twenty thousand feet could have adverse effects on the parachute’s steer-ability. This would ultimately result in loss of control and prevent the payload from landing at the designated site.

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Appendix

Appendix 1: Annotated FAA Regulations 4
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Appendix 1: Annotated FAA Regulations

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14 CFR PART 101 -- MOORED BALLOONS, KITES, UNMANNED ROCKETS AND UNMANNED FREE BALLOONS

Subpart A -- General

§101.1 Applicability.

(a) This part prescribes rules governing the operation in the United States, of the following:

(4) Except as provided for in §101.7, any unmanned free balloon {1} that --

(i) Carries a payload package that weighs more than four pounds and has a weight/size ratio of more than three ounces per square inch on any surface of the package, determined by dividing the total weight in ounces of the payload package by the area in square inches of its smallest surface;

(ii) Carries a payload package that weighs more than six pounds;

(iii) Carries a payload, of two or more packages, that weighs more than 12 pounds; or

(iv) Uses a rope or other device for suspension of the payload that requires an impact force of more than 50 pounds to separate the suspended payload from the balloon {2}.

§101.3 Waivers.

No person may conduct operations that require a deviation from this part except under a certificate of waiver issued by the Administrator.

§101.5 Operations in prohibited or restricted areas.

No person may operate a moored balloon, kite, unmanned rocket, or unmanned free balloon in a prohibited or restricted area unless he has permission from the using or controlling agency, as appropriate.

§101.7 Hazardous operations.

(a) No person may operate any moored balloon, kite, unmanned rocket, or unmanned free balloon in a manner that creates a hazard to other persons, or their property {3}.

(b) No person operating any moored balloon, kite, unmanned rocket, or unmanned free balloon may allow an object to be dropped therefrom, if such action creates a hazard to other persons or their property.

Subpart D -- Unmanned Free Balloons {4}

§101.31 Applicability.

This subpart applies to the operation of unmanned free balloons. However, a person operating an unmanned free balloon within a restricted area must comply only with §101.33 (d) and (e) and with any additional limitations that are imposed by the using or controlling agency, as appropriate.

§101.33 Operating limitations.

No person may operate an unmanned free balloon --

(a) Unless otherwise authorized by ATC, below 2,000 feet above the surface within the lateral boundaries of the surface areas of Class B, Class C, Class D, or Class E airspace designated for an airport;

(b) At any altitude where there are clouds or obscuring phenomena of more than five-tenths coverage;

(c) At any altitude below 60,000 feet standard pressure altitude where the horizontal visibility is less than five miles;

(d) During the first 1,000 feet of ascent, over a congested area of a city, town, or settlement or an open-air assembly of persons not associated with the operation; or

(e) In such a manner that impact of the balloon, or part thereof including its payload, with the surface creates a hazard to persons or property not associated with the operation.

§101.35 Equipment and marking requirements.

(a) No person may operate an unmanned free balloon unless --

> (1) It is equipped with at least two payload cut-down systems or devices that operate independently of each other; {5}
>
> (2) At least two methods, systems, devices, or combinations thereof, that function independently of each other, are employed for terminating the flight of the balloon envelope; {6} and
>
> (3) The balloon envelope is equipped with a radar reflective device(s) or material that will present an echo to surface radar operating in the 200 MHz to 2700 MHz frequency range.{7}
>
> The operator shall activate the appropriate devices required by paragraphs (a) (1) and (2) of this section when weather conditions are less than those prescribed for operation under this subpart, or if a malfunction or any other reason makes the further operation hazardous to other air traffic or to persons and property on the surface {8}.

(b) No person may operate an unmanned free balloon below 60,000 feet standard pressure altitude between sunset and sunrise (as corrected to the altitude of operation) unless the balloon and its attachments and payload, whether or not they become separated during the operation, are equipped with lights that are visible for at least 5 miles and have a flash frequency of at least 40, and not more than 100, cycles per minute {9}.

(c) No person may operate an unmanned free balloon that is equipped with a trailing antenna that requires an impact force of more than 50 pounds to break it at any point, unless the antenna has colored pennants or streamers that are attached at not more than 50 foot intervals and that are visible for at least one mile {10}.

(d) No person may operate between sunrise and sunset an unmanned free balloon that is equipped with a suspension device (other than a highly conspicuously colored open parachute) more than 50 feet along, unless the suspension device is colored in alternate bands of high conspicuity colors or has colored pennants or streamers attached which are visible for at least one mile.

§101.37 Notice requirements.

(a) Prelaunch notice: Except as provided in paragraph (b) of this section, no person may operate an unmanned free balloon unless, within 6 to 24 hours before beginning the operation, he gives the following information to the FAA ATC facility that is nearest to the place of intended operation: {11}

(1) The balloon identification.

(2) The estimated date and time of launching, amended as necessary to remain within plus or minus 30 minutes.

(3) The location of the launching site.

(4) The cruising altitude.

(5) The forecast trajectory and estimated time to cruising altitude or 60,000 feet standard pressure altitude, whichever is lower.

(6) The length and diameter of the balloon, length of the suspension device, weight of the payload, and length of the trailing antenna.

(7) The duration of flight.

(8) The forecast time and location of impact with the surface of the earth.

(b) For solar or cosmic disturbance investigations involving a critical time element, the information in paragraph (a) of this section shall be given within 30 minutes to 24 hours before beginning the operation.

(c) Cancellation notice: If the operation is canceled, the person who intended to conduct the operation shall immediately notify the nearest FAA ATC facility.

(d) Launch notice: Each person operating an unmanned free balloon shall notify the nearest FAA or military ATC facility of the launch time immediately after the balloon is launched {12}.

§101.39 Balloon position reports {13}.

(a) Each person operating an unmanned free balloon shall:

(1) Unless ATC requires otherwise, monitor the course of the balloon and record its position at least every two hours; and

(2) Forward any balloon position reports requested by ATC.

(b) One hour before beginning descent, each person operating an unmanned free balloon shall forward to the nearest FAA ATC facility the following information regarding the balloon:

(1) The current geographical position.

(2) The altitude.

(3) The forecast time of penetration of 60,000 feet standard pressure altitude (if applicable).

(4) The forecast trajectory for the balance of the flight.

(5) The forecast time and location of impact with the surface of the earth.

(c) If a balloon position report is not recorded for any two-hour period of flight, the person operating an unmanned free balloon shall immediately notify the nearest FAA ATC facility. The notice shall include the last recorded position and any revision of the forecast trajectory. The nearest FAA ATC facility shall be notified immediately when tracking of the balloon is re-established.

(d) Each person operating an unmanned free balloon shall notify the nearest FAA ATC facility when the operation is ended.

Annotation:
{1} Payload strings that don't exceed <u>any</u> of these four limits are exempted from <u>all</u> other FAR 101 provisions, <u>except</u> 101.7. EOSS reads "payload" to mean those parts of the flight string that do the work of the mission, independent of how they get to altitude and back down. Thus we do not include the weight of the balloon, parachute or cut-downs in this tally; the latter are members of the "flight system". Tracking beacons, although arguably flight system components, are included in payload weight, however, since they are critical to the payload recovery mission goal.

{2} This applies only to the load line between the balloon and parachute. "Impact strength" is undefined, but should <u>not</u> be equated to the line's rated tensile strength; a 50 lb tensile line will break during launch. The intent of this limit is to ensure that the balloon detaches in the event of collision with an aircraft. EOSS uses 250 lb woven nylon kite line which did break at a knot during "post-burst chaos" on one flight.

{3} This is the dreaded "Catch 22" clause that the FAA may impose on those who have gained its unfavorable attention. One cannot successfully argue that a payload string in flight is totally free from all risks to others. However, taking all reasonable steps to mitigate those risks, such as keeping the flight crews and controllers up to date on your location and altitude and avoiding heavily populated areas, will garner the FAA's respect and cooperation.

{4} This subPart applies <u>only</u> to those payloads which are <u>not</u> exempt according to Section 101.1 (a) (4). However, it's still advisable to adhere to as many of these requirements as reasonably possible (Ibid).

{5} A latex balloon which will burst at altitude is considered to be its own independent cutdown device. The second device should be a radio-commandable cutter. Plastic balloons <u>must</u> have a commandable primary cut-down and an independent timer-based backup.

{6} A plastic balloon must have some means to dump the fill gas to ensure that it returns to the surface. A latex "burster" serves as its own destruct device.

{7} The FAA rarely tracks "primary returns" from balloons, relying more on Mode C transponders, and they may require one on "heavy" non-exempt flights. However, having a GPS-based beacon and a reputation for accurate and timely reports on prior exempt flights may alleviate you from having to carry along this expensive and heavy (7 lb) RFI generator.

{8} A balloon which fails to return to the surface via either commanded or timed termination means or burst is labeled a "derelict" and presents a serious hazard to air navigation. It will descend into commercial airspace at night, and if its batteries die, its location and altitude are unknown except by visual encounter by flight crews. Flying a derelict is the surest means to gain the unfavorable attention mentioned in footnote 3 above.

{9} Battery-operated xenon flashtube strobe lights, available at sporting goods stores, have been used for this service, but special care should be taken to conformal coat the high-voltage circuitry which may develop corona or destructive arcover at altitude. The latest generation of high intensity LEDs, such as those seen more and more in traffic lights, may met this requirement while avoiding high-voltage problems. (1)

{10}These visibility requirements highlight the FAA's reliance upon visual collision avoidance by flight crews. Thus it is a good idea to give your payloads a light coat of dayglo orange. This also helps the recovery crew make a tally-ho call at a distance. The physical dimensions conforming to the one mile visibility requirement are unclear and may be highly dependent upon the viewer's visual acuity.

{11}This section describes the minimum content of the "HiBal Prelaunch Notice" filed with ARTCC, the TRACON of the nearest airport and FSS. EOSS faxes this notice about 1 week in advance to give the ARTCC Airways and Procedures folks a chance to respond. The EOSS HiBal requests a written response with "special provisions" instructions to be returned a couple of days before the launch. Those provisions typically include a prelaunch call with forecast trajectory thru several flight levels. This FAA response has served to alleviate concerns by visitors from time to time.

http://www.eoss.org/pubs/far_annotated.htm - _ftnref12{12} EOSS also makes a T-0:30 phone call to ARTCC and TRACON per the "special provisions". The operations folks invariably have a copy of our HiBal Notice, so there are no surprises. EOSS uses Rick von Glahn's Balloon Track with the latest NWS RAOB winds for our forecast position and altitude estimates. The FAA controllers prefer position reports in radial and NM range from the nearest high altitude VOR. This prelaunch call also includes the launch site cell phone number. If launch is delayed by over 10 minutes, we call in a new estimated launch time.

{13} The TRACON operations folks are typically interested in position reports below FL240, and ARTCC usually requests reports out of FL260, 450 and 600 in ascent and descent. Position accuracy to within a 5-mile radius is sufficient. The GPS-based APRS beacon makes this simple, but good RDF fixes and barometric altitude telemetry will serve just fine. (1)

Appendix 2: Prediction Software

Prediction Software

```
%This program will take an averaged widn profile from 10,000 ft. in
%altitude and the landing location of a strictly drogue parachute descent,
%and plot the latitude and longitude of the system at 10,000 ft. It will
%also output the accessible area the ram air parachute could reach in the given
%wind conditions.

%Author: Wyatt Shallbetter 07/21/1989
%Date Last Edited: 4/15/11

close all
clear all
clc

%specify the desired name of the .kml file
name = ['Potential Landing Area No Wind'];
folder=['Possible Landing Area'];

kmlfile=fopen([name '.kml'], 'wt');
fprintf(kmlfile,'<?xml version="1.0" encoding="UTF-8"?>\n<kml xmlns="http://www.opengis.net/kml/2.2" xmlns:gx="http://www.google.com/kml/ext/2.2" xmlns:kml="http://www.opengis.net/kml/2.2" xmlns:atom="http://www.w3.org/2005/Atom">\n<Document><name>\n');
fprintf(kmlfile,'%s\n',name);
fprintf(kmlfile,'</name><Folder><name>\n');
fprintf(kmlfile,'%s\n',folder);
fprintf(kmlfile,'</name><Placemark><name>\n');
fprintf(kmlfile,'%s\n',name);
fprintf(kmlfile,'</name><LineString><tessellate>1</tessellate><coordinates>\n');

% % %***************END OF .kml HEADER SECTION*********************************
%
% %User inputs landing location data for a drogue descent to Earth

LatLanding = input('Enter landing location latitude: ');
LonLanding = input('Enter landing location longitude: ');
Wind = input('Enter average wind velocity (m/s): ');
Heading = input('Enter what direction the wind IS BLOWING IN Cartesion Coordinates\n(North=90, East=0, South=270, West=180 degrees): ');

AGL = 0;
Deploy = 10000;

%User Sets the average horizontal velocity of the ram air parachute in m/s
Hvelocity = 6.62;

%User Sets the parachute descent time from 10,000 ft in seconds
Descent = 1555.17;

%Wind vector information is calculated given user inputs

Wx = Wind * Descent * cos (Heading * pi / 180);
Wy = Wind * Descent * sin (Heading * pi / 180);
```

```
%************Calculate Latitude and Longitude of Deployment Altitude*********

%calls the function that converts lat lon to UTM coordinates
[x,y,utmzone]=deg2utm(LatLanding,LonLanding);

%generate a vector that tells the postion of the drogue landing in m
Zone=utmzone;
P=[x,y,AGL];

%Calculates the latitude and longitude of the system at 10,000 feet
Sx = Wx;
Sy = Wy;

xx = x - Sx;
yy = y - Sy;

%takes the results of the conversion and puts it in matrix in order
[Lat_Dep,Lon_Dep] = utm2deg(xx,yy,utmzone);
latlon=[Lat_Dep,Lon_Dep];

%Sets the latitude and longitude of the deployment location aka the
%location from which the parachute will begin steering from
Lat = Lat_Dep;
Lon = Lon_Dep;

%******************End of location section******************

%calls the function that converts lat lon to UTM coordinates
[x,y,utmzone]=deg2utm(Lat,Lon);

%generate a vector that tells the postion of the deployment in m
Zone=utmzone;
P=[x,y,AGL];

for i=0:360
    Direction = i;
    Px = Hvelocity * Descent * cos (i * pi / 180);
    Py = Hvelocity * Descent * sin (i * pi / 180);

    Sx = Px + Wx;
    Sy = Py + Wy;

    xx = x + Sx;
    yy = y + Sy;

    [Lat_Loc,Lon_Loc] = utm2deg(xx,yy,utmzone);

    %takes the results of the conversion and puts it in matrix in order
    format long;
    latlon=[Lat_Loc,Lon_Loc];

    d=flipud(rot90(fliplr(latlon)));
    fprintf(kmlfile, '%.6f, %.6f, 0.0 \n', d);

end
```

```
%dlmwrite([name '.kml'], latlon, 'delimiter', ',', 'precision', '%.8g', '-append');
fclose(kmlfile);
kmlfile=fopen([name '.kml'], 'a');
fprintf(kmlfile,'</coordinates></LineString></Placemark></Folder></Document></kml>');
fclose(kmlfile);


%********************Plot the Drogue Landing Location****************************

%specify the desired name of the .kml file
name=['Landing and Deployment Locations No Wind'];
Landing=['Landing Location'];
Deployment=['Deployment Location'];
folder=['Coordinates'];

fcdn=fopen([name '.kml'], 'wt');
fprintf(fcdn,'<?xml version="1.0" encoding="UTF-8"?>\n<kml xmlns="http://www.opengis.net/kml/2.2" xmlns:gx="http://www.google.com/kml/ext/2.2" xmlns:kml="http://www.opengis.net/kml/2.2" xmlns:atom="http://www.w3.org/2005/Atom">\n');
fprintf(fcdn,'<Folder><name>\n');
fprintf(fcdn,'%s\n',folder);
fprintf(fcdn,'</name><Placemark><name>\n');
fprintf(fcdn,'%s\n',Landing);

latlonLanding=[LonLanding, LatLanding, AGL];

%list of all the required headers
format2=['</name><styleUrl>#msn_camera</styleUrl><Point><coordinates>'];
format3=['</coordinates></Point></Placemark>'];

fprintf(fcdn, '%s \n',format2);
fprintf(fcdn, '%.6f, %.6f,\n', latlonLanding);
fprintf(fcdn, '%s \n',format3);

%********************Plot the Deployment Location****************************

%specify the desired name of the .kml file
fprintf(fcdn,'<Placemark><name>\n');
fprintf(fcdn,'%s\n',Deployment);

latlonDeployment=[Lon, Lat, Deploy];

%list of all the required headers
format2=['</name><styleUrl>#msn_camera</styleUrl><Point><coordinates>'];
format3=['</coordinates></Point></Placemark>'];

fprintf(fcdn, '%s \n',format2);
fprintf(fcdn, '%.6f, %.6f,\n', latlonDeployment);
fprintf(fcdn, '%s \n',format3);

footer=['</Folder></kml>'];

fprintf(fcdn, '%s', footer);
fclose(fcdn);
```

Appendix 3: Parachute Analysis

Parachute Analysis

Accurate delivery of a payload by parachute is a requirement in both the space and military fields. The cost savings available from the recovery and re-use of expensive space vehicle elements provides an incentive to develop systems capable of allowing recovery to land sites. A parachute with glide and a control system can compensate for inaccuracies in drop point and wind. The greater the glide angle the greater the offset that can be achieved for a given drop altitude. Because of its high glide capability and its controllability the ram air parachute offers considerable scope for the delivery or recovery of payloads to a point by automatic control linked to a guidance system. Figure 14 shows a schematic of what a precision aerial delivery system looks like when the ram air parachute has been deployed. In it you can see the general conic shape that represents the volume of air a system can fly through. The cross section at its base, a circular area, represents the area on the ground the parachute system is capable of reaching.

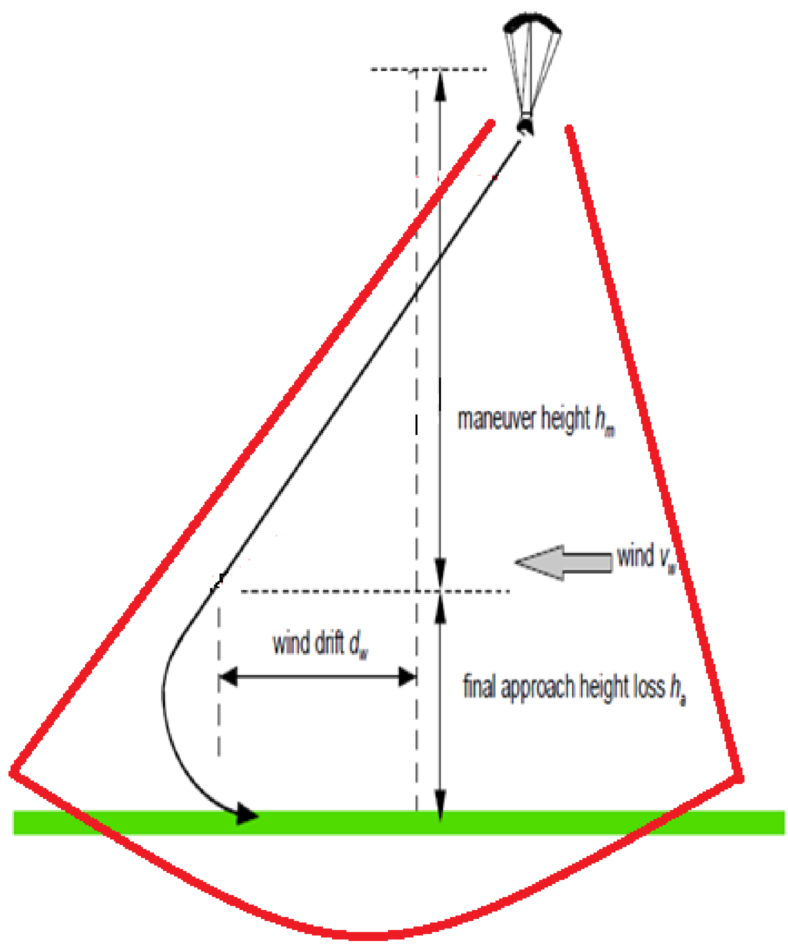

Figure 11: Precision Aerial Delivery System Principle

The operation of a precision aerial delivery system can be broken down into four steps:

- Deployment of a drag parachute and establishment of a steady decent;
- Deployment of a ram air parachute and establishment of a steady glide;
- Maneuvering flight to the landing zone;
- Final approach maneuver to landing point.

The altitude available for maneuver from an initial drop altitude h_o is:

$h_m = h_o - h_d - h_a$.

Equation 1

In the absence of wind the maneuvering radius R_m from any altitude h is:

$R_m = (h - h_a)$ ´ L/D

Equation 2

Where L/D is the parachute lift to drag ratio. The volume within which the system can maneuver to the landing zone is therefore a cone which, in zero wind, has a half angle of $\tan^{-1}(L/D)$. Therefore, the greater the L/D of a parachute, the greater the offset of initial drop it can tolerate and the more flexible it is for the PADS role. The effect of wind is to distort the cone. At any altitude the centre of the cone is moved by a distance d_w from the target where

$$\bar{d}_w = \int_0^h \frac{\bar{v}_w}{|w|} dh$$

Equation 3

Where v_w is the wind vector and w = rate of descent of the parachute. If the parachute is placed within the distorted cone an efficient guidance system will result in accurate delivery. If the system strays outside the cone the parachute will fail to reach the target.

The standard components that make up a precision aerial delivery system include:

- Drogue assembly
- Parafoil assembly
- Control unit
- Rigging and attachment hardware
- Deployment bag
- Release cutters

Ram Air Parachute Information

The ram-air parachute, when inflated, resembles a low aspect ratio wing. It is entirely constructed from fabric with no rigid members, which allows it to be packed and deployed in a manner similar to a conventional parachute canopy. The wing has upper and lower membrane surfaces, an airfoil cross section, and a rectangular planform. The airfoil section is formed by airfoil shaped ribs sewn chordwise between the upper and lower membrane surfaces at a number of spanwise intervals forming a series of cells. The leading edge of the wing is open over its entire length so that ram air pressure maintains the wing shape. The ribs usually have apertures cut in them. This allows the transmission of pressure from cell to cell during inflation and pressure equalization after. The fabric used in the manufacture of ram-air parachutes is as non-porous as possible to obviate pressure loss. Figure 15 shows the parts that make up a ram air parachute.

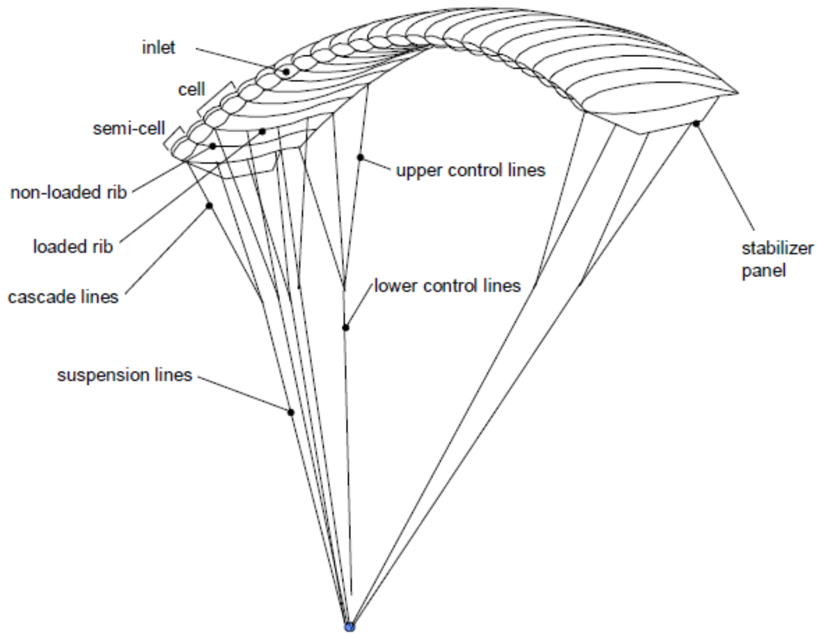

Figure 12: Ram Air Parachute

On current designs rigging lines are typically 0.6 - 1.0 spans in length, with the wing crown rigged, that is the lines in a given spanwise bank are equal in length. The wing therefore flies with arc-anhedral. Several airfoil sections have been used on ram air parachutes: most early wings used the Clark Y section with a section depth of typically 18% chord however recent designs have benefited from glider technology and use a range of low speed sections (e.g. NASA LS1-0417). Various nose aperture shapes have also been investigated as nose shape affects inflation and airfoil drag. There is also a trend to reduce section depth to reduce drag but this has proceeded slowly since inflation performance can be adversely affected. Means for lateral-directional and longitudinal control are provided by steering lines attached to the trailing edge of the canopy. These lines form a crow's-foot pattern such that pulling down on one line causes the trailing edge on one side of the canopy to deflect. Turn control is accomplished by an asymmetric deflection of the steering lines, and angle of incidence control and flare for landing are accomplished by symmetric deflection.

Ram Air Parachute Lift Coefficient

For small aspect ratio wings (aspect ratio < 5) the lifting line theory can be used with a slight modification to the calculation of the lift curve for the airfoil. Therefore the new sets of equations that can be used to calculate the coefficient of lift are as follows:

$$a = \frac{\pi^2 A a_0'}{180(\pi A + a_0'(1+\tau)}$$

Equation 4

$$a_0' = a_0 k$$

Equation 5

$$k = \frac{2\pi A}{a_0} tanh \frac{a_0}{2\pi A}$$

Equation 6

$A = width * depth$

Equation 7

Where $a = lift\ curve$
A = aspect ratio
$a_0 = .12\ deg^{-1}$
$\tau = .12$

The ram air parachute that is to be used has the following parameters:

- Width = 2.15 m
- Depth = 0.54 m
- Weight = 0.190 kg

Using equations Equation 4 through Equation 7 gives the following values:

A = 3.98
$a = .073\ deg^{-1}$

From this value for a can be calculated the coefficient of lift for the ram air parachute using the following equation:

$$\boldsymbol{C_L = a(\alpha - \alpha_{ZL})}$$

Equation 8

Where $C_L = Coefficient\ of\ Lift$
$a = lift\ curve$
$\alpha = angle\ of\ attack$
$\alpha_{ZL} = zero\ angle = -7^o\ for\ thin\ airfoils$

A plot of the theoretical coefficient of lift for the chosen ram air parachute can be seen below in Figure 13. It is important to note that experimental observations of parachutes has shown that at angles of attack below zero and above six degrees has shown fairly significant deviation from the theoretical coefficient of lift and it is thus important to remain within this region to obtain the theoretical flight characteristics.

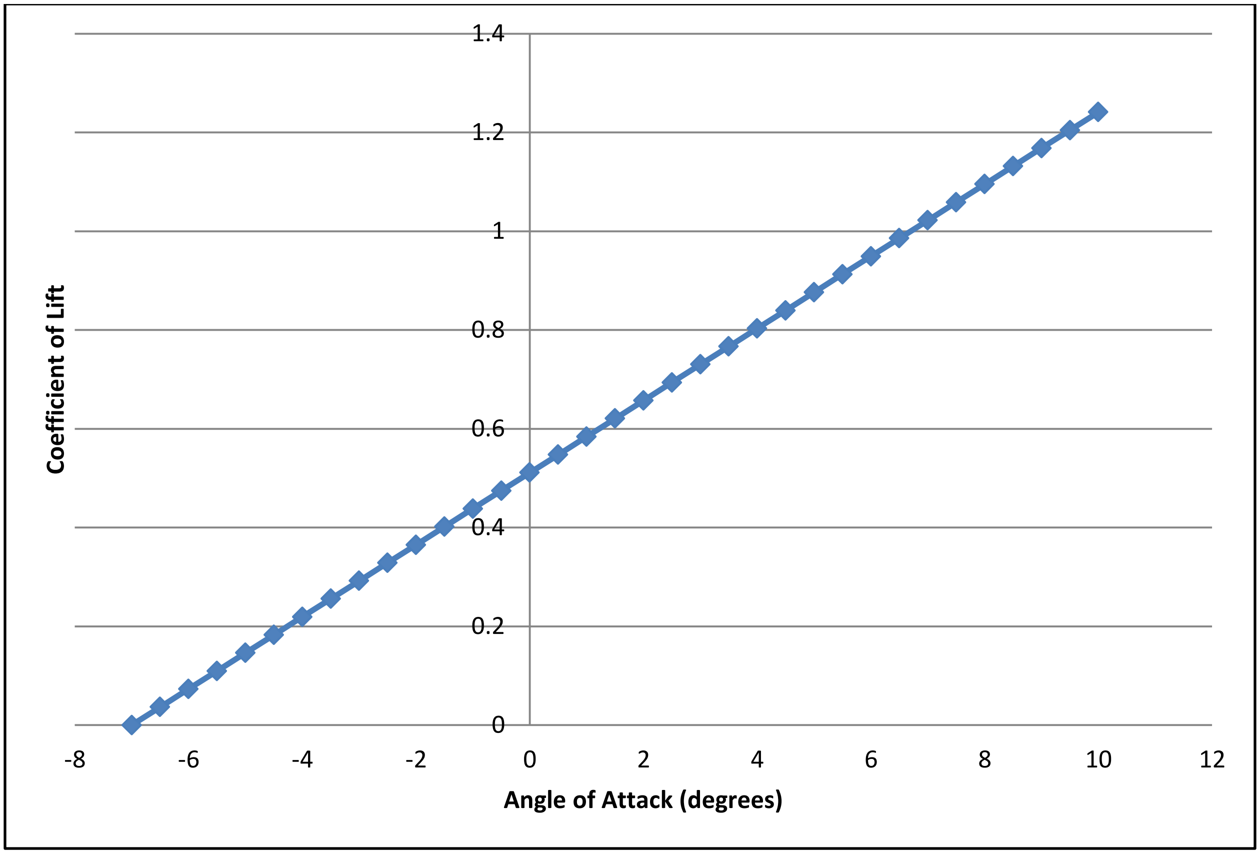

Figure 13: Theoretical Coefficient of Lift for Selected Ram Air Parachute

We then further refined analysis of the theoretical coefficient of lift for a ram air parachute by taking into account the anhedral angle of the parachute. Figure 14 displays what is meant by the anhedral angle.

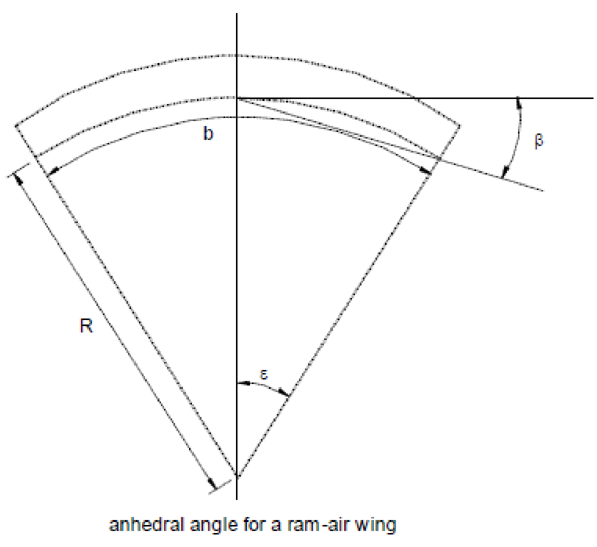

Figure 14: Anhedral Angle for Ram Air Parachute

For the current parachute being used the exact line rigging is yet unknown and thus it is not currently possible to calculate the anhedral angle. The calculated coefficient of lift taking into account the anhedral angle can be accomplished by adding a further term to equation eight and produces a new further refined calculation as can be seen in equation nine.

$$C_L = a(\alpha - \alpha_{ZL})cos^2\beta$$

Equation 9

Where $\beta = anhedral\ angle$

Ram Air Parachute Drag Coefficient

The overall drag of a gliding parachute system comprises the sum of wing drag, line drag and store drag. To simplify the estimation of line drag it is assumed that all lines are the same length and are subject to the same normal velocity *V*cos*a* where *V* is the system velocity. For typical Reynolds numbers the drag coefficient of a suspension line would be approximately 1.0. The contribution of line drag to the total system drag may therefore be estimated by:

$$C_{Dl} = \frac{nRdcos^3\alpha}{S}$$

Equation 10

Where n = number of lines
R = mean line length
d = line diameter
S = canopy area

The overall drag for the system can thus be estimated as:

$$C_D = C_{DO} + C_{Dl} + C_{Ds} + \frac{C_L^2(1+\delta)}{\pi A}$$

Equation 11

Where $C_{DO} = profile\ drag$
$C_{Dl} = line\ drag$
$C_{Ds} = store\ drag$
$\delta = .028\ \ (non - elliptic\ loading\ factor)$

The profile drag of a parachute can be estimated based on the dimensions of the parachute and is composed of a sum of the following parameters:

- Basic airfoil drag = 0.015
- Surface irregularities and fabric roughness = 0.004
- Open airfoil nose = 0.5*H/C
    - H = inlet height
    - C = chord length

Therefore based on the parameters of the airfoil selected for this system the profile drag can be calculated to be 0.1905. The store drag of the parachute selected can be estimated to be 0.006 which is based on the selected size of the payload that will be carried by the parachute.

These values can then be used to calculate the theoretical coefficient of drag for selected ram air parachute at given angles of attack. These calculations are plotted in Figure 18.

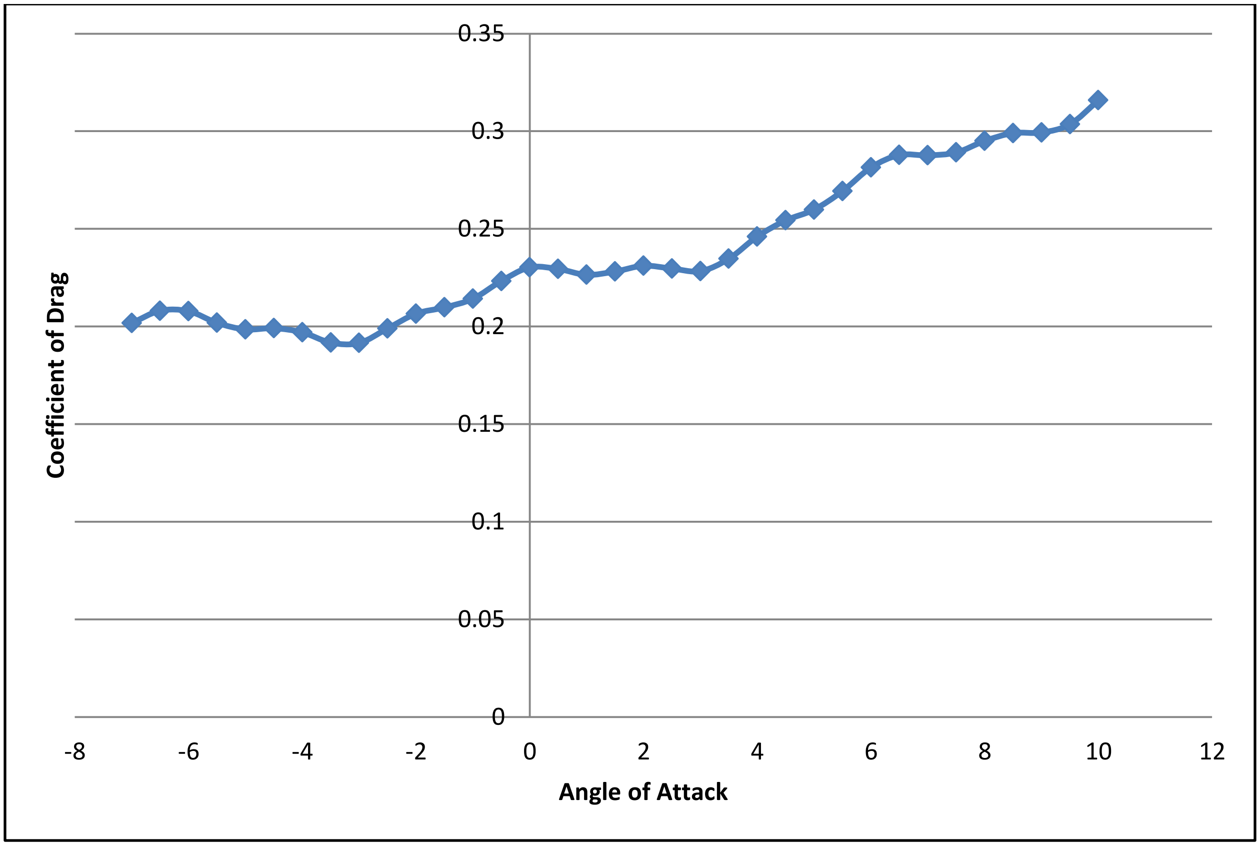

Figure 15: Theoretical Coefficient of Drag for Selected Ram Air Parachute

Ram Air Parachute Lift to Drag Ratio

To obtain the maximum flight performance for a parachute it is desirable to have the highest lift to drag ratio possible. Similar to the coefficient of lift the theoretical approximation for the coefficient of lift is only reasonably accurate for angles of attack between zero and six degrees. Experimental results for a number of parachutes have further shown that the lift to drag ratio is generally maximum just before the angle of attack that the parachute stalls at. The plotted lift to drag ratio can be seen in Figure 16.

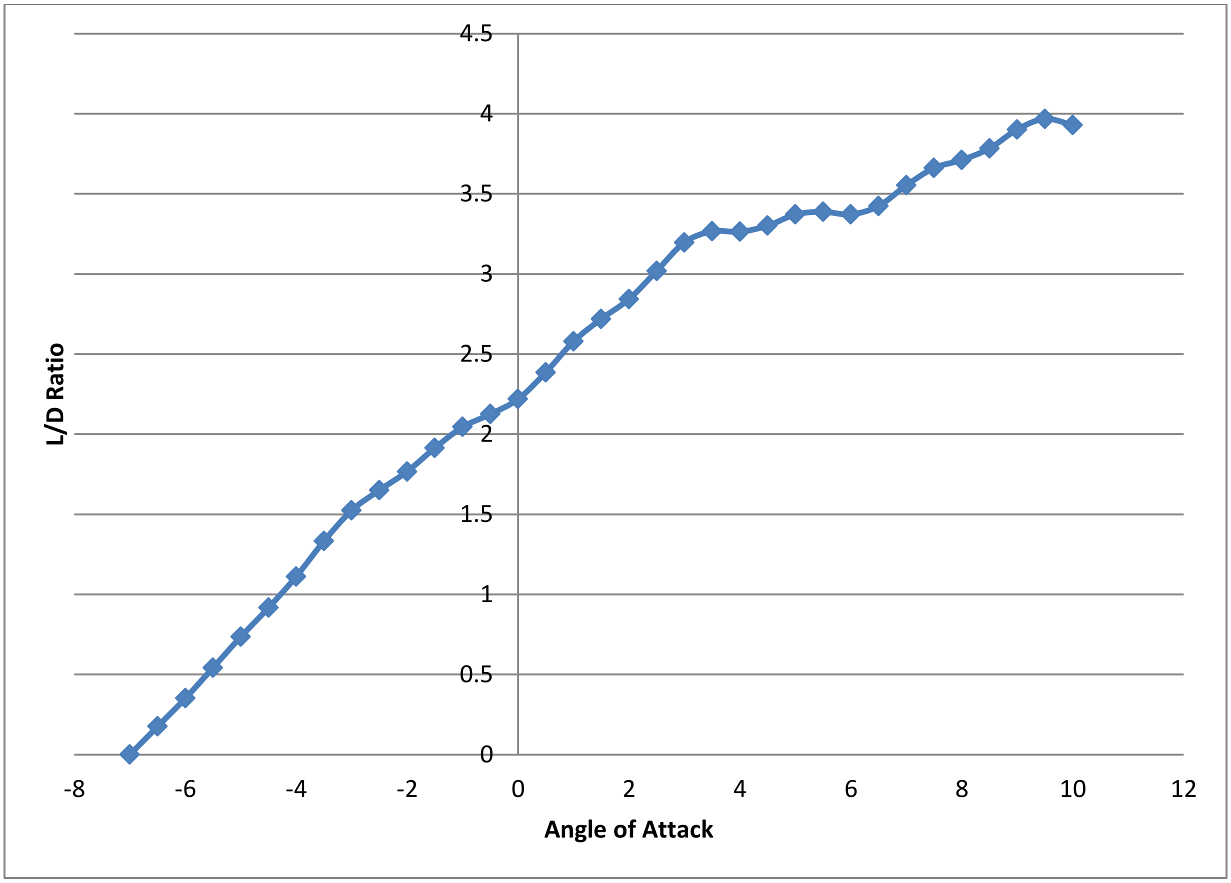

Figure 16: Theoretical Lift to Drag Ratio for Selected Ram Air Parachute

Ram Air Parachute Flight Performance

In order to best predict the flight behavior of the ram air parachute it is necessary to do a free body diagram of the system and calculate the forces acting on the parachute. It is necessary for a precision delivery system to have some ability to penetrate winds thus it is essential to know the attainable velocities for a system at various lift to drag ratios. In order to accomplish these conditions a parachute with simplified payload is modeled in Figure 17. The flight analysis of this set up follows.

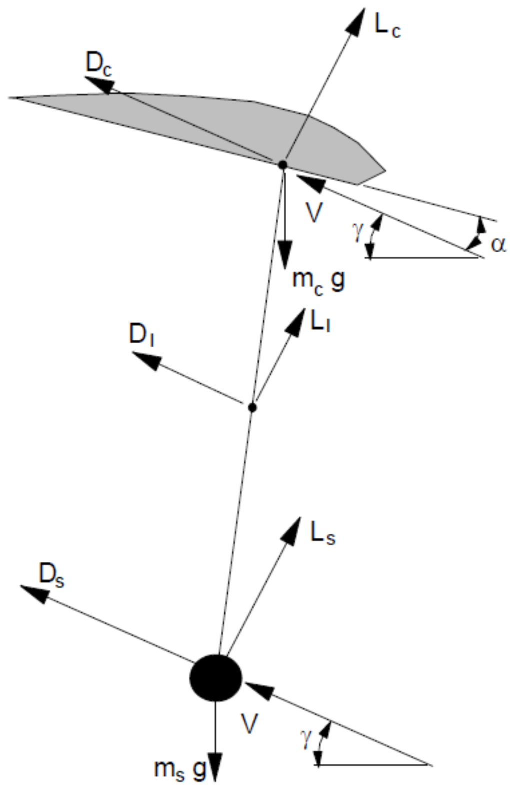

Figure 17: Ram Air Parachute in Steady, No Wind Glide

Sum of the Forces:

X-Direction $(L_c + L_l + L_s)sin\gamma - (D_c + D_l + D_s)cos\gamma = 0$

Equation 12

Y-Direction $(m_s + m_c)g - (L_c + L_l + L_s)cos\gamma - (D_c + D_l + D_s)sin\gamma = 0$

Equation 13

Where L_c = lifting force on canopy
L_l = lifting force acting on suspension lines
L_s = lifting force acting on payload
D_c = drag force on canopy
D_l = drag force on suspension lines
D_s = drag force on payload
m_c = mass of canopy
m_c = mass of payload
g = acceleration due to gravity

From the sum of forces in the x-direction we can obtain the relation:

$$\frac{L}{D} = \frac{C_L}{C_D} = \frac{1}{tan\gamma}$$

Equation 14

Where $L = L_c + L_l + L_s$ = total system lift
$D = D_c + D_l + D_s$ = total system lift
$C_L = \frac{L}{0.5\rho V^2 S}$
$C_D = \frac{D}{0.5\rho V^2 S}$
S = reference area
$\rho = air\ density$

With these relations the sum of the forces in the y-direction can also be transformed into a simplified equation.

$$W = 0.5\rho V^2 S(C_D cos\gamma + C_L sin\gamma)$$

Equation 15

Where $W = (m_c + m_s)g$

Equation 16

Substituting in the simplified relation from the forces in the x-direction leads to the equation:

$$W = 0.5\rho V^2 S(C_L^2 + C_D^2)^{0.5}$$

Equation 17

From this equation we can calculate the velocity of the parachute for a given angle of attack or applicable lift to drag ratio using the following equation:

$$V = \left(\frac{2}{\rho} * \frac{W}{S} * \frac{1}{(C_L^2 + C_D^2)^{0.5}}\right)^{0.5}$$

Equation 18

The horizontal (u) and vertical (v) velocities of the parachute can then be calculated by the following relations:

Where **u** = Vcosγ
v = Vsinγ

As the density of air changes based on the temperature and altitude it is important to take into account the changing density as this will alter the parachutes forward velocity and descent rate. The approximate density of air corresponding to a given altitude is displayed in Table 1: Density of Air at a Given Altitude. These densities were then used to calculate the approximate velocity of the parachute at the corresponding altitude which can be seen in Figure 18.

Table 1: Density of Air at a Given Altitude

Altitude (ft)	Density (kg/m^3)
0	1.23
5000	1.06

10000	0.91
15000	0.77
20000	0.65

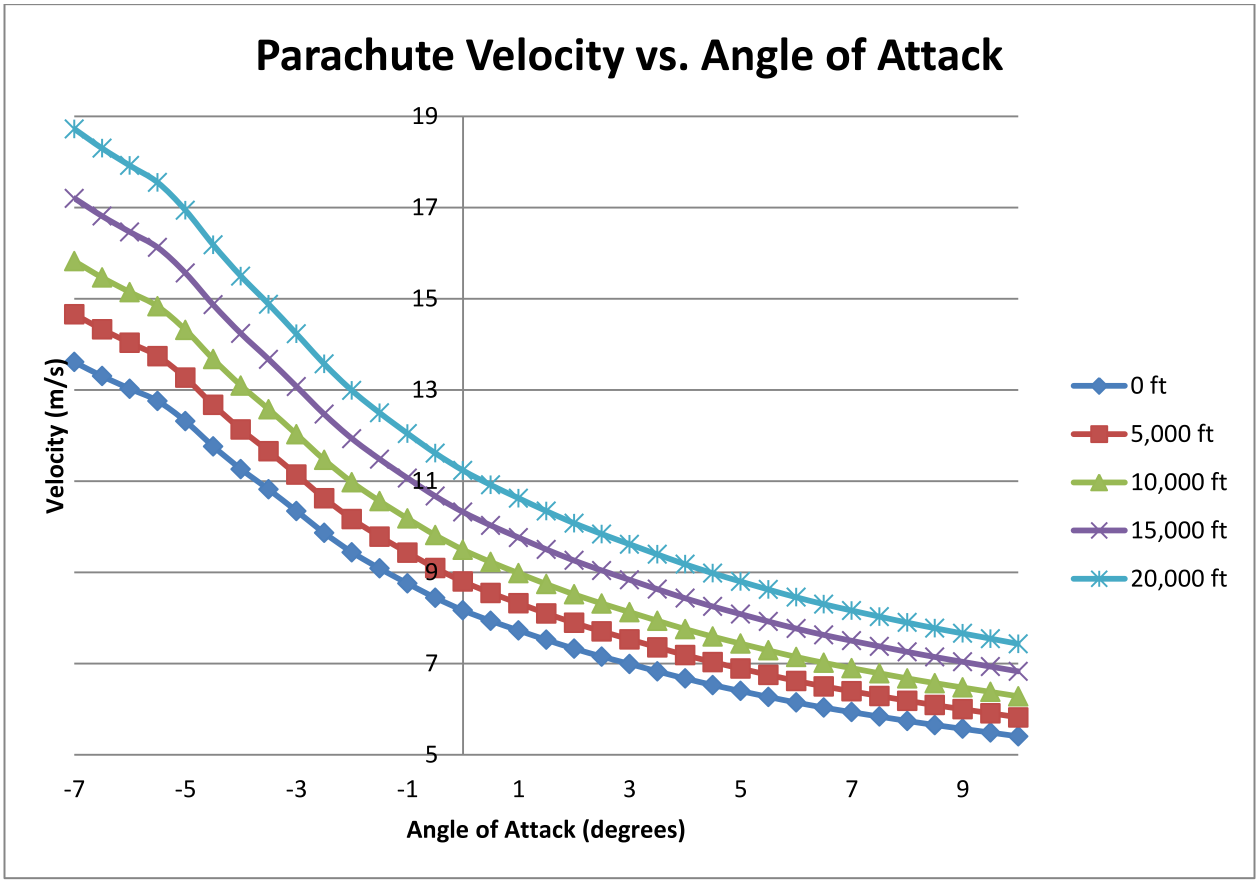

Figure 18: Parachute Velocity At A Given Angle Of Attack And Altitude

In order to fully determine the flight characteristics of the parachute it is necessary to break the parachute's velocity down into its horizontal and vertical characteristics. As it was previously stated that theoretical calculations for the coefficient of lift are only accurate for angles of attack between zero and six, only these parameters will be used in calculating velocity. Figure 19 displays the estimated horizontal velocity of the parachute for a given altitude and angle of attack.

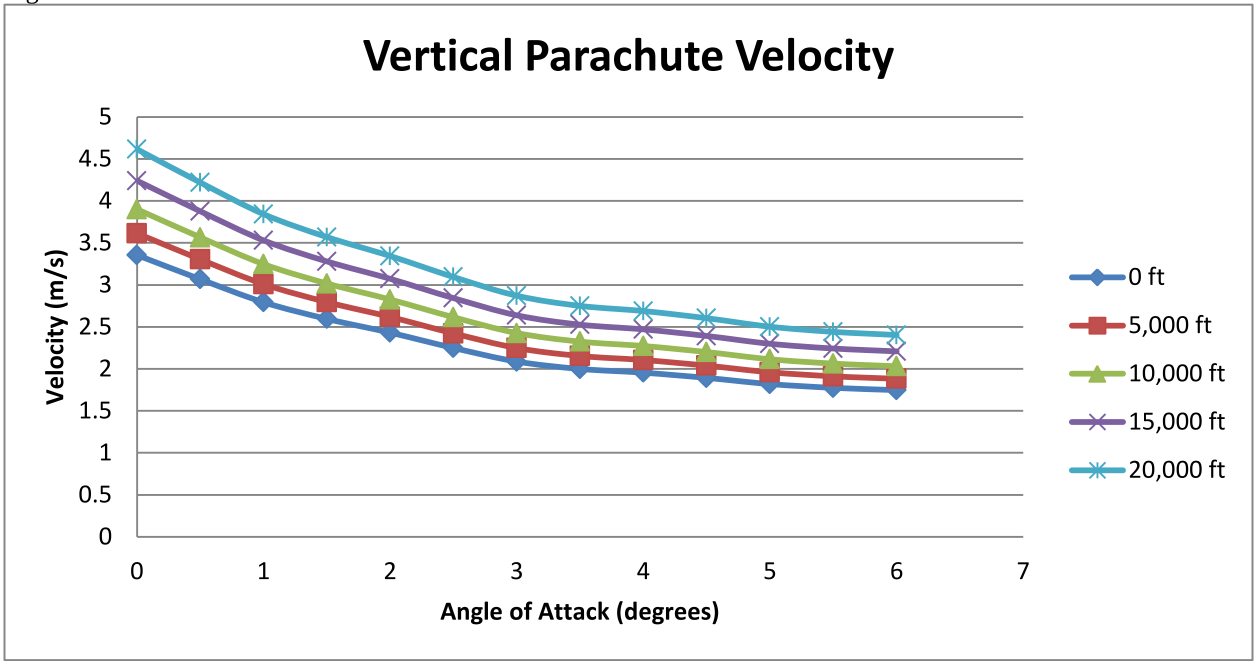

Figure 20 displays the estimated vertical velocity the parachute at a given velocity and angle of attack.

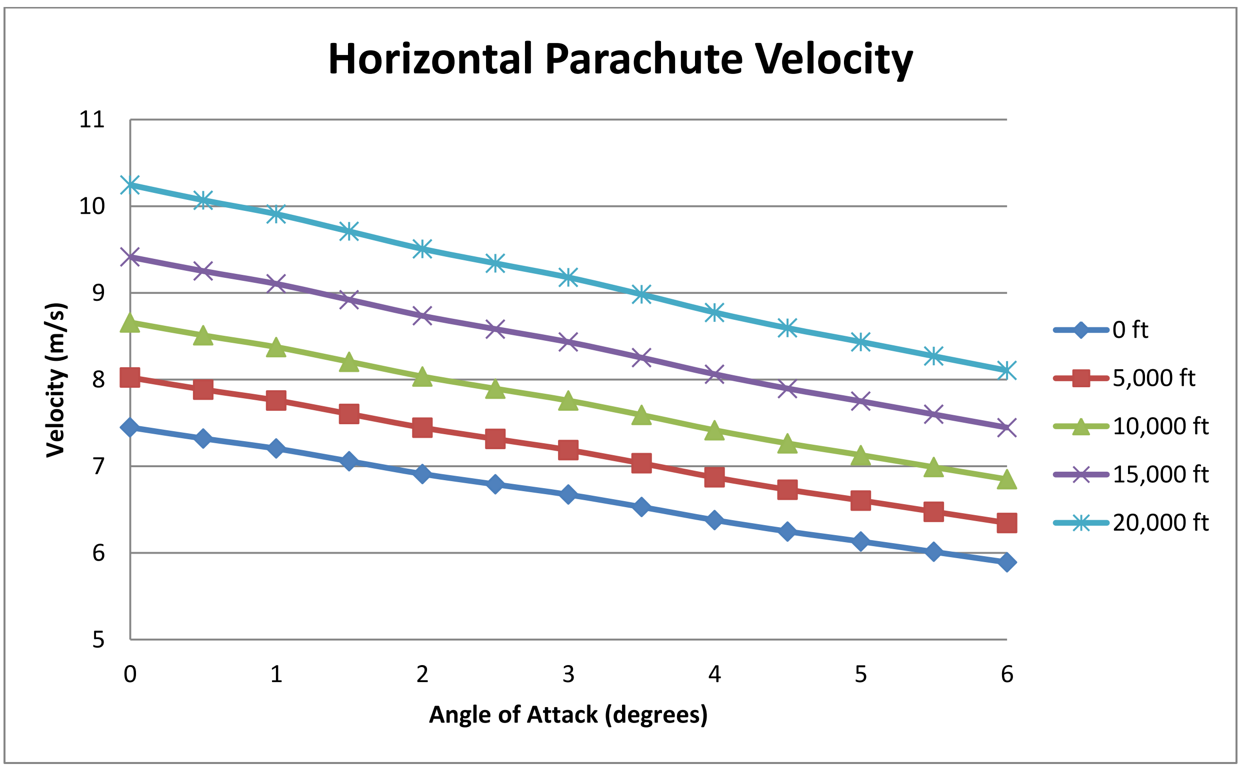

Figure 19: Estimated Parachute Horizontal Velocity At Various Altitudes And Angle Of Attacks

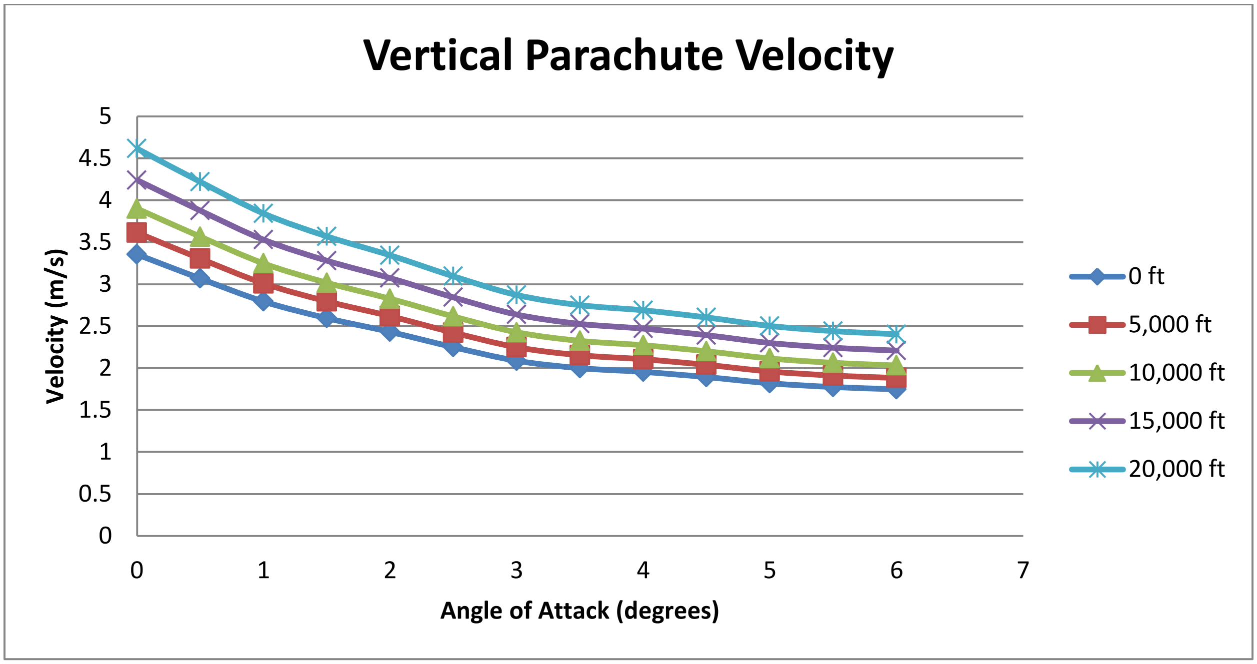

Figure 20: Estimated parachute vertical velocity at various altitudes and angle of Attacks

For the ram air parachute the wing loading of the airfoil can be calculated with the following equation:

$$Wing\ loading = \frac{mass}{wing\ area}$$

Equation 19

The ram air parachute selected for use has a weight of 2.72 kg and an area of 1.16 m^2 giving a wing loading of 2.34 kg/m^2. This is a relatively low value of wing loading for ram air parachutes. Most systems utilizing ram air parachutes have wing loadings ranging from 15-20 kg/m^2.

There are both benefits and disadvantages to having a low wing loading. The lower wing loading will result in less forward velocity making the system unable to fly into stronger winds. Additionally the low wing loading will make the parachute's flight more susceptible to being affected by turbulence.

The low wing loading will provide a slower vertical descent rate for the payload providing a gentler landing. Furthermore low wing loadings provide more maneuverable platforms leading to the ability of the parachute to make quicker turns. Based on the slower descent rate and susceptibility to turbulence and strong winds the team has elected to use a maximum deployment altitude of 10,000 ft msl. At this altitude and a five degree angle of attack the ram air parachute would take approximately 26 minutes to descend to sea level and would have a maximum horizontal travel range of six miles.

For the flight from 10,000 ft to sea level it can be seen that the small variation in air density changes the vertical and horizontal velocities of the ram air parachute in a linear fashion. Figure 24 displays the vertical and horizontal velocities of the ram air parachute system for two different configurations, 0° angle of attack and 5° angle of attack. The linear nature of the change in horizontal and vertical velocities makes it a valid assumption to average the velocities over the range of 10,000 ft down to sea level. This is important as it simplifies the calculations required for predicting the descent time and range of flight for the parachute system. In tables 14-17 general information about the flight velocities, time for descent, and travel distance are displayed for both 0° and 5° angle of attack settings. In order to maintain stable flight a angle of attack must be configured between 0-5°. Above 5° you will stall the parachute and may enter an unrecoverable spin. For initial flights the plan is to maintain a single angle of attack until just before landing. Later, when the system is better understood there may be the possibility of altering the angle of attack while descending to obtain optimal performance.

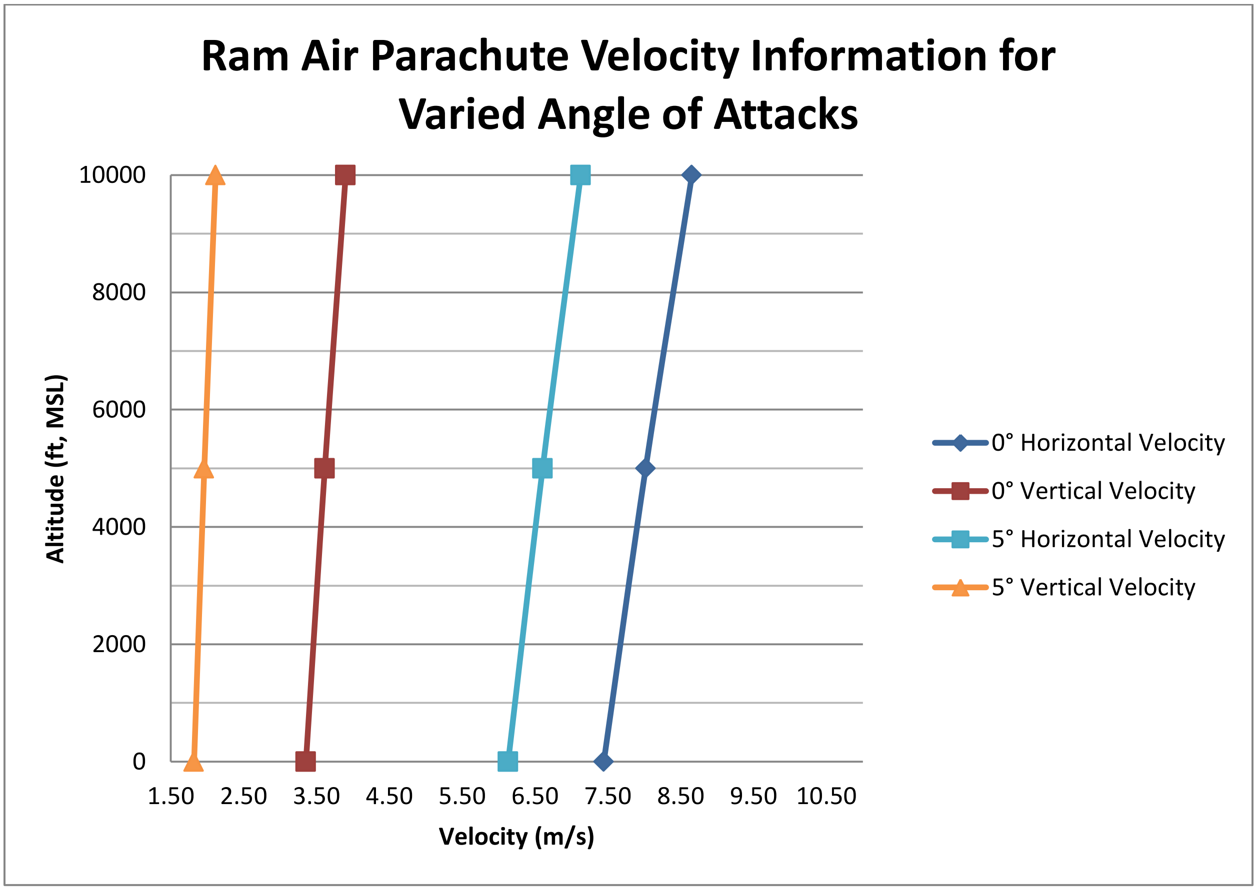

Figure 24: Estimated parachute velocities at 0° and 5° angle of attacks from 10,000 ft to sea level

Table 14: 0° Angle of Attack Vertical Information

Altitude	0	5000	10000
Velocity (m/s)	3.35	3.61	3.9
Velocity (ft/s)	10.99	11.84	12.80
Velocity (ft/min)	659.48	710.66	767.75
Velocity (mph)	7.49	8.08	8.72
Interval Time (s)	437.91	405.84	0.00
Total Time (s)	843.75	405.84	0.00
Interval Time (min)	7.30	6.76	0.00
Total Time (min)	14.06	6.76	0.00
Average Velocity	3.62		

Table 15: 0° Angle of Attack Horizontal Information

Altitude	0	5000	10000
Velocity (m/s)	7.44	8.02	8.65
Velocity (ft/s)	24.41	26.31	28.38
Velocity (ft/min)	1464.64	1578.82	1702.84
Velocity (mph)	16.64	17.94	19.35
Average Velocity	8.04		
Travel Distance (m)	6780.93		
Travel Distance (ft)	22248.22		
Travel Distance (mile)	4.21		

Table 16: 5° Angle of Attack Vertical Information

Altitude	0	5000	10000
Velocity (m/s)	1.82	1.96	2.11
Velocity (ft/s)	5.97	6.43	6.92
Velocity (ft/min)	358.29	385.85	415.37
Velocity (mph)	4.07	4.38	4.72
Interval Time (s)	806.31	748.86	0.00
Total Time (s)	1555.17	748.86	0.00
Interval Time (min)	13.44	12.48	0.00
Total Time (min)	25.92	12.48	0.00
Average Velocity	1.96		

Table 17: 5° Angle of Attack Horizontal Information

Altitude	0	5000	10000
Velocity (m/s)	6.13	6.6	7.13
Velocity (ft/s)	20.11	21.65	23.39
Velocity (ft/min)	1206.75	1299.28	1403.61
Velocity (mph)	13.71	14.76	15.95
Average Velocity	6.62		
Travel Distance (m)	10295.21		
Travel Distance (ft)	33778.58		
Travel Distance (mile)	6.40		

Drogue Parachute Design

For the original descent portion of the flight a drogue parachute will be used to stabilize the payload system and descend to a preset altitude where the ram air parachute will be deployed. The ram air parachute selected for use is a round type throw-able skydiving pilot parachute. The parachute selected is manufactured by Parachute Labs Incorporated. The parachute selected has a 28 inch diameter. The parachute has a mesh base and will be connected to the payload bus through one attachment line. This single line attachment helps reduce the risk of tangling.

The drogue parachute is suspended beneath the balloon on the ascent portion of the flight. This ensures that immediately upon balloon burst or cut down that the drogue parachute is opened and stabilizing the descent of the payload and bus systems. Based on the calculations performed for the drogue parachute an expected descent rate of approximately 175 mph is expected at 100,000 ft msl and reduces to around 27 mph at standard sea level. A graph is provided displaying the entire expected descent rate of the parachute over the entire flight range.

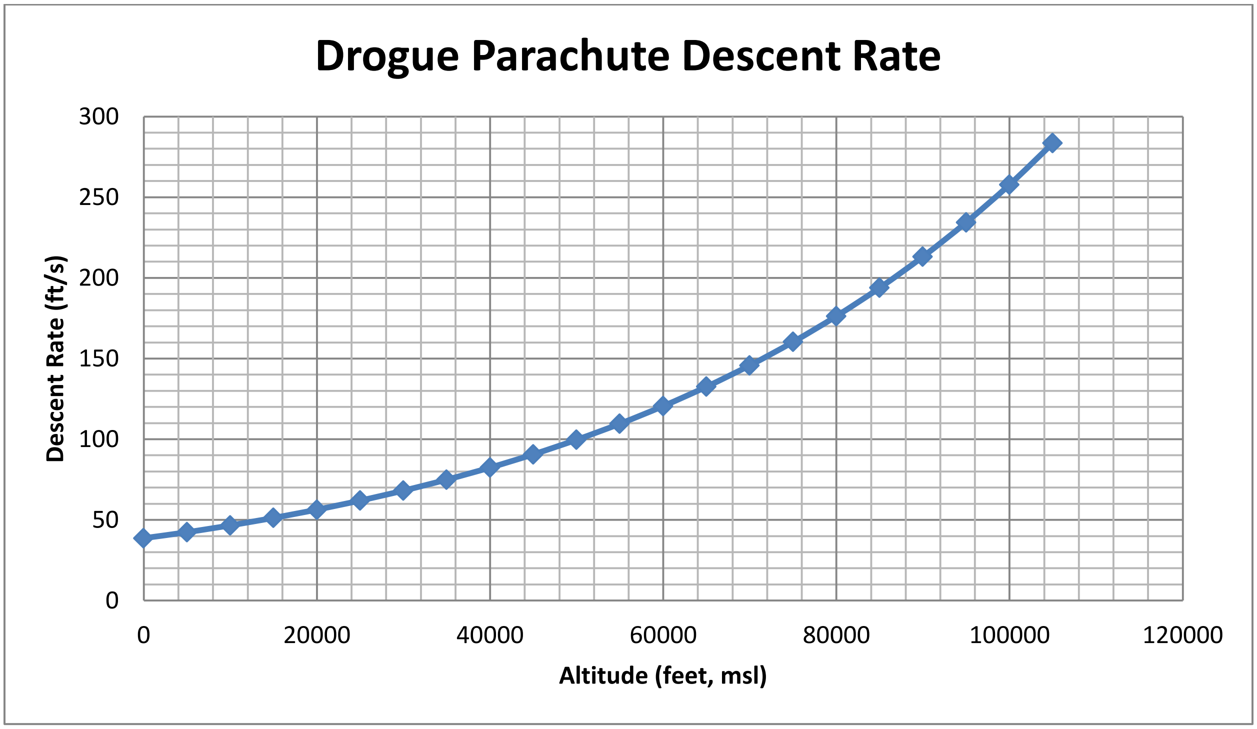

Figure 25: Estimated drogue velocities from 100,000 ft to sea level

This data can then be used to help predict the fall time for the drogue parachute. If the system were to fall strictly under the drogue parachute the time for descent from 100,000 ft to sea level would take approximately 19 minutes. The approximate time to fall to the max deployment altitude of 10,000 ft msl for the ram air parachute is 15 minutes. An entire profile of the descent times can be seen in Figure 26.

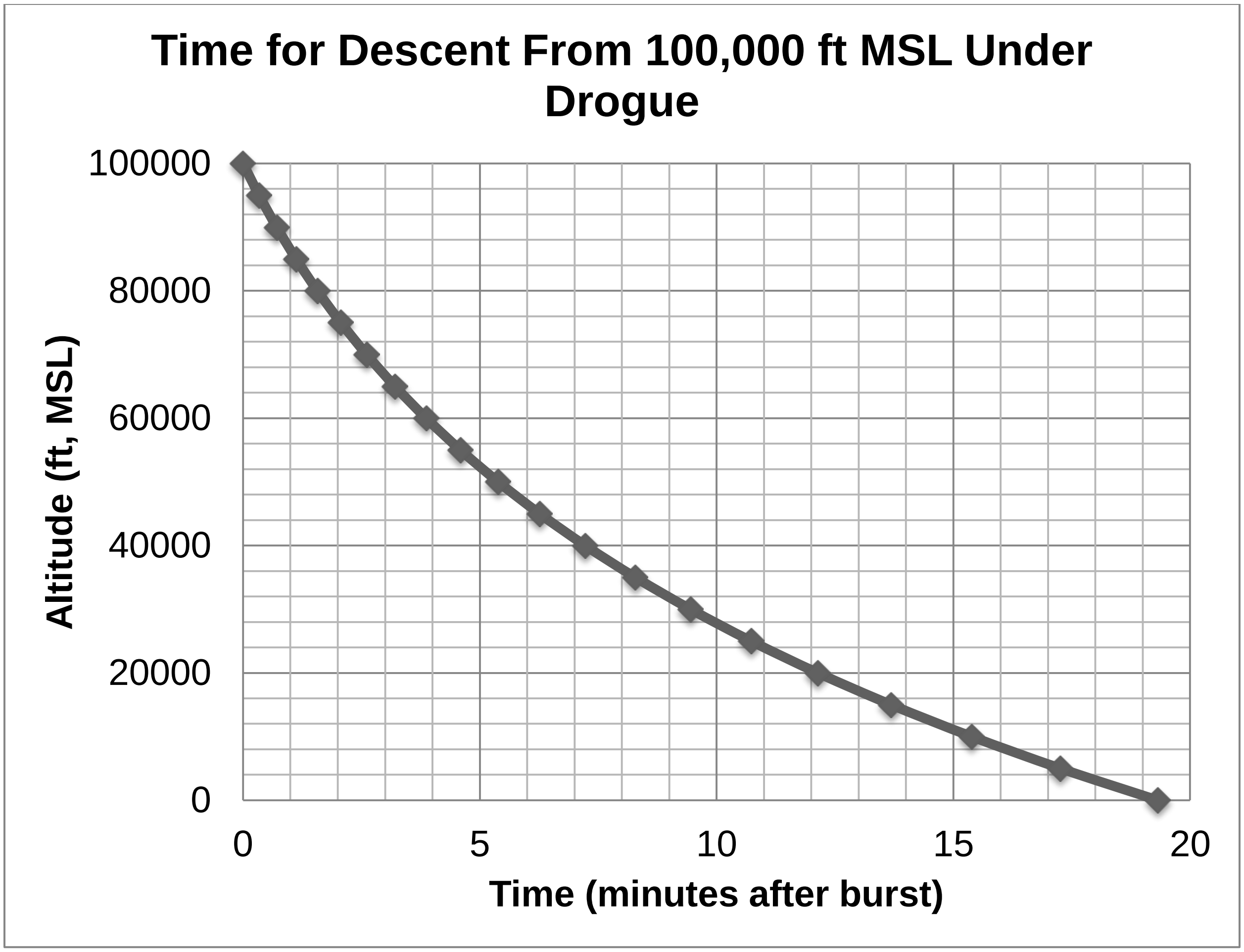

Figure 26: Estimated drogue descent time from 100,000 ft to sea level

Alternative Deployable Parachutes

As an alternative to a deployable ram air parachute or for a different size drogue parachute the flight profiles for a 36" and 48" round parachute were generated. Following the general rule for safe landing velocities only the 48" parachute would be an acceptable main parachute for landing as its landing velocity would be approximately 15 mph. The descent time from 100,000 ft msl is just this parachute was used would be approximately 30 minutes. For the 36" parachute it would only be advisable to serve as a drogue parachute if a slightly slower initial descent was desired. At sea level the descent rate for this parachute would be just over 20 mph, slightly faster than recommended for a safe descent rate on impact. Flight descent velocities and descent rates for the 48" parachute are provided in figures 27 and 28 respectively.

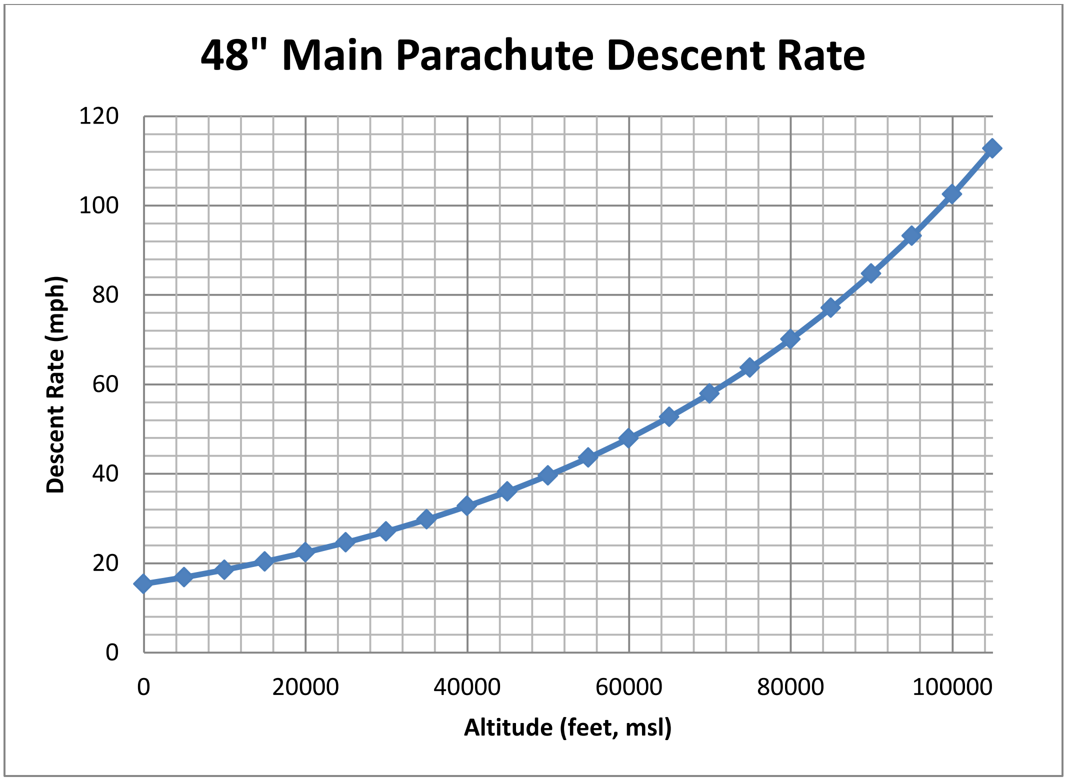

Figure 27: Estimated 48" parachute descent velocities from 100,000 ft to sea level

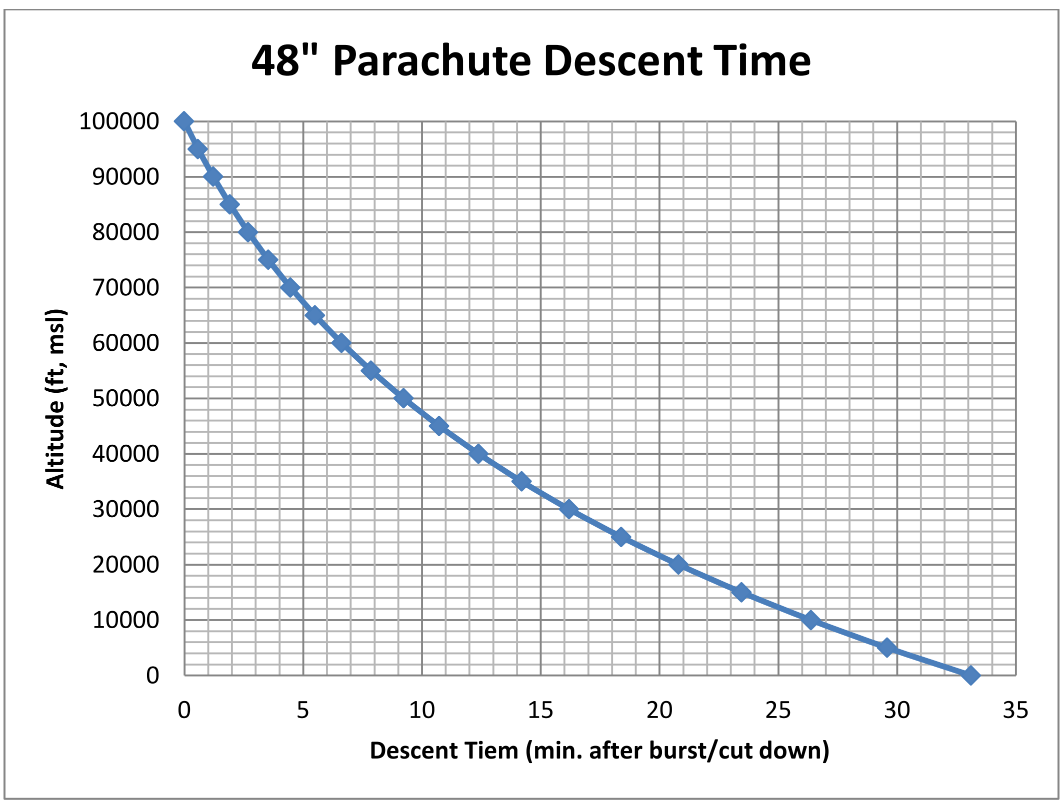

Figure 28: Estimated 48" parachute descent time from 100,000 ft to sea level

Parachute Attachment

While in flight the ram air parachute is held to the top of the Styrofoam box with a special stringing system. In order to ensure maximum reliability the parachute is folded in a specific manner. By folding the parachute in a specific set of steps the chances of tangling on deployment are reduced and the opening shock of the parachute can be reduced if the parachute unfolds in steps. To start the parachute is laid out flat and all the lines are placed out in front of the parachute, see Figure 21.

Figure 21: Parachute is laid flat with lines strung out

The next step is to fold the parachute inwards from the ends in sets of two cells. When completed correctly this leaves a single open center cell with nothing folded over it. The parachute lines are then strung along this open cell, see Figure 22 and Figure 23.

Figure 22: Parachute is folded inwards in sets of 2 cells

Figure 23: Parachute lines are strung along the center cell.

In the final step the parachute is folded in half along its length with the lines coming out one side. This puts the parachute in its final folded position and how it will sit on top of the system while it is being held down by the Diawa line, see Figure 24.

Figure 24: Parachute folded to its final folded setup

By folding the parachute in this manner when the lines holding the main to the mounts on the bus go tight they force the parachute to unfold length wise, allowing the center cells to fill with air. Then due to the air being forced through the middle cells the outer cells expand opening the parachute. This multi-stage opening helps reduce the initial shock experienced by the bus and payloads when the parachute deploys.

Appendix 4: Drogue to Main Attachment

The drogue parachute will be attached to the main parachute by means of a sewed on strap and a D-ring. The current setup has been tested under the maximum conditions and has held together without coming off or ripping the parachute. The strap is a backpack strap which is placed horizontally along the middle cell so that as the drogue pulls on the D-ring the strap does not pull the insides of the cell close together closing it preventing air from opening the parachute. The strap was placed in the center of the parachute in order to make sure that the parachute does not twist, or in other words to make sure the force of the drogue pulling on the parachute does not change the angle of attack of the parachute causing it to dive or stall. The stitching pattern of the strap is that first one must sew around the edges then run a zig-zag pattern between the corners to the loop, this pattern is illustrated by the red lines in Figure 25. This pattern helps to distribute the force so that the parachute will not rip. The thread used to hold the strap onto the parachute was size 33 thread. This is one of the smaller sizes and the smaller thread was chosen in order to reduce the stress on the parachute nylon due to the holes created by the needle and thread.

Figure 25: Drogue attachment point on ram air parachute