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Preliminary Design and Evaluation of a Tethered Balloon System with a Constant Volume Torus Envelope for Low Altitude Operations in Light Winds

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I am submitting herewith a thesis written by Khoy Noel Callwood entitled "Preliminary Design and Evaluation of a Tethered Balloon System with a Constant Volume Torus Envelope for Low Altitude Operations in Light Winds." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Engineering Science.

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Preliminary Design and Evaluation of a Tethered Balloon System with a Constant Volume Torus Envelope for Low Altitude Operations in Light Winds

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ABSTRACT

This document proposes the use of a tethered aerostat system with a constant volume, torus-shaped envelope as a platform for atmospheric monitoring at low altitudes. Manufacturers can make balloons into a variety of shapes, but the most common are spherical and ellipsoidal. Tethered balloons and constant volume balloons have been in use for years but it is not common to see both in combination. This document serves to guide the reader through the preliminary development and evaluation of the tethered balloon system. This preliminary design study concluded that a balloon system using a tethered, constant volume torus envelope could be viable but the envelope must be very large to withstand low to moderate winds.

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SYMBOLS AND CONSTANTS

a – Radius of torus ring cross section, synonymous with r (See Figure 11) [ft]

AGL – Altitude Above Ground Level [ft]

B – Buoyant Force [lbf]

c – Radius of torus ring centerline, synonymous with r_{bend} (See Figure 11) [ft]

D – Drag [lbf]

EASA – European Aviation Safety Agency

FAR – Federal Aviation Regulation

F.S. – Factor of Safety

g – acceleration due to gravity, 32.174 ft/s^2

ISA – International Standard Atmosphere

K – Envelope Fabric Density [lbf/ft^2]

L_{excess} – Excess Lift [lbf]

L_s – Aerostatic Lift [lbf]

l_w – Main tether line weight per foot [lbf/ft]

MSL – Altitude Above Mean Sea Level [ft]

P – Applied pressure for hoop stress calculation [psi]

P_{amb} – Ambient air pressure [psi]

R_{gas} – Helium Specific Gas Constant, 12420 lbf.ft /slug.°R

r_1 – Inner radius of torus [ft] (See Figure 11)

r – Radius of torus ring cross section [ft] (See Figure 12)

r_{bend} - Radius of torus ring centerline [ft] (See Figure 12)

S – Envelope surface Area [ft^2]

T – Main Tether Line Tension [lbf]

T_{gas} – Internal Gas Temperature [°R]

T_s – Standard Atmosphere Temperature [°R]

T_L – Tether Length in Zero Wind at Operational Altitude [ft]

T_{LADD} – Additional Tether Required To Maintain Equilibrium in Wind [ft]

t – Envelope Thickness [ft]

UTSI – University of Tennessee Space Institute

V – Envelope Volume [ft^3]

v_∞ - Freestream Velocity [ft/s^2]

W –Total system weight, excludes W_{gas} [lbf]

W_{air} – Weight of air [lbf]

W_{bridle} – Total weight of bridle lines [lbf]

W_{env} – Weight of Envelope [lbf]

W_{fixed} – Total weight of constant weight items, includes W_{bridle} and W_{susp} [lbf]

W_{gas} – Weight of displacing gas [lbf]

W_{susp} – Total weight of suspension lines [lbf]

W_{tether} – Tether weight in Zero Wind [lbf]

y – Vertical Height of Tether (See Figure 17) [ft]

α – Suspension Cable Angle (See Figure 13) [degrees]

β – Bridle Cable Angle (See Figure 14) [degrees]

ε – Suspension Cable Angle (See Figure 13) [degrees]

ρ_{air} – Air Density [slugs/ft^3]

ρ_{gas} – Gas Density [slugs/ft^3]

θ – Temperature ratio

δ – Pressure ratio

σ – Density ratio

σ_{hoop} – Hoop stress [lbf/ft^2]

φ – Tether angle in wind (See Figure 15) [degrees]

ρ_A – Off-Standard Atmosphere Density [slugs/ft^3]

ρ_s – Standard Atmosphere Density [slugs/ft^3]

ΔT – Difference in Temperature from Standard Atmosphere Temperature [°R]

1. INTRODUCTION AND GENERAL INFORMATION

1.1 Introduction

The Aviation Systems department at the University of Tennessee Space Institute uses instrumented airplanes as a platform to conduct operations such as atmospheric research and surveillance for various agencies. Thus far, the department's use of airplanes has proven successful for operations, but there is a desire to introduce a new platform to replace or supplement the use of airplanes, particularly for low altitude operations. Using an airplane for atmospheric monitoring limits the minimum safe altitude attainable and the maximum mission time. The airplane is also unable to be stationary. There are a few engineered solutions that can address the limits the airplane imposes. Airships, tethered balloons and kites are possible solutions to improving those limits.

The Merriam Webster online dictionary defines an aerostat as "a lighter-than-air craft (as a balloon or blimp)" (1). Several aerostat manufacturers provide airship and tethered balloon solutions. Most aerostat manufacturers tend to provide airship and tethered balloon solutions that can lift a large range of weights, but their solutions are geared towards using instruments that only need to reference a downward direction to measure, such as cameras. The balloon shapes that manufacturers tend to promote are the ellipsoidal and spherical shape. However, aboard UTSI's airplanes, there are instruments, such as radiometers, that need to reference in the direction of the sky to make measurements.

There is a single balloon shape that would be a natural choice for accommodating both upward and downward looking instruments. This shape is the torus; it is the shape of a donut and has an opening in its center. Unlike other shapes, the torus envelope has the advantage of surrounding the payload rather than being above it. For simplicity of structure and operation, there is also a desire to make the torus envelope constant volume.

To investigate the probable use of a tethered, constant volume, torus balloon at low altitudes, this document presents a preliminary design and configuration evaluation for an unconventional tethered balloon system. The primary feature of the design is the toroidal, constant volume envelope. The choice of shape and the desire to tether a constant volume envelope is what makes the system unconventional. All other components chosen to be a part of the system will be readily available off-the shelf components that are typically apart of balloon systems.

1.2 Purpose of Design

There are two main reasons for designing the proposed tethered aerostat system. The first reason is to provide a solution that meets the requirements of the aviation systems department, especially to accommodate upward looking instruments by using a torus envelope. The proposed design is somewhat exploratory. There are not many examples of tethered balloons that use a torus shape. There is also an aim to tether a constant volume envelope at a low altitude. Therefore, a secondary purpose of this design is to identify any key advantages and drawbacks that the use of a tethered constant volume torus envelope presents in comparison to more conventional aerostat solutions.

The main goal of this design is to maximize the lift to weight ratio of the design by minimizing the weight of components that are not instruments or critical to their operation. These non-critical items to the instruments operation would be the tether, suspension and bridle lines, and the weight of the envelope gas bag. By minimizing the weight of these items, the size of the envelope, amount of helium required and size and strength of the winch required on the ground will all decrease, reducing the cost of the system. Helium especially, is the biggest contributor to the cost of the system, as it is a very expensive lifting gas.

1.3 Design Goals and Legal Requirements

To legally launch any tethered aerostat system, one must abide by regulations that are enforced by the appropriate aviation agency. In the United States, this agency is the Federal Aviation Administration and there are rules made specifically for tethered aerostat operation in FAR Part 101 Subpart B. In this document, to evaluate if chosen components are safe in different conditions, reference is made to the safety factors recommended by the European Aviation Safety Agency. These safety factors account for dynamic or asymmetric loading effects associated with the initial element’s failure (EASA 12). These safety factors and their respective components are displayed in Table 1. All tables and figures are in the appendix.

The design goals presented here are representative of what might be ideal of a tethered balloon system lifting atmospheric monitoring instruments operating in Tullahoma, Tennessee. Design goals for the system include:

1) Being able to operate at 3000 ft MSL

2) Lift approximately 50 pounds of weight which consists of:

    a. 20 lbs in payload (See Table 2 for sample payload)

b. 30 lbs allocated for suspension structures, additional payload, connections and other supporting equipment

3) Operate in light winds on the Beaufort scale up to 10 mph.

4) Operate in average temperatures ranging from 29°F to 89°F

Along with the previous design goals, the maximum operational loads for the system must be determined that will not exceed the previously prescribed factors of safety and cause failure in:

1) Tether Line

2) Suspension Line

3) Bridle Line

4) Envelope

1.4 Design Visions

The vision for this project is to be able to house instruments in some structure which may vary depending on the instruments being lifted. In this structure, allowances would be made for instruments to have the ability to make upward and downward looking measurement. For instruments to measure upwards and downwards without being blocked by the balloon, the housing structure would have to be at least as tall as the height of the torus balloon as shown in Figure 1.

The housing structure ideally would be situated in the geometrical center of the torus as shown in Figure 2. By placing the housing structure in the geometrical center of the balloon, the bridle and suspension cables can be symmetrically connected to the balloon as shown in Figure 3.

A very challenging part of the torus balloon design is devising a way to suspend the payload and its housing structure in the center of the balloon. Figure 3 shows a three dimensional perspective of using cables to suspend a structure in the center of the torus. Suspension cables run from the envelope to the housing structure. The connection of bridle cables are also shown. Bridle cables run from the envelope to the confluence point where the bridle cable assembly will meet the main tether line from the ground. Figure 4 clearly shows the layout of these cables and the naming conventions that will appear later in this document.

Another design vision for this project although not evaluated, is to use an hour glass shaped structure to house payloads. The hour glass shaped structure would allow the balloon to connect to the housing structure like two pieces of a puzzle. Straps can be run from the top of the housing structure and into the bridle, eliminating the need for suspension cables. This idea allows for a more sturdy system and for the balloon's radius to be minimal. This idea is shown in Figure 5.

1.5 Recent Works with Torus Balloons

There are some notable works with torus shaped envelopes. The image at the left of Figure 6 shows a wind turbine carrying torus balloon developed by Altaeros Energies. This example uses several cables to suspend the turbine and tether the balloon. The image at the right of the same figure shows a Torus balloon developed by Lindstrand Technologies. This 80m aerostat was being used for entertainment purposes and was so huge, it was built in four sections. Lindstrand claims it is the largest aerostat built to date.

Although neither of these examples is being used for atmospheric monitoring, they show the versatility that the torus balloon shape has to offer. They show that torus balloons can be used floating in a vertical or horizontal position, depending on the application. Torus balloons may end up having to be very large as compared to the weight they are lifting. Both balloons use helium as a lifting gas.

2. LITERATURE REVIEW/ INVESTIGATION OF ALTERNATIVES

2.1 Conventional Airships and Tethered Balloon Systems

The term conventional airship usually applies to describe any free-flying aerostat with an ellipsoidal shape, such as those seen above sports games. Many tethered balloons are also made with this shape. Besides for shape, Gabriel Khoury in his book Airship Technology describes modern conventional airships as having aerostatic lift, helium lifting gas, petroleum fuel, non-rigid envelope, pilots and payload capability of less than 50 tons (Khoury 458). The conventional airship is beneficial as a design choice because its shape provides some lift and the included fins help to provide stability while in flight. Conventional airships do have the disadvantage of having to be long and skinny as compared to other aerostat shapes of the same volume. Ground handling becomes an issue with the conventional aerostat. Because the conventional airship is usually unrestrained, pilots are often needed for conventional aerostats, whether they are onboard, remotely piloting, or an autopilot is developed. In general, the conventional airship is preferable in applications where it needs to move or there are high winds.

Unlike the conventional airship, tethered balloon systems are not free-flying; they are tethered or moored to an object on the ground. To change the vertical position of this system, an operator has to adjust the amount of tether that is let out from a winch. Adjusting the horizontal position of this system is rather difficult because it would mean having to relocate equipment on the ground to which it is tethered. Tethered aerostat systems tend to be best suited to applications where there is a need to remain over a certain location for a long period of time. As the name might suggest, the tether and the aerostat (the envelope) are the major structural elements of this system. In some setups, one tether cable can provide the aerostat with electricity, data and a secure connection to the ground. Figure 7 shows the typical elements of and main forces acting in a tethered balloon system.

2.1 Envelope

The envelope of the tethered aerostat system is perhaps the most important structural element. It is responsible for containing the lifting gas that helps to provide aerostatic lift to lift the envelope and all structures attached to it. Presently, the common gases used in aerostatics are hot air and helium. There are different types of envelopes that are used in aerostatic applications, as well as materials used to make them. There are three main types of envelopes: rigid, semi-rigid and non-rigid. The material that is commonly used to make these envelopes is some type of polymer, such as nylon.

Different envelope types have different advantages and disadvantages. Non-rigid envelopes have no internal solid parts supporting the gas bag and therefore rely on the pressure of the gas to keep its shape. Semi-rigid envelopes on an airship combine a

gas bag with a keel structure. Rigid envelopes normally have an overall skeletal frame, to hold their form and have gas containment cells (Khoury 149).

Balloon envelopes can be either variable volume or constant volume. Variable volume balloons are not completely filled with lifting gas at sea level so that the gasbag can ascend without losing lift. Variable volume balloons contain ballonets that expand or contract as the gas bag rises or falls. These balloons are more complicated to use because they are often used with ballonets and do not maintain a constant volume. Their performance in the atmosphere is more difficult to predict. Constant volume balloons use envelopes that are strong enough to withstand the applied pressure of their containing gas. These balloons are filled to capacity with lifting gas from on the ground. Constant volume balloons are designed so that the net lift is positive, causing continuing ascent to a predetermined equilibrium altitude where net lift becomes zero. At this altitude, the balloon should in theory, float indefinitely (Khoury 10). For a simplistic design, a constant volume balloon is desirable because the density of the lifting gas remains constant. Constant volume balloons are commonly used with light payloads for very long duration flights at heights between 1 and 16 km, and balloons are tethered as high as 20 km (Riedler 5). “The maximum internal pressure stress in a constant volume or superpressure balloon is usually many times larger than local stresses applied by the load suspension system” (Riedler 48).

There are several characteristics that are desirable for an aerostat envelope. The envelope should possess high strength, high strength-to-weight ratio, resistance to environmental degradation, high tear resistance, enough flexibility to inflate and deflate numerous times, and low permeability to the lifting gas (Khoury 114). These characteristics not only come from the envelope fabric, but also fabric weave patterns and fabric coatings. In his book Airship Technology, Khoury compares the properties of common fabrics, weave patterns and coatings. Based on the properties presented by Khoury (115-129), polyurethane coated ripstop nylon is the fabric – pattern style – coating combination that would meet much of the desired characteristics of the envelope.

2.2 Tethering and Connections

An aerostat can be tethered in several configurations and with different types of tethers. Figure 8 shows the commonly used tether configurations: single, dual, three, four and five cable. The tether configurations are numbered 1-5 in the figure respectively.

There are tethers available that only restrain the aerostat, as well as tethers that can restrain and provide a path for electricity and data. According to Myers, “The tether’s diameter should be as small as possible and still retain the strength capabilities necessary to maintain the balloon’s position in all anticipated winds. A tether’s drag, strength and weight vary as functions of tether diameter. The diameter of the tether will

determine sheave size, size of winch drum and the amount of cable stored on the winch's drum." (Myers 102)

Along with having knowledge of appropriate tether configurations and types, it is also important to be aware of the various connectors available to connect cables together, to the envelope and other components in the system. The brummel hook, swivel and load patch help to create important connections in the tethered balloon system. The brummel hook is one of the simplest connectors for easily connecting several cables together while keeping a secure connection. It is shown in Figure 9. Figure 10 shows the load patch, load strap and net connections.

One of the challenges in designing a tethered aerostat system is choosing suitable tethering and suspension components. A tethering component connects the envelope to the tether line and ultimately the ground whereas a suspension component allows some payload structure to hang in some certain fixed position from the balloon. The challenge with tethering and suspension components is that in most setups they connect directly to the balloon envelope causing point loads which make the balloon susceptible to rupture in high winds. Miller and Nahon experimented with the tethering methods of the load patch, strap, and net with a tethered spherical balloon. They found that tethering using a net was the simplest method but heaviest compared to the other two methods. When subjected to wind, their test balloon with the load patch and strap dimpled. The load patch is perhaps the best connection method to choose for a first design attempt, because it easily allows for the attachment of suspension cables from any orientation and provides an anchor point that will not move.

Another connection that is important in tethered balloon operation, is the swivel joint. This device allows the main tether line to be connected to the bridle and to also allow one end of the system to be fixed and the other end to rotate. The swivel point is the connection between the tether system and balloon system allowing rotation of the balloon independent from the tether cable (EASA 10).

2.3 Winches

The winch is probably the most important ground machinery that is a part of the tethered balloon system. The winch provides a grounding point for the balloon system and stores the tether line. It allows for the operation altitude of the system to be changed. Desirable characteristics of a winch depend on the size of the balloon system and the type of mission. According to Myers, "Most winches need to be designed for their particular application" (Myers 69). However, winches are available with a large range of pulling and rope storing capability.

3. MATERIALS AND METHODS

In this thesis, the approach taken to design a balloon system is to start with a payload weight and build a balloon system around it. In addition to sizing the envelope, methodology is needed to determine envelope stresses and cable loads, and to estimate the system performance in a steady wind condition.

3.1 Envelope Sizing

The aerostat envelope is perhaps the most challenging part of a tethered aerostat system to design correctly. Determining the required size of the envelope depends on factors such as:

- The fixed weight being lifted
- The weight of and number of tether lines
- The envelope weight
- The lifting gas used
- The maximum altitude of operation
- The maximum operating winds
- The maximum operating temperature

In Myers' 'Tethered Balloon Handbook' and Khoury's 'Airship Technology,' both authors provide methods for sizing conventional shaped aerostat envelopes based on the preceding factors and more. For unconventional shapes such as the torus, there does not appear to be any conventional method for envelope sizing, and the methodology is left up to the designer using fundamental physics principles.

Archimedes Principle states that the buoyant force acting on a floating body is equal to the weight of the fluid displaced. Also, by definition the aerostatic lift is equal to the difference between the buoyant force and the weight of the displacing gas. For a balloon containing some gas and floating in air:

$$L_s = B - W_{gas} \qquad (1)$$

$$L_s = W_{air} - W_{gas} \qquad (2)$$

$$L_s = Vg\left(\rho_{air} - \rho_{gas}\right) \qquad (3)$$

At the floating altitude in a zero wind condition, the desire would be to have the aerostatic lift equal to the total weight being lifted (excluding helium weight), so that the

system will theoretically neither rise nor sink. However, when the balloon is subjected to any wind, if the net lift is zero the balloon will fall to the ground. Therefore, the balloon should be designed with a net lift, or excess lift, that keeps the balloon in equilibrium at maximum wind condition. For the tethered aerostat system, this design condition can be met by the following equation:

$$L_s = W_{env} + W_{tether} + W_{fixed} + L_{excess} \qquad (4)$$

In the previous equation, the envelope weight is a linear function of surface area. The weight of lines depends on the number of lines and the length of lines that are used.

For a torus shaped aerostat, forming an expression for excess lift by referencing equation 4 results in:

$$(\rho_{air} - \rho_{gas})Vg - KS - l_w T_L - W_{fixed} = L_{excess} \qquad (5)$$

Relations for the torus geometry are as follows in equations 6-9, some of which are seen in Figure 11 (Weisstein 1):

$$V = \frac{\pi^2}{4}(R + r_1)(R - r_1)^2 \qquad (6)$$

$$S = \pi^2(R + r_1)(R - r_1) \qquad (7)$$

$$a = \frac{1}{2}(R - r_1) \qquad (8)$$

$$c = \frac{1}{2}(R + r_1) \qquad (9)$$

Section 4.1 shows the resulting envelope geometry and properties calculated from this envelope sizing methodology. In equation 5, ground level is referenced at 1000 feet above sea level. The previous altitude is the approximate local ground elevation above sea level for Tullahoma, Tennessee. To solve for the outer radius, R in equation 5, the inner radius of the torus, r_1 was fixed at 6 feet for this first design attempt.

3.2 Determination of Envelope Stresses

The envelope of the tethered aerostat system can be treated as a pressure vessel. It encloses a lifting gas which imposes pressure on the envelope material causing stresses in three directions, but of most concern is the hoop direction. If the stress due to a particular pressure of the lifting gas exceeds the envelope material's strength, the envelope will burst. It is important to make sure that for all planned flight conditions, the

envelope stress remains at or below the appropriate factor of safety limit. In this document a classical formula for torus hoop stress determines the maximum expected stresses for the envelope. This formula provided by French, equation 10, will determine the maximum expected hoop stress due to the lifting gas within the envelope. Figure 12 shows the geometry associated with equation 10.

$$\sigma_{hoop} = \frac{\mathrm{Pr}}{2\mathrm{t}}\left[\frac{2\mathrm{r}_{\mathrm{bend}} - \mathrm{r}}{\mathrm{r}_{\mathrm{bend}} - \mathrm{r}}\right] \qquad (10)$$

In equation 10, the applied pressure, P, is the difference between the internal gas pressure and the ambient pressure, P_{amb} at altitude. The internal gas pressure is determined by the ideal gas law as shown by the first term in equation 11. Helium is an ideal gas. There is an assumption that the same ambient air pressure acts on all points on the balloon. Section 4.3.3 shows allowable applied pressures.

$$P = \rho_{gas} R_{gas} T_{gas} - P_{amb} \qquad (11)$$

3.3 Prediction of Suspension Cable Forces

Suspension cables allow for attachment of the payload and housing structure to the balloon envelope and keep the payload structure and balloon envelope moving together. A sixteen cable system, with groups of four cables spaced 90 degrees apart will make up the suspension structure (See Figure 4). This system is statically indeterminate.

To estimate the maximum force in the suspension cables the system is reduced to a statically determinate system with the understanding that the loads found in this system would be the maximum that any cable in the statically indeterminate system will bear. If cables T_3 and T_8 are kept as shown in Figure 13, the forces in the suspension cables can be determined by Newton's first law:

$$\sum F_x = T_8 \cos\varepsilon - T_3 \cos\alpha = 0 \qquad (12)$$

$$\sum F_y = T_8 \sin\varepsilon + T_3 \sin\alpha - W = 0 \qquad (13)$$

$$T_3 = \frac{W}{(\cos\alpha \tan\varepsilon + \sin\alpha)} \qquad (14)$$

$$T_8 = T_3 \frac{\cos\alpha}{\cos\varepsilon} \qquad (15)$$

3.4 Prediction of Bridle Forces

The bridle helps to reduce the movement of the envelope during flight. A four-cable system with cables spaced 90 degrees apart will make up the bridle as shown in Figure 4. This system is also statically indeterminate. Section 4.3.4 shows resulting bridle and suspension cable forces.

When the wind speed is zero or steady, the tether line aligns itself on the centerline of the aerostat system. The location of the bridle beneath the balloon causes a coupling to be formed by the tension vector and the resultant vector of the excess lift and drag. This coupling causes the system to rotate into a position as shown in Figure 14, as the wind speed becomes steady.

The bridle cable system is reduced to a statically determinate system consisting of two bridle members (T_A and T_B) and the main tether line, with the understanding that the bridle members in the statically indeterminate system will bear loads less than or equal to the loads found in the statically determinate system. With just two bridle members, the forces in the cables in the statically determinate system can again be determined by Newton's First Law:

$$\sum F_x = T_B \cos\beta - T_A \cos\beta = 0 \qquad (16)$$

$$\sum F_y = T_B \sin\beta + T_A \sin\beta - T = 0 \qquad (17)$$

$$T_A = T_B = \frac{T}{2\sin\beta} \qquad (18)$$

3.5 Estimation of System Performance

The free body diagram in Figure 15 shows the external forces (not to scale) that would act on the tethered aerostat when it is in the air and at the grounding point. The forces acting on the tethered aerostat include:

- the aerostatic lift (L_S)
- total weight lifted (W), which includes the weight of the tether line

- tether line tension (T)
- drag (D) caused by wind.

At the grounding point, the tension force also acts and a reaction force (L) which by Newton's third law would be equal and opposite to the tension force. This assumes no wind drag while on the ground. The same figure also shows the angle φ, created between the tension force and the vertical at the grounding point and between the tension force and weight up at the aerostat whenever the wind blows.

When the entire tethered aerostat system is in operation, the desire is to have the entire system in equilibrium. Focusing on just the tethered aerostat, and applying Newton's first law, the sum of forces are as shown in Equations 19 and 20. There is an assumption that the lines of action of the aerostatic lift, total system weight and the tether tension all intersect at a common point.

$$\sum F_x = D - T\sin\phi = 0 \qquad (19)$$

$$\sum F_y = L_s - W - T\cos\phi = 0 \qquad (20)$$

By manipulation of equations 19 and 20, one can obtain the expression in equation 21 that relates the angle that the wind causes between the tether line and vertical to the drag and excess lift. Manipulating the same two equations can also provide a single equation for the tether line tension in terms of excess lift and drag as shown in equation 22.

$$\tan\varphi = \frac{D}{L_s - W} = \frac{\frac{1}{2} C_D \; \rho_{air} \, v_\infty{}^2 \, V^{\frac{2}{3}}}{Vg(\rho_{air} - \rho_{gas}) - W} \qquad (21)$$

$$T = \sqrt{(L_s - W)^2 + D^2} \qquad (22)$$

The drag coefficient, C_D, in equation 21, is the three dimensional drag coefficient of the torus. Due to the unavailability of empirical drag coefficient data for a torus, the value being used for C_D is 0.6, which is the highest experimental value associated with a natural shape balloon (Myers 10). Figure 16 shows the drag coefficient data for the natural shape, sphere, and streamline balloons. The natural shape balloon has the greatest drag coefficients of the balloon shapes compared by Myers. The torus, natural shape and sphere are not considered streamlined shapes. Therefore, it is reasonable to

expect that their drag coefficients will be much greater than those for streamline shapes. In addition, the intent is to have the torus balloon remain horizontal in all steady winds, but if the angle of attack of the balloon changes, so can the balloon's drag coefficient.

The balloon volume is used as the reference area in the expression $V^{2/3}$. "The lift of a buoyant craft is related directly to its volume, so the reference area is often chosen to be (buoyant volume) $^{2/3}$. However, owing to the large surface area of buoyant craft, skin friction is the largest fraction of the total drag. For this reason, many reports use force coefficients, in which the reference area is the balloon surface area." (Khoury 26). The drag coefficient used for the design effort is taken from Myers' drag coefficient data in Figure 16 where the reference area is $V^{2/3}$.

The main purposes of formulating equations 21 and 22 is to provide a way to determine the main tether line tension in different wind conditions and altitudes; determine the horizontal displacement of the balloon due to wind; and provide an envelope of operation when operating in an equilibrium condition. When these equations are in use, there is an implication that as the wind speed increases, the tether angle increases. Section 4.3.2 discusses results for these conditions.

This section has two important assumptions. The first assumption is that the tether line is taut at all altitudes and wind speeds. Secondly, for simplification the main tether weight vector is not distributed along the tether length and does not act at the halfway point of the tether line but the weight of the tether line is included in the total system weight.

The length and extra weight of tether needed to maintain the aerostat in equilibrium when the wind blows can be determined by knowing the zero wind tether length and the angle φ.

In Figure 17, the purple arrow represents the tether length in zero wind. The blue arrow represents the position the tether line would take under the influence of wind without letting out any extra tether. It is assumed that the tether line traces a circular path from the position of the purple arrow to the blue arrow. The green arrow represents the new vertical height of the tether line when the wind blows. This distance of y is found with equation 23. The red arrow represents the additional tether needed to maintain equilibrium at a particular wind speed. The additional tether required is found from equation 24.

$$y = T_L \cos\varphi \qquad (23)$$

$$T_{LADD} = \frac{{T_L}^2 - yT_L}{y} \qquad (24)$$

To find the zero wind net lift at particular altitudes, the standard atmosphere equations for the troposphere are used to calculate the density of air at those altitudes. The temperature ratio, pressure ratio and density ratio can be computed from equations 25 – 27 respectively (Solies 2). Knowing those ratios for every altitude, the temperature, pressure and density can be calculated from sea level conditions of 518.7 °R, 0.002377 slugs/ft^3 and 2115.7 lbf/ft^2.

$$\theta = 1 - 6.875 \times 10^{-6}\, h\, [ft] \qquad (25)$$

$$\delta = \theta^{5.256} \qquad (26)$$

$$\sigma = \theta^{4.256} \qquad (27)$$

The density in an off-standard atmosphere must be calculated to find the zero net lift in off-standard conditions. Equation 28 provided by Khoury shows how to calculate the off-standard density (190).

$$\rho_A = \rho_S \frac{T_s}{T_s + \Delta T} \qquad (28)$$

3.6 Planned Materials and Equipment

Table 3 lists the main equipment and materials to be used with the proposed tethered aerostat system on a first design iteration. These items are chosen because they are readily available from manufacturers and their properties are among the best of their class needed to produce a system that lifts minimum structural weight and meet the design goals. These items also have properties as recommended by authors in the literature review. The table also lists the properties of these items.

Adhesive backed tie down rings are similar to load patches. These tie down rings are attached to a surface with an adhesive and are preferable because no hole is made in the envelope to make a connection and they can conform easily to the curved surface of a torus.

4. RESULTS AND DISCUSSION

4.1 Resulting Envelope Geometry and Properties

Table 4 shows the calculated properties of a torus envelope that can lift 61.51 lbf of weight (excluding gas weight) to an altitude of 2000 ft AGL in Tullahoma or 3000 ft MSL on a standard day. The values in the table are a result of the envelope sizing methodology previously discussed. The design excess lift of 61.5 lbf resulted in a diameter and height of the torus that is similar to that of conventional streamlined aerostat shapes that are capable of lifting similar weights as this system.

On this iteration, the design lift of 61.5 lbf was chosen because it was a value of excess lift that could be used without breaking the tether line and also allow some resistance to the wind. With the chosen design excess lift, the main tether line can be used in winds up to 31 mph, before exceeding the tether line limit load in Table 7. In a 10 mph wind, the horizontal displacement of the balloon from the zero wind condition would be 741 ft on a standard day as shown in Table 8. Increasing the design excess lift decreases the horizontal displacement due to the wind, but at the cost of needing a larger balloon, and lowering the wind speed at which the tether line tension exceeds its limit load.

In addition to the sketch in Figure18, Table 5 shows the lengths of the bridle cables and suspension cables and their associated acute angles from the horizontal at either end. The information in Figure 18 and Table 5, together communicate the cable positioning and lengths in relation to the balloon envelope and housing structure.

4.2 System Weight Breakdown

Table 6 shows the weights of components that make up the tethered balloon system. The main contributors to the weight of the system are the envelope, main tether line and items of fixed weight which include the instruments, housing structure, W_{bridle} and W_{susp}. The tether weight, W_{tether} is for 2000 ft of cable weighing 0.0012 lbf/ft.

4.3 Predicted Performance

The primary parts of a tethered aerostat system as the name suggests are the tether and the aerostat itself. The results of the assessments conducted in this portion of the document concentrate on what loads/stresses will cause the torus envelope, tether line, bridle and suspension cables to be in unsafe operation. To operate within the prescribed factors of safety as earlier introduced the following loads/stresses must not exceed the factor of safety load limits as displayed in Table 7.

4.3.1 Lift Availability

Figure 19 shows the zero wind net lift available with altitude above mean sea level on a standard day and at +/- 30 degrees change in temperature from standard day. This net lift only considers aerostatic lift. At 3000 ft MSL the net lift available on standard day, 30 degrees above standard and 30 degrees below standard is approximately 65 lbf, 53 lbf and 73 lbf, respectively. In a no wind condition, this figure also shows that the envelope and a total lifted weight of 61.51 lbf (excluding the weight of the lifting gas) will theoretically float in equilibrium at about 17 000 ft MSL when the air temperature is 29°F. However, the balloon will not be able to rise above 4125 ft, using polyurethane coated nylon as the envelope. Section 4.3.3 discusses this limit.

4.3.2 Performance of System at Desired Operational Altitude

Tables 8-10 show the variation of drag, tether line angle, tether line tension, additional tether, extra tether weight, new tether length and horizontal displacement with wind speed for the first design iteration. Using the properties of the balloon sized, it was found that a wind speed of 8 mph would displace the balloon more than 400 ft horizontally in the desired temperature range of operation. Similarly to airplanes, the performance of the system improves when temperatures are colder, especially at higher wind speeds.

4.3.3 Maximum Envelope Pressure and Stress

The maximum allowed applied pressure to the balloon envelope is 5.69 psi; this pressure results in the limit hoop stress of 23206 psi when applying a safety factor of 5. The balloon can be inflated to a maximum of 4.16 psi gage pressure and not exceed the pressure limit at the desired operating pressure altitude of 3000 ft MSL on a standard day.

On a standard day, Figure 20 shows that the balloon will be able to rise to a pressure altitude of 3000 ft MSL, assuming that the internal temperature of the helium gas remains constant at the current sea level temperature. If the balloon rises and the gas cools while being equal to the surrounding air temperature, the figure shows that the balloon will be able to rise to a pressure altitude of about 4125 ft.

4.3.1 Bridle and Suspension Loads

Through trial and error it was found that the suspension cables can accommodate up to a maximum of 50 lbf of fixed weight and only produce 82 lbf and 68 lbf in cables T_3 and T_8 of the statically determinate suspension system, respectively.

Table 11 shows that the bridle cables from their statically determinate system will not exceed their factor of safety limit of 229 lbf when operating at minimum and maximum wind speeds in a steady condition.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Limitations

The methodology used to design and evaluate the tethered balloon system are with the following limitations:

- The simplifying assumptions used in determining the system performance do not take into account tether cable dynamics, nor stability based on equations of motion. The tether line is assumed to be taut at all conditions for a preliminary analysis, but works by Ajani and Aglietti show that tether lines take on curved shapes when in wind and can account for a significant amount of drag.

- The analyses in the results assume that all of the drag of the system is being generated by the envelope and as if it were a natural shape balloon, which "normally exhibits the lowest tolerance for wind" (Myers 10). This approach may have overestimated the drag of the envelope but underestimated the system drag without considering tether drag. Tether line drag needs to be considered in system drag which can be determined accurately by analyzing the forces acting on finite elements of the main tether line.

- The loads found from the evaluation of the bridle and suspension lines are conservative. The exact solution of the bridle and suspension loads will need to be found by generating more equations for the systems based on structural compatibility conditions and material properties to solve the statically indeterminate system.

  For the suspension cable system, if the housing structure and suspension cables are isolated from the system, the exact solution requires solving the problem:

$$\sum \boldsymbol{F} = \boldsymbol{0}$$

$$\boldsymbol{T_1} + \boldsymbol{T_2} + \boldsymbol{T_3} + \boldsymbol{T_4} + \boldsymbol{T_5} + \boldsymbol{T_6} + \boldsymbol{T_7} + \boldsymbol{T_8} + \boldsymbol{T_9} + \boldsymbol{T_{10}} + \boldsymbol{T_{11}} + \boldsymbol{T_{12}} + \boldsymbol{T_{13}} + \boldsymbol{T_{14}} + \boldsymbol{T_{15}} + \boldsymbol{T_{16}} = -\boldsymbol{W_{fixed}}$$

  For the bridle system, the exact solution requires solving the problem:

$$\sum \boldsymbol{F} = \boldsymbol{0}$$

$$\boldsymbol{T_A} + \boldsymbol{T_B} + \boldsymbol{T_C} + \boldsymbol{T_D} = -\boldsymbol{T}$$

- Dynamic loading from wind gusts were ignored in structural and performance analyses. All analyses were evaluated in a steady wind condition.

5.2 Improvements

Although optimistic results were obtained from this study, improvements and further research that can be made to improving the torus-based-design include:

- Increasing the lift and decreasing the weight of the system. The lift can be increased by using hydrogen as a lifting gas which provides more lift than helium, and it is also a cheaper gas. It may be a viable gas as advancements in hydrogen safety are made. Perhaps a gas mixture can be made that is less dense than helium. The weight of the system can be decreased with high strength to weight ratio materials such as fiber reinforced composites.

- The system can be made more wind resistant by adding lifting surfaces or a motorized stabilizing system. Lifting surfaces can add dynamic lift to the aerostatic lift and a motorized system can provide a thrust force to counteract the drag force.

- The current geometry of the bridle does not allow the balloon to remain horizontal in the wind. For the balloon to remain horizontal in all winds, requires suggestions from the previous paragraph or the design of an adjustable bridle that will allow the tension vector and the resultant of the lift and drag vector to be inline.

- Investigating dynamic loading resulting from wind gusts.

5.3 Conclusions

For the purpose of carrying out atmospheric monitoring with the instruments at UTSI's Aviation Systems department, a tethered aerostat system using a constant volume torus balloon seems promising. By choosing the torus, the layout of the structures in the system is able to be kept symmetric. The constant volume feature allows simpler operation than a variable volume balloon.

The results from this study showed that designing a tethered aerostat system using a torus shaped envelope is challenging because of the envelope's high drag coefficient. The analysis confirmed the findings in literature that any balloon not of the streamlined shape will not perform well in high winds. The cabling required in this balloon design also resulted in an excessively statically indeterminate system.

Despite, the problems discovered, improvements and further work on the limitations of the proposed design should make it simpler to operate, fulfill most of the design goals and operate safely with the current selection of materials.

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APPENDIX

Table 1. Safety Factors for Different Tethered Balloon Components (EASA 12).

Component	Safety Factor
Envelope	5.00
Suspension and tethering components (fibrous or non-metallic)	3.50
Suspension and tethering components (metallic)	2.50
Other	1.50

Table 2. Sample Payloads Weights

Instrument/ Equipment	Weight (lbf)
Laser Altimeter	8.0
Spectrometer	1.5
Pyrometer	6.4
NI USB 6009	0.1
Outside Air Temperature Probe	1.0
Nadir Camera	1.2
Radiometer	1.0
	Total = 19.2

Table 3. Properties of Planned Materials and Equipment

Equipment/Material	Properties
Winch: Force 5 Guideline Winch Supplier: Ingersoll-Rand	Storage Drum Capacity: 5262 ft of 7/8” rope Max Pulling Force: 3400 lbf
Tether: Spectra Tether Supplier: Aerial Products Corporation.	Breaking Strength: 800 lbf Theoretical Breaking Length: 667 000 ft Line Weight: 0.0012 lbf/ft Diameter: 0.78mm
Envelope Fabric: Polyurethane Coated Nylon Supplier: Seattle Fabrics Inc.	Tear Strength: 0.8 GPa, 116 030 psi Fabric Density: 0.007373 lbf/ft^2 Thickness: 0.32 mm (0.0126 in)
Lifting Gas: Helium Supplier: PRAXAIR	Density: 0.0003282 slugs/ft^3 at sea level std. Lift Capability: 0.0595 lbf/ft^3 at 3000 ft MSL std.
Bridle Lines: Spectra Tether Supplier: Aerial Products Inc.	Same properties as in second row.
Suspension Lines: Spectra Tether Supplier: Aerial Products Inc.	Same properties as in second row.
Bearing Swivels Supplier: McMaster Carr	Type: Clevis and Clevis Working Load Limit: 1000 lbf
Adhesive Backed Tie Down rings Supplier: McMaster Carr	Working Load Limit: 140 lbf

Table 4. Properties of the Envelope

Parameter	Value
Outer Radius, R (ft)	12.70
Cross sectional radius, a(ft)	3.35
Axis to cross section center, c (ft)	9.35
Volume Required, V (ft^3)	2071
Surface Area Required, S (ft^2)	1237
Aerostatic Lift (L_s) at operating Altitude, AGL (lbf)	123.01
Design Excess Lift (L_{excess}) at Operating Altitude (lbf)	61.50
Envelope Weight (lbf)	9.11
Total Weight Lifted (lbf)	61.51

Table 5. Lengths and Angles of Bridle and Suspension Cables

Cable	Length (ft)	Angle (degrees)
Bridle Cables: $T_A = T_B = T_C = T_D$	9.56	12
Suspension Cables: $T_1 = T_4 = T_5 = T_8 = T_9 = T_{12} = T_{13} = T_{16}$	9.37	4
Suspension Cables $T_2 = T_3 = T_6 = T_7 = T_{10} = T_{11} = T_{14} = T_{15}$	7.21	34

Table 6. Weights of System Components

Item	Weight (lbf)
W_{fixed}	50.0000
W_{enve}	9.1100
W_{bridle}	0.0459
W_{susp}	0.1590
W_{tether}	2.4000

Table 7. Factor of Safety Limits, Factor of Safety and strength of balloon system Components

Material/Equipment	Limit Load	F.S.	Strength
Envelope	23206 psi	5	116030 psi
Tether Line	229 lbf	3.5	800 lbf
Bridle Line	229 lbf	3.5	800 lbf
Suspension Line	229 lbf	3.5	800 lbf
Adhesive Backed Tie Down Ring	40 lbf	3.5	140 lbf

Table 8. Performance at 3000 FT MSL on Standard Day

Standard Day							
Wind Speed (mph)	**Expected Drag (lbf)**	**Φ (deg)**	**Expected Tether Tension (lbf)**	**Additional Tether (ft)**	**Extra Tether Weight (lbf)**	**New Tether Length (ft)**	**Horizontal Displacement (ft)**
0	0.0	0.0	61.5	0.0	0.000	2000.0	0
1	0.2	0.2	61.5	0.0	0.000	2000.0	7
2	0.9	0.8	61.5	0.2	0.000	2000.2	30
3	2.1	1.9	61.6	1.1	0.001	2001.1	67
4	3.6	3.4	61.6	3.5	0.004	2003.5	118
5	5.7	5.3	61.8	8.6	0.010	2008.6	185
6	8.2	7.6	62.1	17.7	0.021	2017.7	267
7	11.2	10.3	62.5	32.7	0.039	2032.7	363
8	14.6	13.3	63.2	55.4	0.066	2055.4	474
9	18.5	16.7	64.2	88.0	0.106	2088.0	600
10	22.8	20.3	65.6	132.7	0.159	2132.7	741

Table 9. Performance at 3000 FT MSL on Standard Day with + 30° Change

Standard Day + 30 Degrees							
Wind Speed (mph)	**Expected Drag (lbf)**	**Φ (deg)**	**Expected Tether Tension (lbf)**	**Additional Tether (ft)**	**Extra Tether Weight (lbf)**	**New Tether Length (ft)**	**Horizontal Displacement (ft)**
0	0.0	0.0	53.6	0.0	0.000	2000.0	0
1	0.2	0.2	53.6	0.0	0.000	2000.0	8
2	0.9	0.9	53.6	0.3	0.000	2000.3	32
3	1.9	2.1	53.6	1.3	0.002	2001.3	72
4	3.4	3.7	53.7	4.1	0.005	2004.1	129
5	5.4	5.7	53.9	10.1	0.012	2010.1	201
6	7.8	8.2	54.2	20.8	0.025	2020.8	289
7	10.6	11.1	54.6	38.4	0.046	2038.4	394
8	13.8	14.4	55.3	65.1	0.078	2065.1	514
9	17.4	18.0	56.4	103.3	0.124	2103.3	651
10	21.5	21.9	57.8	155.4	0.186	2155.4	804

Table 10. Performance at 3000 FT MSL on Standard Day with - 30° Change

Standard Day - 30 Degrees							
Wind Speed (mph)	**Expected Drag (lbf)**	**Φ (deg)**	**Expected Tether Tension (lbf)**	**Additional Tether (ft)**	**Extra Tether Weight (lbf)**	**New Tether Length (ft)**	**Horizontal Displacement (ft)**
0	0.0	0.0	70.4	0.0	0.000	2000.0	0
1	0.2	0.2	70.4	0.0	0.000	2000.0	7
2	1.0	0.8	70.4	0.2	0.000	2000.2	27
3	2.2	1.8	70.4	1.0	0.001	2001.0	62
4	3.9	3.1	70.5	3.0	0.004	2003.0	110
5	6.0	4.9	70.7	7.4	0.009	2007.4	172
6	8.7	7.0	71.0	15.2	0.018	2015.2	247
7	11.8	9.6	71.4	28.1	0.034	2028.1	337
8	15.5	12.4	72.1	47.7	0.057	2047.7	440
9	19.6	15.5	73.1	75.9	0.091	2075.9	556
10	24.2	19.0	74.5	114.6	0.138	2114.6	687

Table 11. Bridle Loads

Atmosphere	**Windspeed (mph)**	**T(lbf)**	**T_A (lbf)**	**T_B (lbf)**
Standard	0	61.5	147	147
	10	65.6	157	157
30	0	53.6	128	128
	10	57.8	138	138
-30	0	70.4	168	168
	10	74.5	178	178

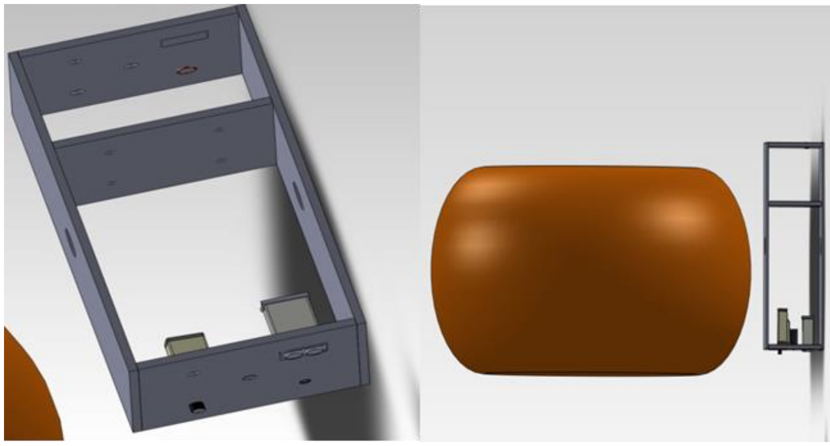

Figure 1. Torus Balloon, Instruments, Example Housing Structure

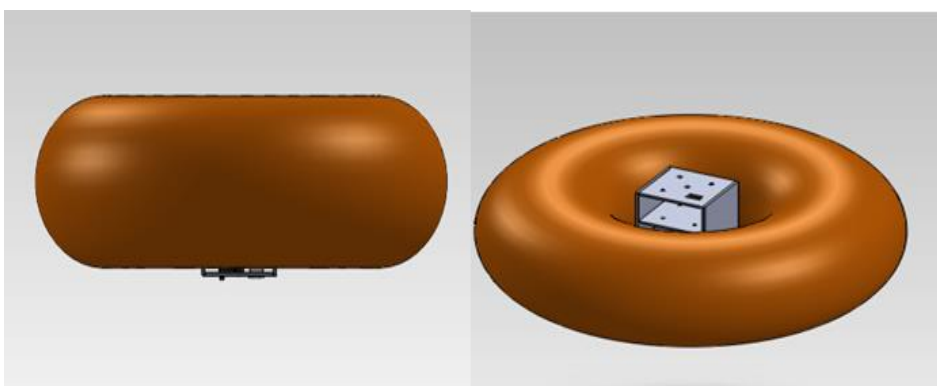

Figure 2. Situating of Housing Structure Relative to Envelope

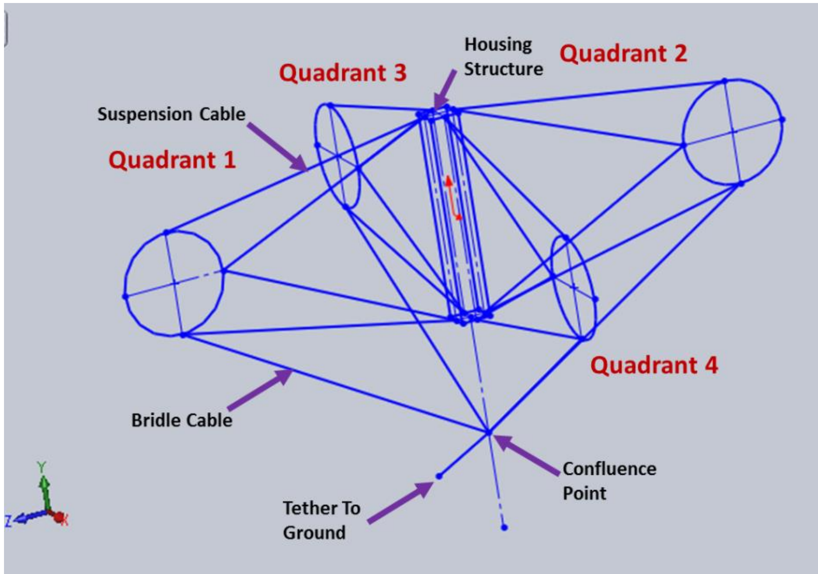

Figure 3. Three Dimensional Perspective for the Total Number of Suspension Cables, Bridle Cables and the Tether Line

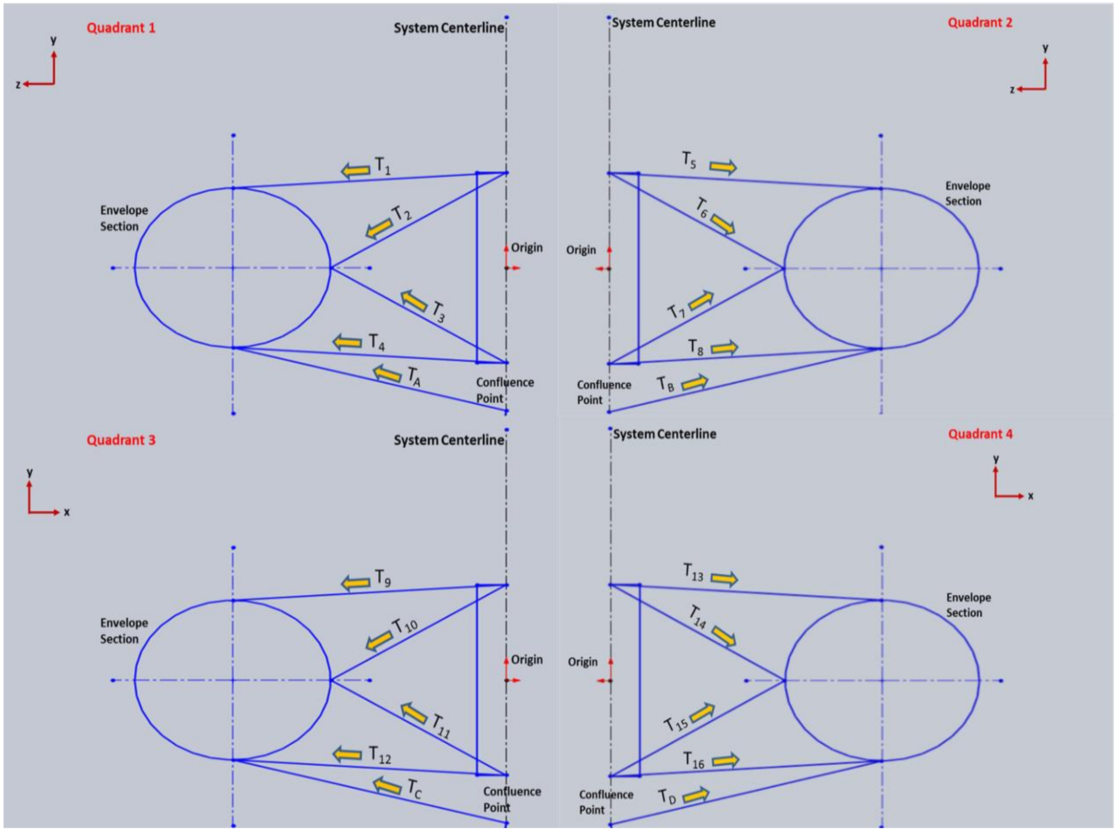

Figure 4. Illustration of Assumed Directions of Suspension, Bridle and Tether Line Vectors

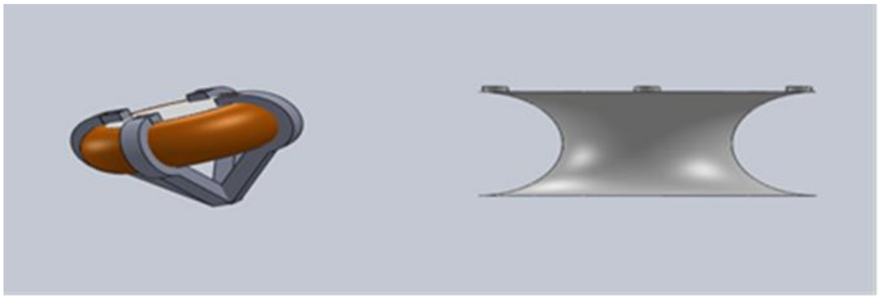

Figure 5. Torus Balloon with Hour-glass Housing Structure and Straps

Figure 6. Altaeros' Wind Blimp (Altaeros Energies) and the AeroTorus (Lindstrand Technologies)

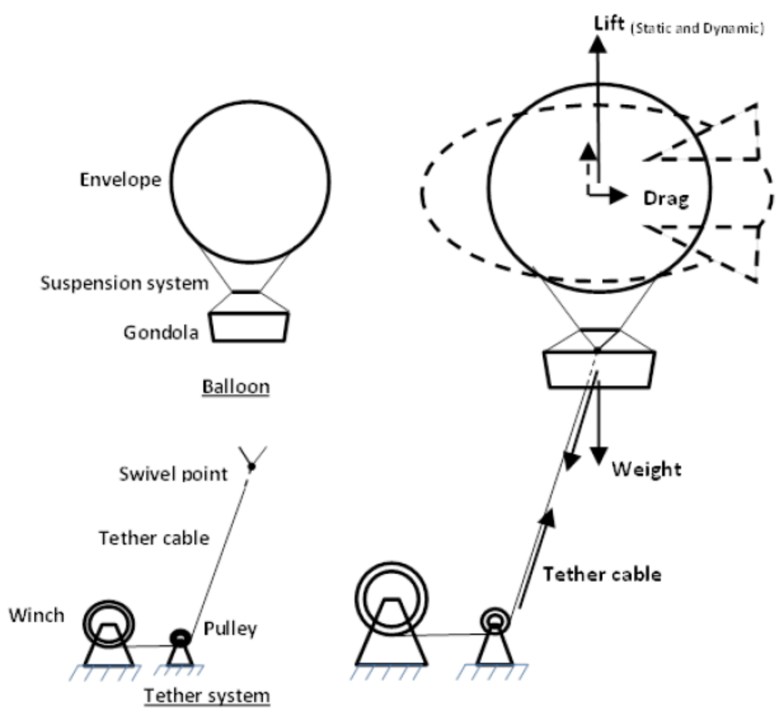

Figure 7. Typical Arrangement of a Tethered Aerostat System and Main Forces Acting on the System (EASA 19).

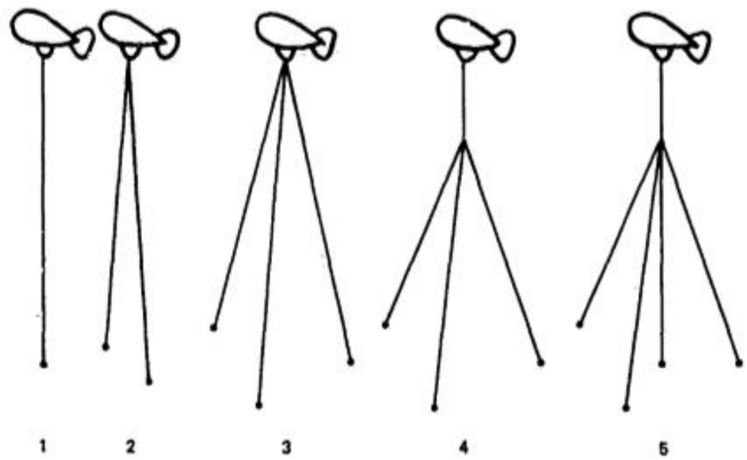

Figure 8. Typical Tethering Configurations (Wright 14)

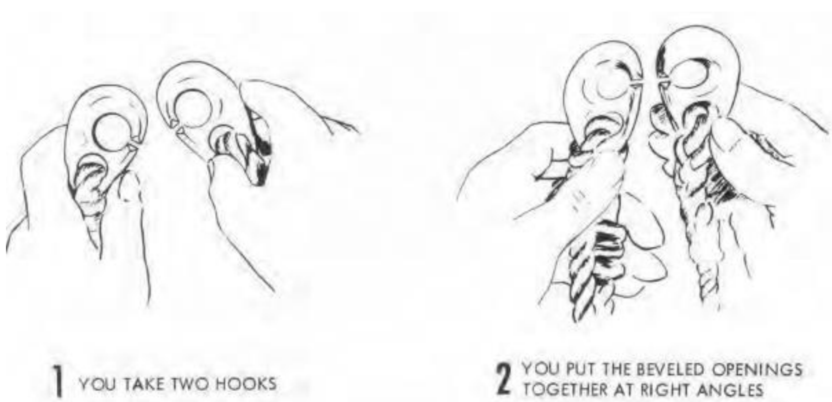

Figure 9. Brummel Hook Connection (Myers 111)

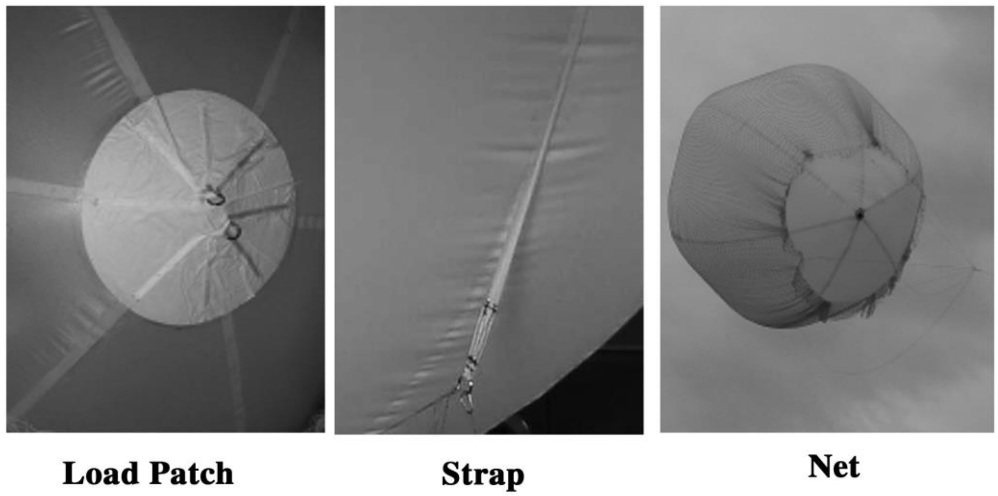

Figure 10. Typical Tether Connections to Balloons (Miller & Nahon 1448)

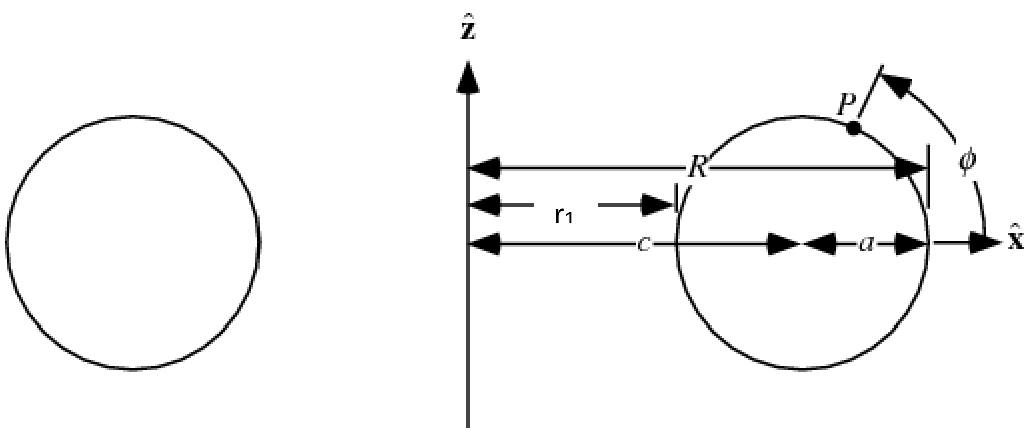

Figure 11. Torus Geometry (Weisstein 1)

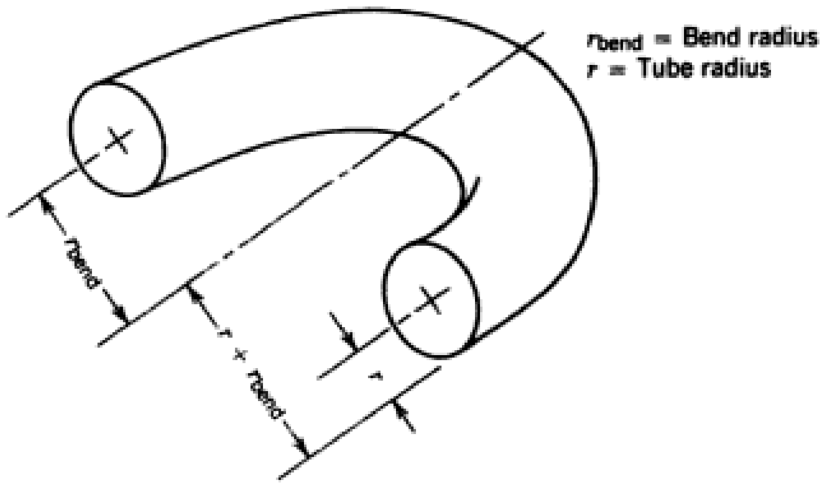

Figure 12. Sketch of Half Torus, Representative of Tube Bend (French 27)

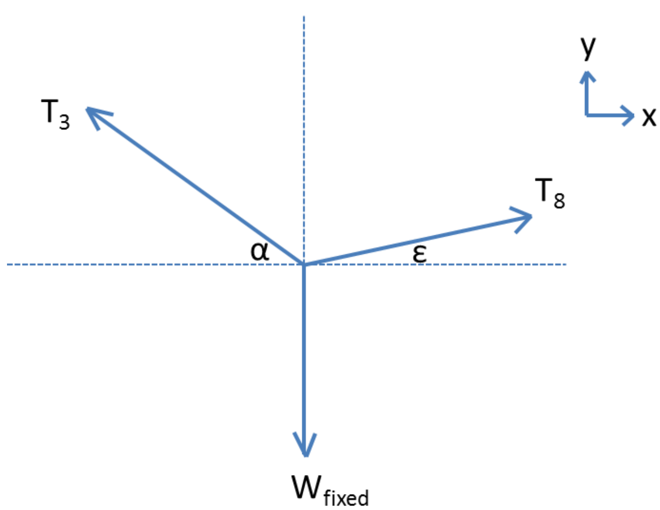

Figure 13. Freebody Diagram of Statically Determinate Suspension Cable System

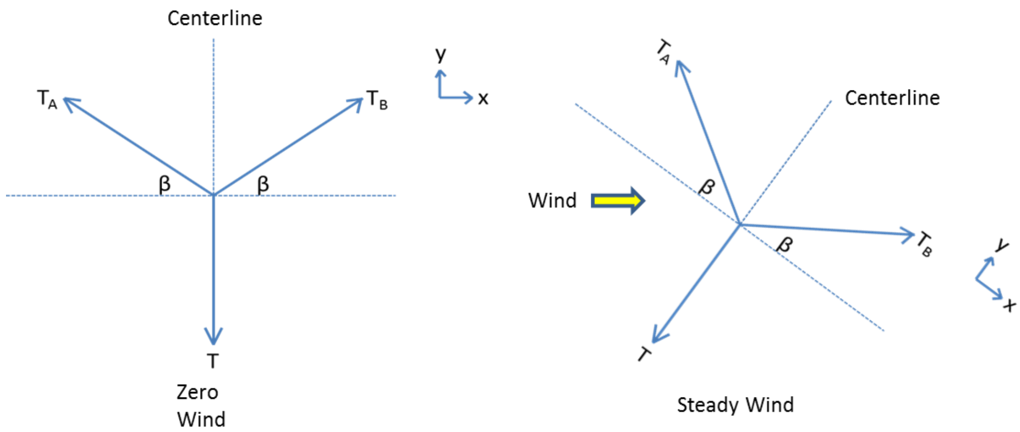

Figure 14. Freebody Diagram of Statically Determinate Bridle in Zero Wind and Steady Wind

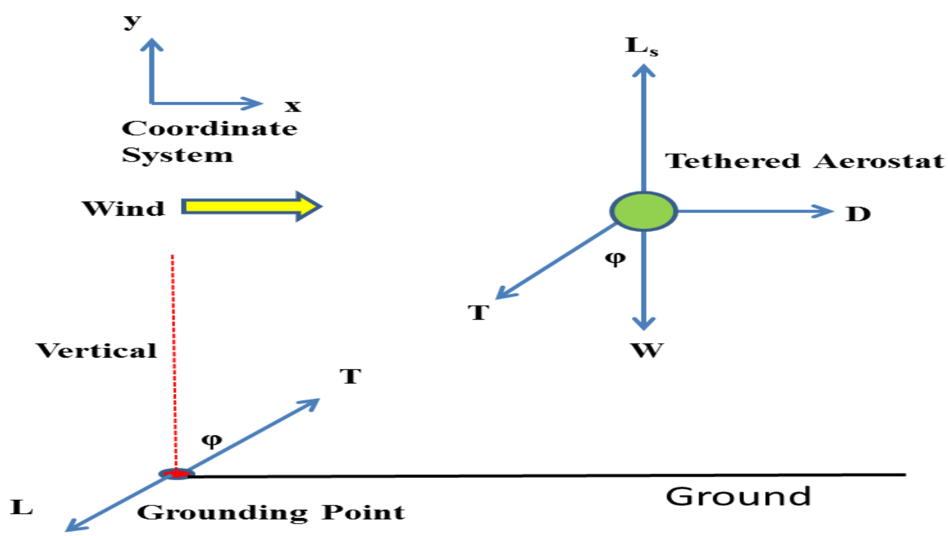

Figure 15. Free Body Diagram of Forces Acting at the Grounding Point and on the Balloon at Altitude

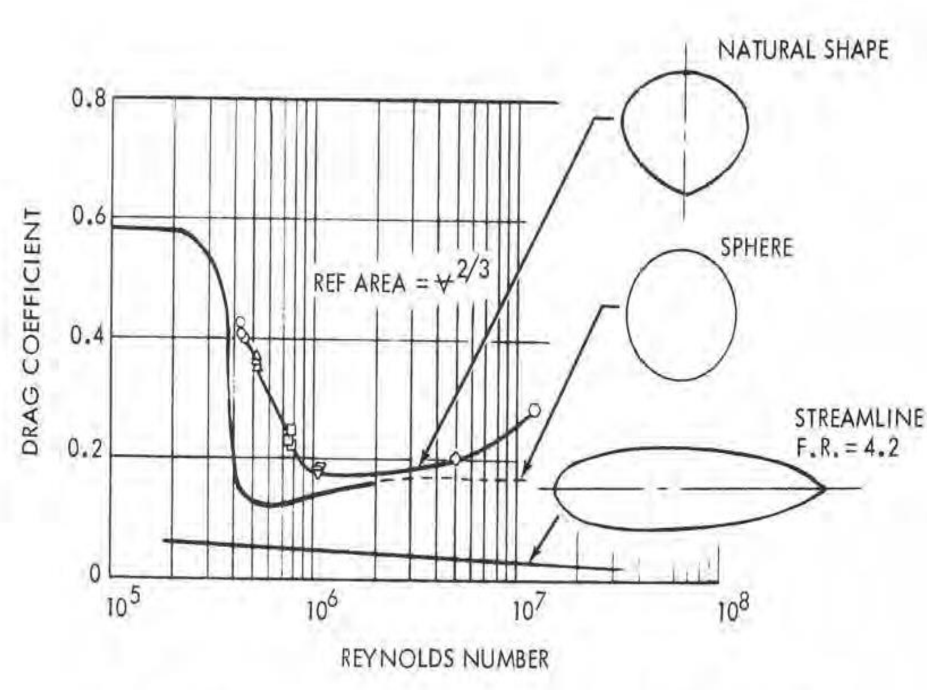

Figure 16. Balloon Drag Coefficient at Zero Angle of Attack versus Reynolds Number (Myers 10)

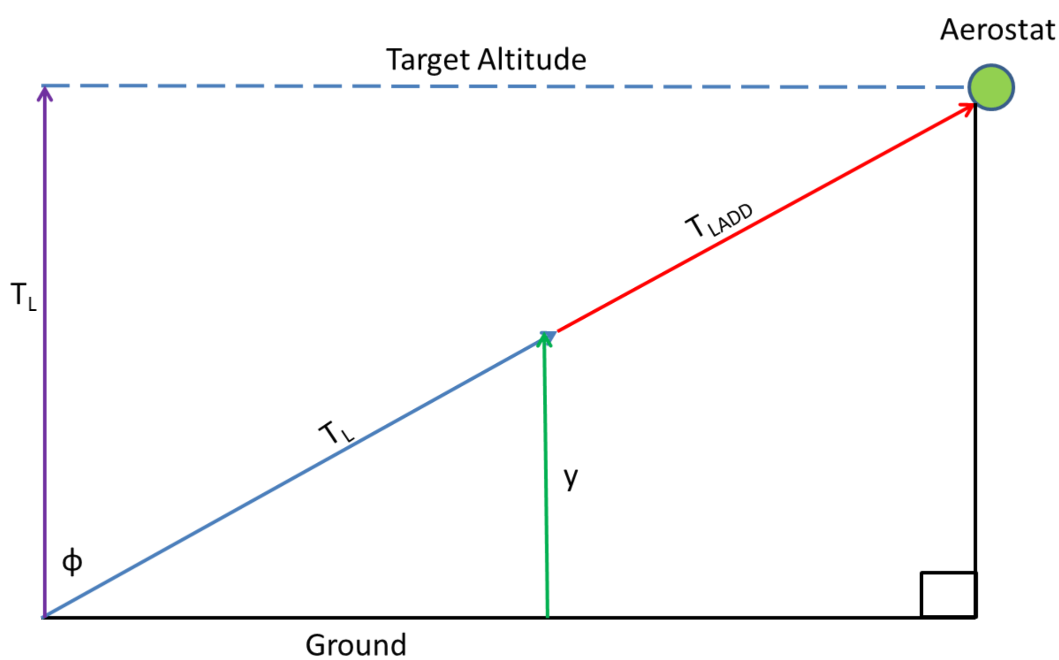

Figure 17. Extra Tether Length and Distance Off-Station Determination

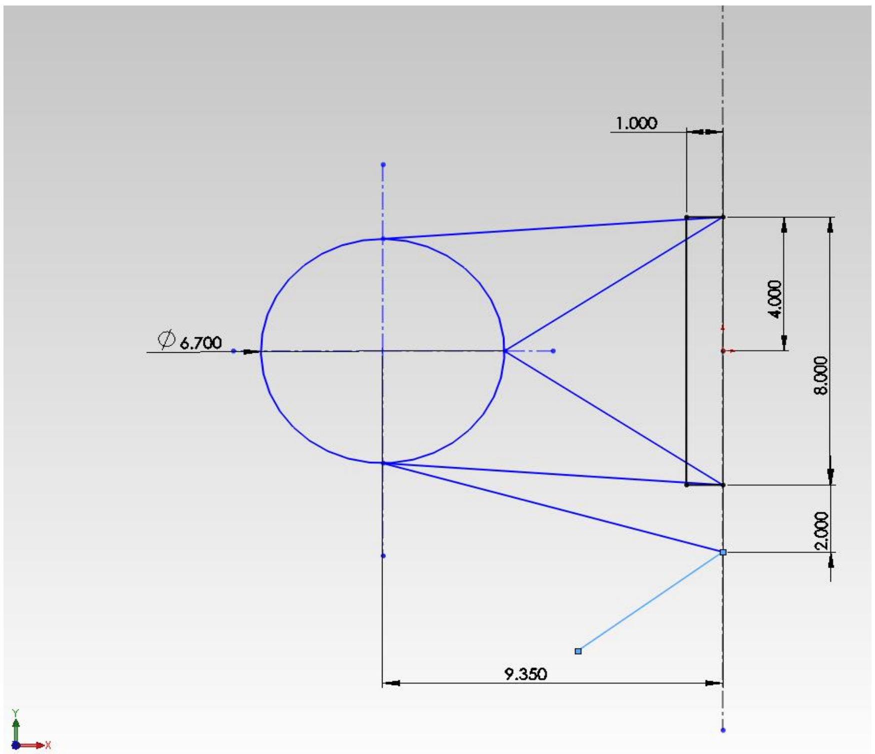

Figure 18. Dimensioned Sketch of Resulting Envelope Geometry and Cable Positioning
(all dimensions in feet)

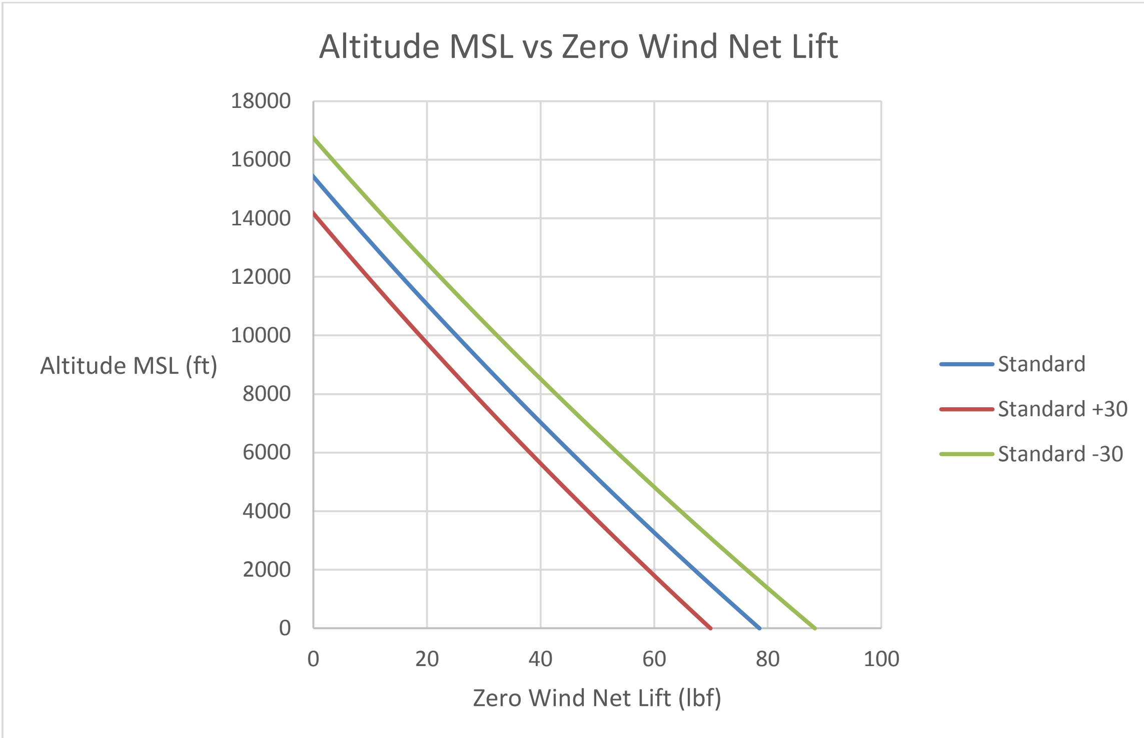

Figure 19. Availability of Zero Wind Net Lift at Different Altitudes MSL

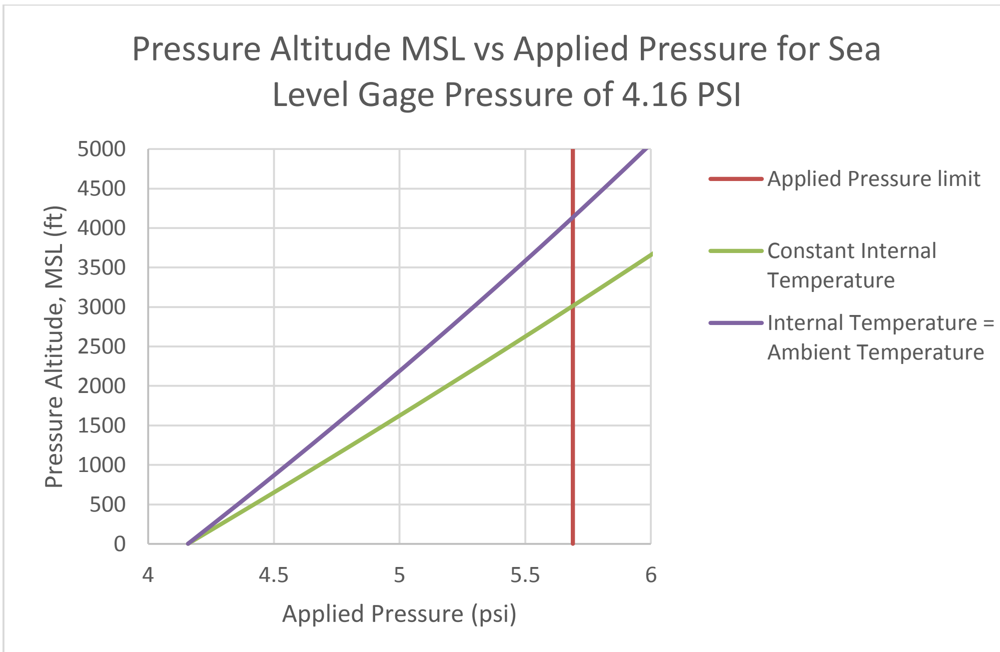

Figure 20. Variation in Applied Gas Pressure with Pressure Altitude MSL

VITA

Khoy Callwood grew up in the Virgin Islands (U.S. and British) for the first eighteen years of his life. Interest in airplanes led him to opportunities working as a trainee air traffic controller and in airport operations at the Terrance B. Lettsome International Airport during summer breaks. In 2010, he graduated from Embry-Riddle Aeronautical University with a Bachelor's of Science in Aerospace Engineering. Khoy is currently pursuing a Master's of Science in Engineering Science with a flight test concentration at the University of Tennessee Space Institute. In the future, he wishes to further his knowledge in test engineering, modeling and simulation, signal processing and obtain pilot licenses.