Utah State University Get Away Special Team
GASPACS AeroBoom Payload Critical Design Document

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The GASPACS (Get Away Special Passive Attitude Control Satellite) deployable payload "AeroBoom" design is discussed. The AeroBoom is an on-orbit, self-contained, inflatable boom structure with many potential uses, including passive attitude stabilization, deployable space nets, solar arrays, and other deployable space structures. The AeroBoom technology demonstration will be a passive stabilization system for a 1U CubeSat. Laboratory testing results, complex computer modeling, and spacecraft system design combine in a design review of the AeroBoom system. Justification for each design element is presented along with expected system performance. Conclusions will show suitability for use of the system on the GASPACS mission, compliance with mission requirements, and design considerations.

Preface

The AeroBoom payload, as described in this document, has reached a critical design phase, where each element has been carefully planned, analyzed, and tested. Significant improvements to the manufacturing, assembly, and testing processes have been made since the writing of the AeroBoom Payload Preliminary Design Document in October of 2019 [15]. The payload has been finalized, manufactured, and tested to meet all necessary requirements. All of the payload-related requirements from both the NanoRacks IDD [11] and the GASPACS Requirements Document [12] are listed throughout this document in their relevant sections. Upon review and approval of the designs enclosed herein, the Utah State University Get Away Special Team intends to proceed with the production of a flight unit AeroBoom payload for the GASPACS satellite.

1.0 Introduction

Maximizing space and weight aboard rockets is a key priority for current space system designers. On-orbit inflatable structures have long been considered by engineers to solve the volume and mass limitations of launch vehicles. The Utah State University Get Away Special Team has developed the "AeroBoom", an on-orbit inflatable boom structure designed to fit into a 0.5U form factor, specifically for integration into a 1U or larger CubeSat platform, see figure (1).

The AeroBoom technology demonstration will provide precedence and data for future on-orbit inflatable structures.

The planned proof-of-concept mission for the AeroBoom payload will be as part of the Utah State University Get Away Special Passive Attitude Control Satellite (GASPACS). This will be a 1U CubeSat deployed from the International Space Station (ISS) via the NanoRacks CubeSat Deployer (NRCSD). The GASPACS primary mission objectives are:

- *Deploy a meter long inflatable UV curable boom from a 1U CubeSat in low-Earth orbit.*
- *Photograph the deployed AeroBoom and transmit a clear picture back to earth.*

The secondary mission objective is:

- *Measure attitude behaviour of GASPACS to determine the effectiveness of the Aero-Boom to passively control the CubeSat.*

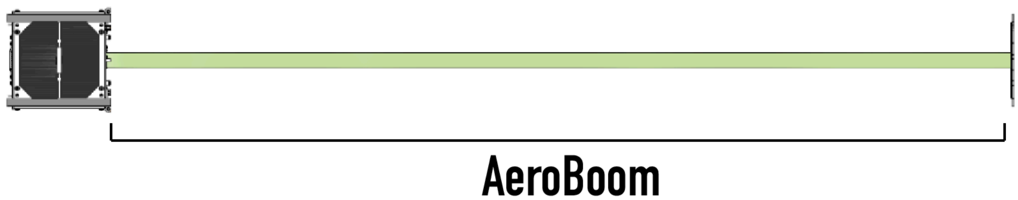


Figure 1. GASPACS CubeSat with AeroBoom Deployed

The AeroBoom is made of three major layers, shown in figures (2) and (3): a pressurized inner PVDF layer containing a small amount of air, a middle fiberglass structural layer impregnated with a UV curable resin, and an outer FEP protection and sealing layer. Detailed construction procedures for the AeroBoom are documented in section 4.1.

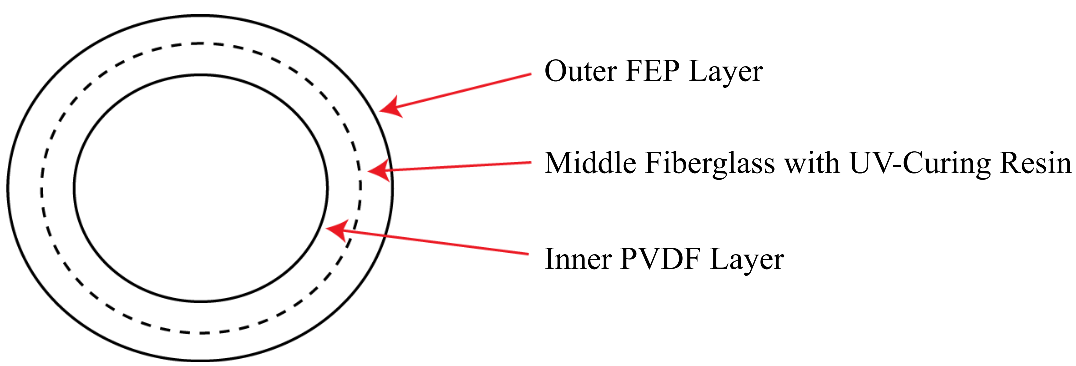


Figure 2. Cross-sectional View of AeroBoom Layers

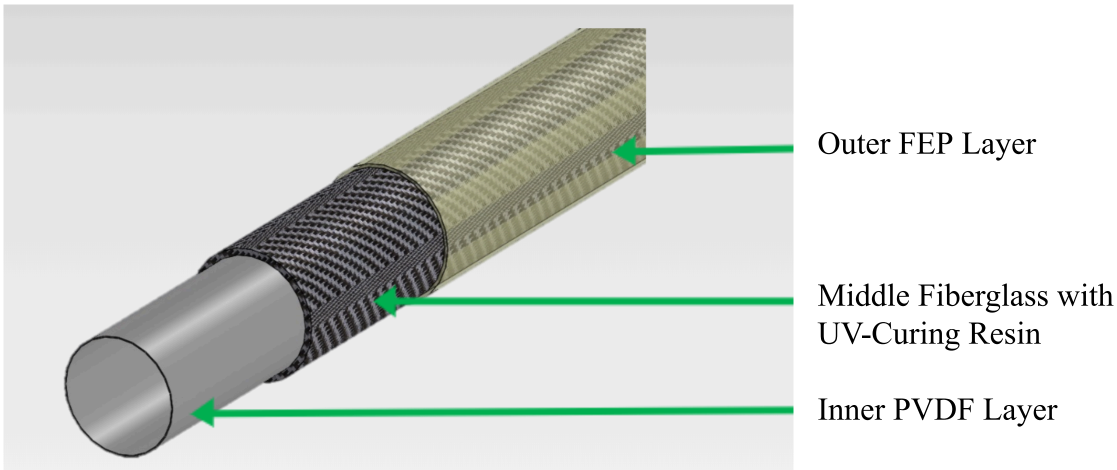


Figure 3. Isometric View of AeroBoom Layers

Initially, the AeroBoom is folded into a storage structure, named the "AeroBoom Box". Figure (4) shows the location of the AeroBoom Box in the GASPACS CubeSat. Note that the specific location and stack order of the components is not crucial; the AeroBoom Box only needs to be placed such that it faces outwards and its deployment is not impeded. Once in orbit, the GASPACS CubeSat will release the AeroBoom through the activation of a releasable melt wire system. The AeroBoom will inflate from the pressure of gas retained within its inner PVDF layer, forcing the AeroBoom to extend away from the main CubeSat structure. Once exposed to sunlight, the UV curable resin will harden and secure the deployed AeroBoom in the extended shape.

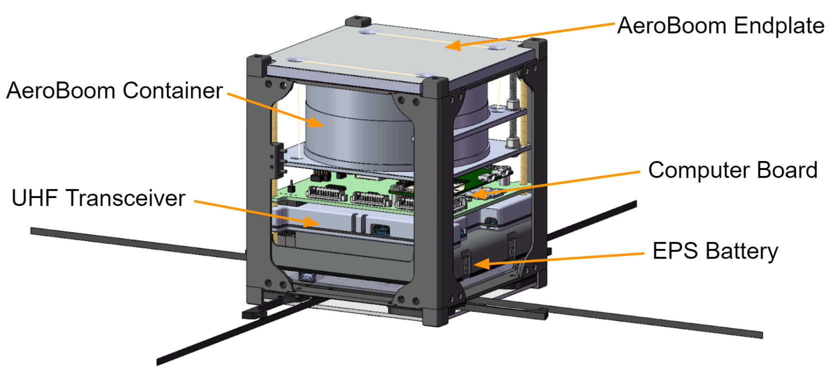


Figure 4. Rendering of GASPACS CubeSat showing the location of the AeroBoom payload

While there are numerous applications for inflatable technology, the GASPACS mission will demonstrate this deployable technology as a passive attitude control system. As the CubeSat moves within the low Earth orbital environment, it will interact with atmospheric particles, solar radiation, and the earth's magnetic and gravitational fields, each imparting small torques on the spacecraft. Deploying the AeroBoom will increase the magnitude of aerodynamic torque, allowing it to dominate all other forces. It was estimated by Gardiner [2] that the end result of a successfully deployed AeroBoom is two-axis passive attitude control of the CubeSat about its velocity vector with 20° pointing accuracy and rotation rates less than 0.1 °/sec. The name AeroBoom was chosen due to the interaction of the deployable boom with aerodynamic drag in LEO.

2.0 AeroBoom Deployment Performance Modeling

In order to avoid unnecessary mechanical complications, no valves, chemical reactions, or exterior reservoirs of gas were included in the AeroBoom design. The AeroBoom actuation, deployment, and inflation are powered by the force of the pressure gradient between a small amount of gas contained within the AeroBoom and the vacuum of space.To rely upon this pressure gradient, the exact amount of gas within the AeroBoom needed to be identified. As is described in equation (1), the pressure gradient $-\nabla f$ is defined by the inverse of the gas density, ρ, multiplied by the difference in pressure, ΔP, over the thickness of the membrane wall, Δx,.

$$-\nabla f = -\frac{1}{\rho}\frac{\Delta P}{\Delta x} \tag{1}$$

On orbit, it can be assumed that the change in pressure from within the inner layer of the AeroBoom to the vacuum of space, ΔP, is equivalent to the internal pressure of the AeroBoom. This assumption is justified, as the internal pressure of the boom is orders of magnitude greater than the ambient pressure found in low Earth orbit, rendering the ambient pressure irrelevant with respect to the internal pressure. The addition of these assumptions into equation (1) indicates that for any measurable pressure of gas within the boom, the pressure gradient points towards the vacuum of space, indicating that the AeroBoom will be forced to inflate when mechanically released from the storage bay.

Optimization of the AeroBoom design was focused on identifying the minimum pressure of gas required for full inflation of the AeroBoom. Full inflation of the AeroBoom was first defined as the point in which the flat AeroBoom expands into a fully cylindrical shape. This definition allows the cross section of an inflating AeroBoom to be described with simple elliptical geometry, permitting the exact point of full inflation to be identified. In its stored and packed state, the AeroBoom lies flat with its minor cross section axis at zero and its major cross section axis at a maximum. When the internal pressure is increased, the AeroBoom materials are forced outward, causing an increase in the minor axis and decrease in the major axis. The extent of the outward movement of the materials is limited to a point at which the interior pressure is equal to that of the exterior pressure. At full inflation, the major and minor axis come into equilibrium and the ellipsis forms a perfect circle. See figure (5).

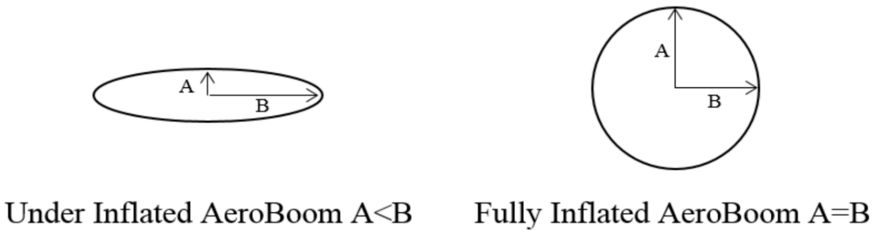


Figure 5. Cross Section View of the AeroBoom as a Function of Inflation

In an ideal situation, the AeroBoom will be deployed in space where the exterior pressure can be approximated as zero. This would indicate that even an extremely low amount of internal pressure could force the AeroBoom into a "fully inflated" cylindrical shape. In practice, however, the exterior pressure on the AeroBoom is not dominated by the ambient pressure of the space environment but rather by the resistance of the AeroBoom materials to inflation. The optimal performance of the AeroBoom is therefore defined as the point at which resistance of the materials is sufficiently overcome by the internal pressure, which forces the major and minor axes into equilibrium. During laboratory testing of multiple AeroBoom prototypes, an empirical model of AeroBoom inflation performance was developed, which characterized the elliptical shape of the AeroBoom as a function of internal pressure.This testing is summarized by Gardiner [2]. Each AeroBoom prototype was connected to an external gas supply and pressure gauge. As the boom was slowly inflated with gas, the shape of the ellipsis was periodically measured and noted as a function of the pressure. The results of the testing are displayed in figure (6).

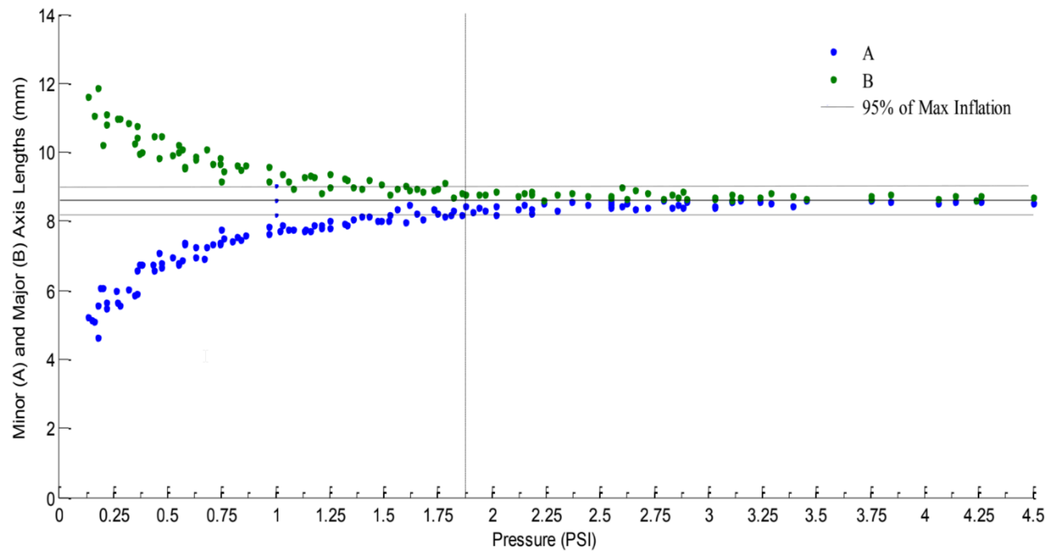


Figure 6. Elliptical shape of the AeroBoom as a function of internal pressure

As predicted in equation (1), when the pressure is increased within the AeroBoom, the minor axis A is forced into equilibrium with the major axis B. The point at which the two axes asymptotically converge indicates the minimum pressure at which the AeroBoom is fully inflated. Therefore, the test validates the theory and outlines a possible operational pressure range for the AeroBoom. Pressures above 1.9 psi are of particular interest, as both the minor and major axis are within 95% of their physical maximum radius. Numerical analysis into permeation of the AeroBoom before deployment has resulted in a worst-case estimate of 0.21 psi pressure loss over the maximum expected 6 days in vacuum before AeroBoom deployment. This analysis is further explained in section 2.1. Accepting 1.9 psi as the desired performance pressure of the AeroBoom and factoring in the maximum expected pressure loss of 0.21 psi, a required pressure of 2.2 psi was chosen to fully inflate the AeroBoom. This provides a safety factor of 1.4 of the maximum allowable loss versus the maximum expected loss. Testing has been done with regards to the permeation of the AeroBoom before deployment (see section 5.3)

2.1 Modeling AeroBoom Deployment Performance in LEO

Modeling the Aeroboom's deployment required an understanding of permeation during CubeSat assembly, integration with the launch vehicle, and pre-mission space operation. Although the AeroBoom is multi-layered and sealed in a non-ventable container, the loss of gas through the AeroBoom pressure container membrane could have an effect on the final performance of the AeroBoom system, as pressure is proportional to the volume of gas in the system, see equation (2).

$$PV = NRT \quad (2)$$
$$\rightarrow P \propto T$$
$$\rightarrow P \propto N$$

P1V1 = P2V2

Significant research and analysis has been conducted into determining how much time the AeroBoom will be able to spend in the vacuum of LEO before there is an unacceptable decrease in pressure inside the AeroBoom. A Matlab script [4] was written by Danos to model the loss of gas through permeation. The script allows user-inputted values including temperature, AeroBoom length, time stored in vacuum, and internal volume of the AeroBoom box. Results of this script estimated a worst-case permeation of 0.21 psi over the course of 6 days. NanoRacks estimates the worst-case time between exposure to vacuum and release from the NRCSD to be 4 days. We plan to deploy the AeroBoom as soon as possible, likely less than 12 hours after release from the NRCSD. This results in a 5 day worst-case exposure to vacuum before deployment. We chose 6 days to account for any unforeseen errors and an additional safety factor.

In order to determine the optimal length of the AeroBoom, an analysis was conducted by Burton [3] based on factors including the strength of the materials, volume of the AeroBoom, and internal volume of the AeroBoom box. The analysis concluded that the optimal length of the AeroBoom is 0.984 m, with a manufacturing tolerance of +/- 0.001 m.

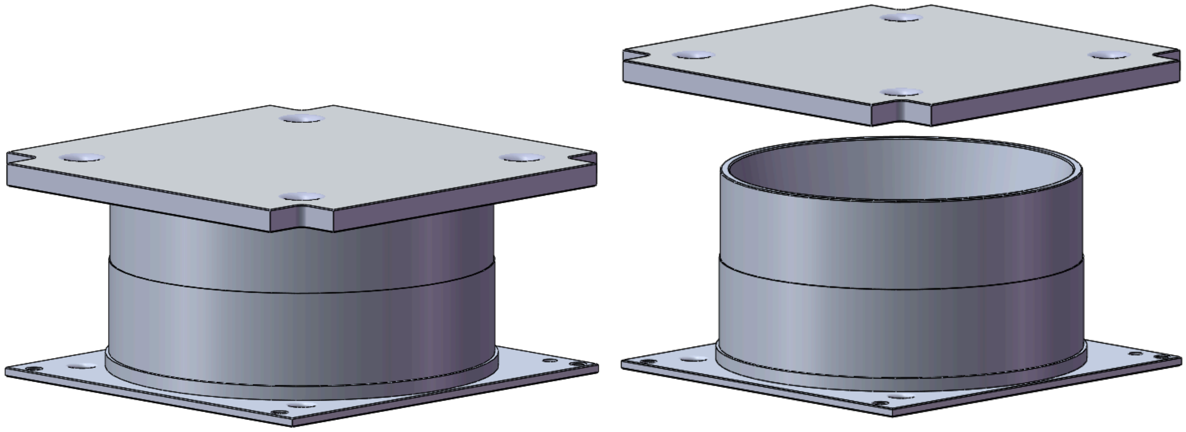
Initial versions of the AeroBoom were manufactured by vacuuming the air out of a section of PVDF plastic, and then injecting in a calculated volume of air. However, exposing the inside of the PVDF to vacuum caused micro-tears, and thus leaks, in the PVDF. This necessitated a change to the filling method for the inner boom. The process is described in section 4.

2.2 Analysis of Passive Attitude Control System on GASPACS

The passive attitude control effects of the AeroBoom system were analyzed in depth by Gardiner [2]. Significant research was conducted into determining the effects of the external forces on the AeroBoom and the GASPACS satellite while in orbit. It was estimated that GASPACS will stabilize along the velocity vector, with a 20° pointing accuracy, within 24 hours of deployment of the AeroBoom.

3.0 Mechanical Implementation

The AeroBoom system consists of four major components: support and storage structure, inflatable pressure container, release wire system, and electronic accessories. The support and storage structure are shown below in figures (7), (8), and (9).



Figures 7 and 8. AeroBoom Storage Structure and Exploded View

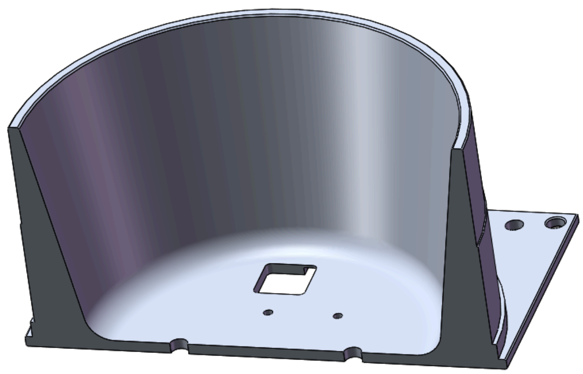


Figure 9: Section View of AeroBoom Box showing sloped walls

3.1 Storage Structure

The storage structure, called the AeroBoom Box, contains the AeroBoom in its packed and stored state prior to deployment. It also protects the AeroBoom from environmental conditions, including ultraviolet light and thermal variations. The support structure assembly consists of two parts: the combined base plate and storage bay, and the upper lid (See Figures 7 and 8).

The base plate connects the support structure assembly to the CubeSat frame. The storage bay attached to the base plate provides 40mm of protected vertical storage space for the folded AeroBoom. The base plate also provides mounting locations for the wire cutter, Raspberry Pi Camera, and ultraviolet sensor. The latter two are mounted outside the base plate but "see" into the storage bay. Together, the base plate and storage space are referred to as the AeroBoom Box

The upper plate forms the lid of the storage bay, and functions as the drag plate (hereto referred to as endplate) attached to the end of the AeroBoom. The endplate works in conjunction with the storage bay and containment system (described in section 3.3) to contain the AeroBoom inside the CubeSat until deployment. Upon deployment, the 10° sloped internal walls of the AeroBoom Box, along with the smooth radius of the bottom edge, as seen in figure (9), assist with a seamless release of the AeroBoom.

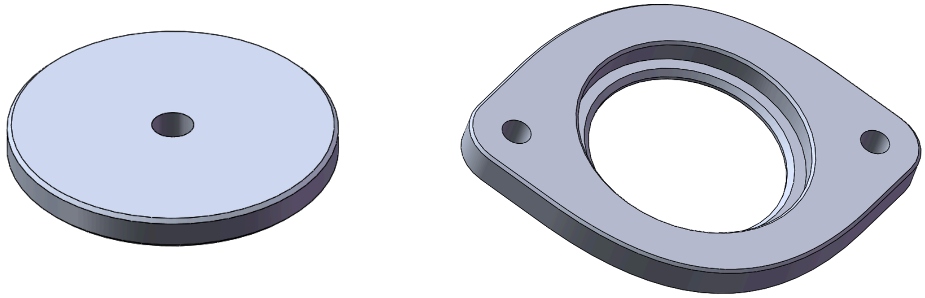
Table 1. AeroBoom Storage Structure Mass and Volume

Storage Bay Internal Volume	151.1 cm^3
Storage Structure Volume (AeroBoom Box and Endplate)	119.6 cm^3
Mass of Storage Structure, Tension System, and Coupling System	340 g
AeroBoom Mass	76 g
Total Mass	416 g

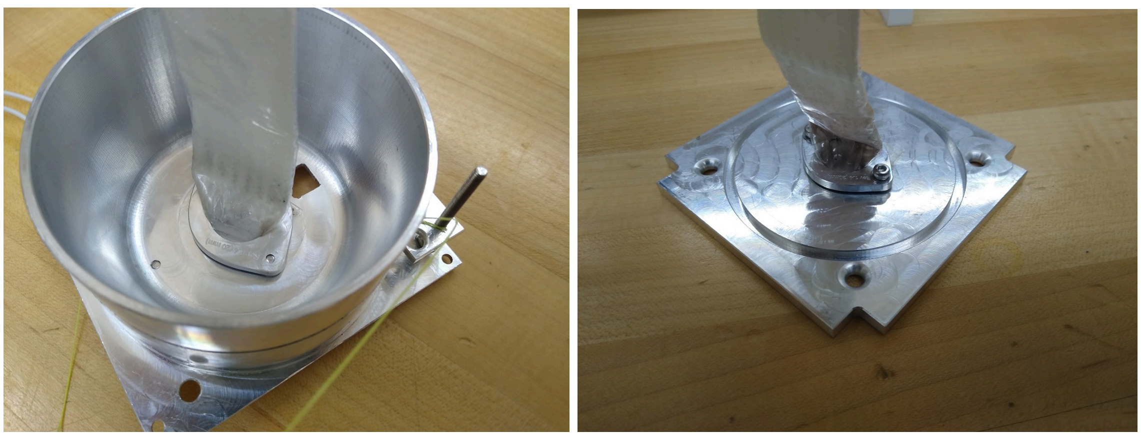
All of the support and storage structure parts are CNC milled out of 6061-T6 billet aluminum. 6061 Aluminum was selected due to its ease of machining, low cost, thermal properties, and extensive history in the aerospace industry. It is the most commonly used aluminum alloy in the world [16].

3.2 AeroBoom Coupling System

The AeroBoom must be securely attached to the AeroBoom Box and the endplate so that, upon deployment, the AeroBoom stays securely attached to both the AeroBoom Box and endplate. A failure of this system would result in both mission failure and a creation of space debris, violating NanoRacks requirement 4.4.6. A clamping method was developed by Danos and improved by Marcusen to secure the AeroBoom to the AeroBoom Box and endplate. The system consists of a circular disk and clamp. During AeroBoom construction, the clamps (see Figure 11.) are slid onto the AeroBoom, with their cavities facing outwards. Then, a disk is placed in each end of the AeroBoom and secured. When the clamps are slid to the end of the AeroBoom, their cavities mate snugly with the disks. The clamps are then bolted to the endplate and the AeroBoom box. This system prevents the AeroBoom from being pulled off the endplate or AeroBoom box by the strenuous forces of deployment. (see Fig. 12-14).



Figures 10 and 11: Circular disk and disk clamp



Figures 12 and 13: AeroBoom clamped to AeroBoom Box and endplate

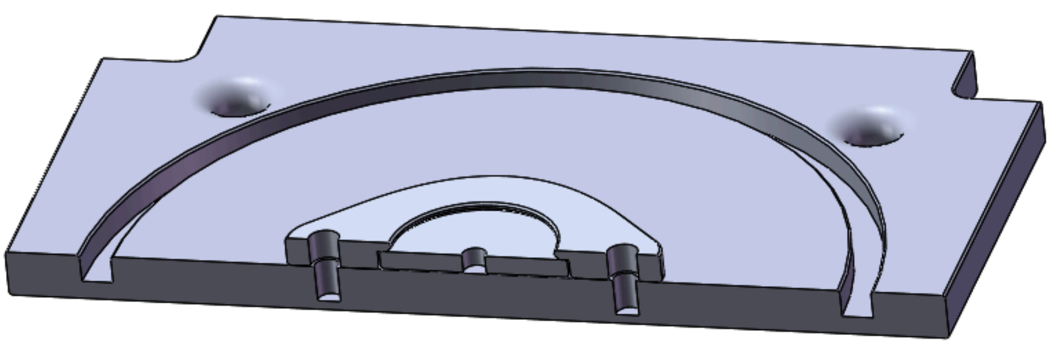


Figure 14: Cutaway view showing how clamp system secures AeroBoom to endplate

This disk-and-clamp mechanism effectively secures the AeroBoom to the AeroBoom Box and endplate. However, to keep the AeroBoom from bending at the connection points, a method was developed to secure the disks inside the AeroBoom during construction. After the disks are placed in the AeroBoom, the FEP plastic is hermetically heat-sealed at the end, locking in the disk and effectively creating a small pocket between the heat seal and the fiberglass for the disks that stops them from bending and keeps the AeroBoom in an approximately perpendicular configuration to the endplate and AeroBoom box after deployment.

3.3 Containment and Deployment System

A nickel chromium (nichrome) wire cutter (NCWC) was adopted for use as the AeroBoom melt wire deployment mechanism. While there are many effective deployment mechanisms for AeroBoom deployment, the NCWC system involves no moving parts, which reduces the potential for failure.

The AeroBoom endplate is secured to the AeroBoom Box with fishing line, tensioned using the tension mechanism described in **3.3**. The specific fishing line chosen for the AeroBoom Payload is SpiderWire Stealth® Braid, a braided line made from Dyneema® PE fibers with a fluoropolymer treatment. Dyneema® is made from Ultra High Molecular Weight Polyethylene (UHMWPE) fibers and was chosen because it effectively does not stretch, has a negative thermal expansion coefficient, and was recommended by NanoRacks for use on CubeSat deployables. SpiderWire Stealth Braid was chosen over other braided fishing lines because of its fluoropolymer treatment that decreases its coefficient of friction, which will aid in a smooth release of the endplate. A 50 lb strength was chosen to provide, at a minimum, a 2x safety factor based on the tension that will be applied to the string of 11-22 lbs.

When tensioned, the Dyneema runs over a groove in a MACOR ceramic block. MACOR was chosen because the block must be non-conductive and able to stand up to very high temperatures for short periods of time. Under the fishing line are two wire cutter systems, a primary and a backup. The tension in the fishing line ensures good contact with the wire cutter systems.

The wire cutter system consists of a piece of 30 gauge nickel chromium wire, which runs under the fishing line. On either side of the MACOR block, a bolt is screwed down on top of the wire, securing it. A ring terminal is also secured with the bolt. The ring terminals attach to the GASPACS electrical board, which controls their activation.

When the onboard computer commands the electrical board to activate the wire cutters, current will run through the nickel chromium wire, heating it up. This will melt the restraining fishing line, and the air pressure inside the AeroBoom will force it out of the AeroBoom Box.

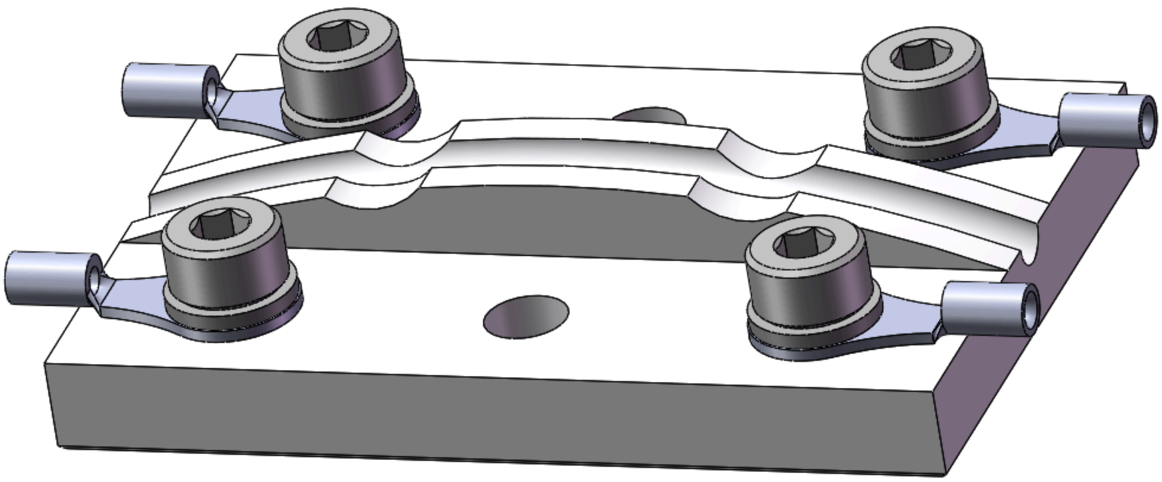


Figure 15: Wire Cutter System. Fishing line runs through the center groove, nickel chromium wire goes through the sideways grooves, under the fishing line.

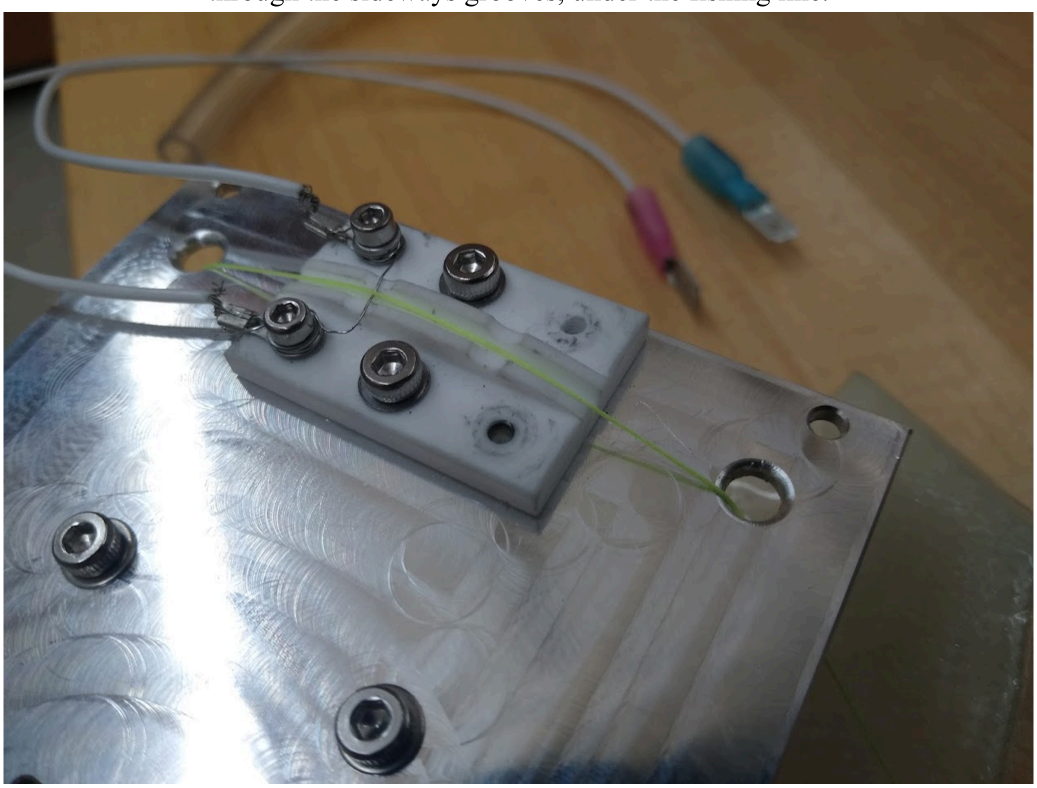
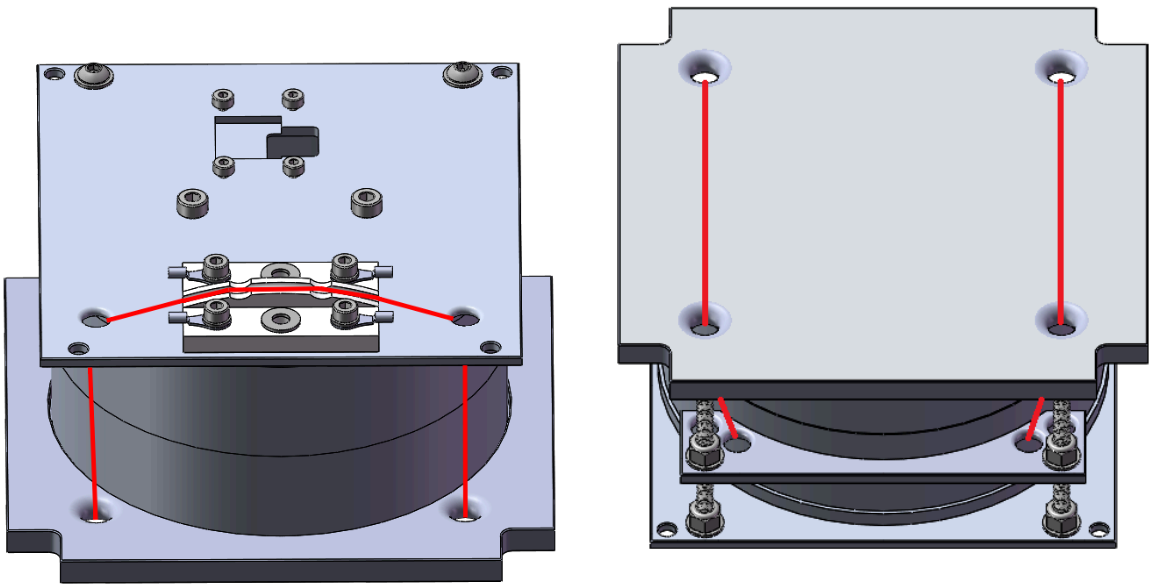


Figure 16: Wire Cutter System attached to Rev. 1.4 AeroBoom Box *Note: In this photo, only the primary wire cutter is attached*

3.3 Restraining and Tensioning System

The volume of the AeroBoom creates a pressure on the endplate when the AeroBoom is packed in the AeroBoom Box, threatening to push it off. This pressure will be greater in the vacuum of space, where there is no ambient atmospheric pressure to hold back the endplate. This necessitates a restraining system to secure the AeroBoom and endplate until deployment.



Figures 17 and 18. Restraint Line System Rendering

The restraining system consists of a fishing line which runs through holes on the endplate and baseplate, and a tensioning system. The tensioning system is composed of a tension bar (See Fig. 17 and 18), and two screws with lock nuts. To secure the endplate, one end of the fishing line is tied into one side of the tension bar. Then, the fishing line is fed through the holes in the endplate and baseplate, over the MACOR block on the underside of the baseplate (See Fig. 17), and then tied to the other side of the tension bar. To tension the system, The tension bar is placed on the screws, which are attached to the baseplate. Lock nuts are attached on top of the tension bar. To tension the system, an allen key is used to turn the screws, which lowers the tension bar, applying tension to the system.

A significant difficulty that was encountered in the course of the development of the tension and restraining system was the difficulty of replicating an exact tension. When fully tensioned, the tension in the system had to remain under half the maximum tension of the fishing line, to preserve the 2.0x safety factor associated with the AeroBoom system. However, the tension also has to consistently be high enough to secure the endplate against the AeroBoom Box. If the endplate is not secure, light might penetrate into the AeroBoom Box, prematurely curing the AeroBoom and resulting in failure of the primary mission.

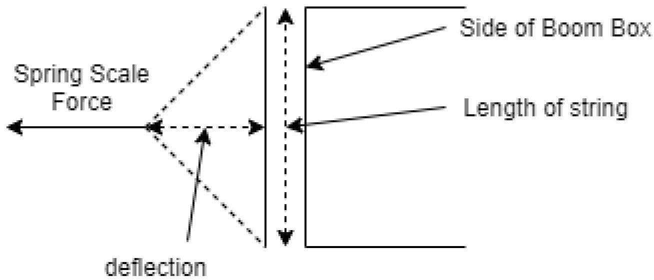


Figure 19: Tensioning measurement system

A method was developed to measure, and thus replicate, the tension in the restraining fishing line. This method is documented in the GASPACS Tensioning Procedure, and a diagram of the method is seen in Figure 19. A spring scale is used to pull the tensioned fishing line, running vertically from the baseplate to the endplate, horizontally. The deflection created by pulling the tensioned fishing line with a spring scale can be measured, and from this measurement the tension in the fishing line can be calculated.

The tension in the fishing line ensures the success of the wire cutter system by pressing the fishing line against the nichrome wire. Furthermore, when the fishing line is cut and the AeroBoom is deployed, the fact that the two ends of the fishing line are tied to the tension bar ensures that no loose string will be released from the satellite, minimizing orbital debris.

3.4 AeroBoom Deployable Pressure Container

The completed AeroBoom is essentially a three layer, lay flat flexible pressure container. As the pressure differential between the AeroBoom and the atmosphere is increased, the layers of the AeroBoom flex and form it into a cylinder. Since the AeroBoom pressure is limited to 2.2 psi absolute pressure, when it is exposed to atmospheric pressure, it is forced mostly flat as the internal pressure is less than that of the external atmosphere. This allows it to be folded and stored in a small volume. When it is deployed in the vacuum of space, the internal pressure forces the AeroBoom to expand and take its natural, cylindrical form.

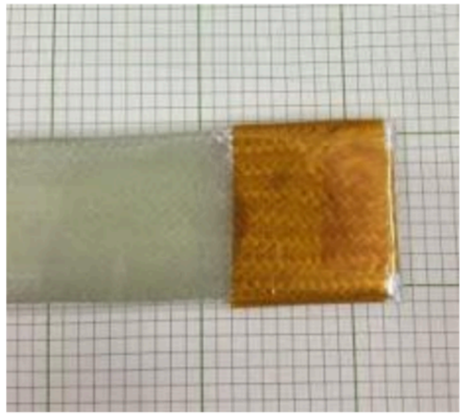


Figure 20. End section of AeroBoom showing fiberglass impregnated with epoxy.

The three layers are made to work in unison to complete the design function of the AeroBoom. The innermost layer is made of PVDF plastic and the outermost of FEP plastic, with a middle layer made of a cylindrical braided fiberglass sleeving that is impregnated with a UV curing resin. Together, the inner PVDF layer and the fiberglass braid represent the load bearing portion of the AeroBoom system. The PVDF inner layer creates a sealed, permeation-resistant membrane, which contains the stored gas. When the AeroBoom is exposed to the vacuum of space, the gas stored in the boom expands the inner PVDF layer. At full inflation the fiberglass braid restricts the expansion of the inner PVDF layer and absorbs the load placed on the layer by the pressure of the stored gas. The fiberglass braid also contains the UV curing resin. When the AeroBoom is exposed to sunlight, the resin in the fiberglass braid cures, making the fiberglass rigid and providing the AeroBoom with structural integrity.

This configuration allows the AeroBoom to be flexible and folded as required, while still maintaining the ability to contain a relatively large pressure. The outer FEP layer seals and protects the ultraviolet curable epoxy, preventing the loss of the resin through the contact with other surfaces and outgassing. In order to prevent the outer layer from containing a small amount of gas and becoming a pressure container itself, the air in the outer FEP tube is squeezed out at the end of the manufacturing process. It has been confirmed through NanoRacks that since the outer FEP layer hermetically seals the UV curing resin, the resin will not have to comply with the standard outgassing requirements and will be permitted to fly to the ISS.

3.5 AeroBoom Material Selection

FEP was chosen as the material used in the outer layer after an extensive search which considered a large number of possible materials including; Kapton, polyethylene, poly-nylon, and Tefzel. The findings of the trade study concluded that FEP was the optimal material to be used on the AeroBoom given its chemical inertness and natural resistance to the space environment. FEP is resistant to atomic oxygen while maintaining a high level of ultraviolet transmissivity. Additionally, FEP can be acquired in lay-flat tubes of the necessary diameter for the AeroBoom.

PVDF was chosen for the inner layer material due to its low rate of air permeability. Many different materials were investigated, however PVDF was the only material that had both a low permeability coefficient [6] and was easily acquirable in lay-flat tubing.

Both the FEP and PVDF are being sourced from Zeus Industrial Products. The specifications for the FEP and PVDF are as follows:

FEP Lay-Flat Extruded
Zeus Part Number – 246737
Specs: ID - .770" +/- .010" Wall - .005" +/- .001"
Minimum order length: 200 ft

PVDF Lay-Flat Extruded
Zeus Part Number – 248392
Specs: ID - .660" +/- .010" Wall - .005" +/- .001"
Minimum order length: 200 ft

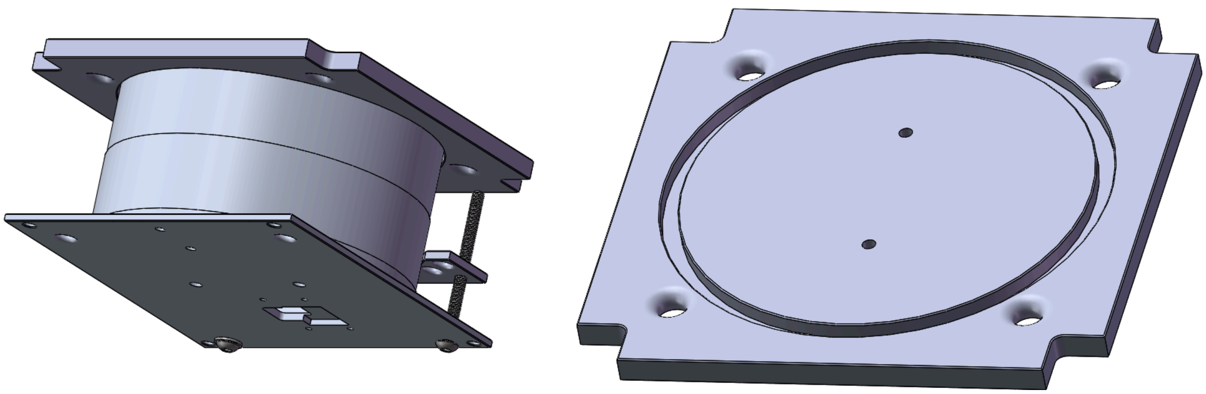
3.6 Ultra Violet Reactive Resin

Figure 21. Epoxy being applied to the AeroBoom fiberglass

Central to the function of the AeroBoom system is the ability to harden and fortify itself in its deployed state. In order to achieve this, Dymax 6-621 Multi-Cure® Adhesive is impregnated into the fiberglass braid, see figure (21). According to the manufacturer, Multi-Cure® 6-621 adhesive is designed for the rapid assembling of parts made of metal, glass, ceramic, phenolic, filled polyamide, and other substrate materials [7]. This product is curable with UV light, heat higher than 110° C, or pre-applied activator. The resin in the AeroBoom will be cured via UV light. A thermal analysis has been performed on the GASPACS satellite to ensure the resin will not be exposed to temperatures higher than 110° C before AeroBoom deployment, and can be found in [13].

The use of this resin allows the AeroBoom to remain flexible and foldable before deployment, and then cure into a hardened state in less than a minute upon deployment in space and exposure to the sun.

3.7 Stray Light Control



Figures 22 and 23. AeroBoom Box mated with slot in endplate

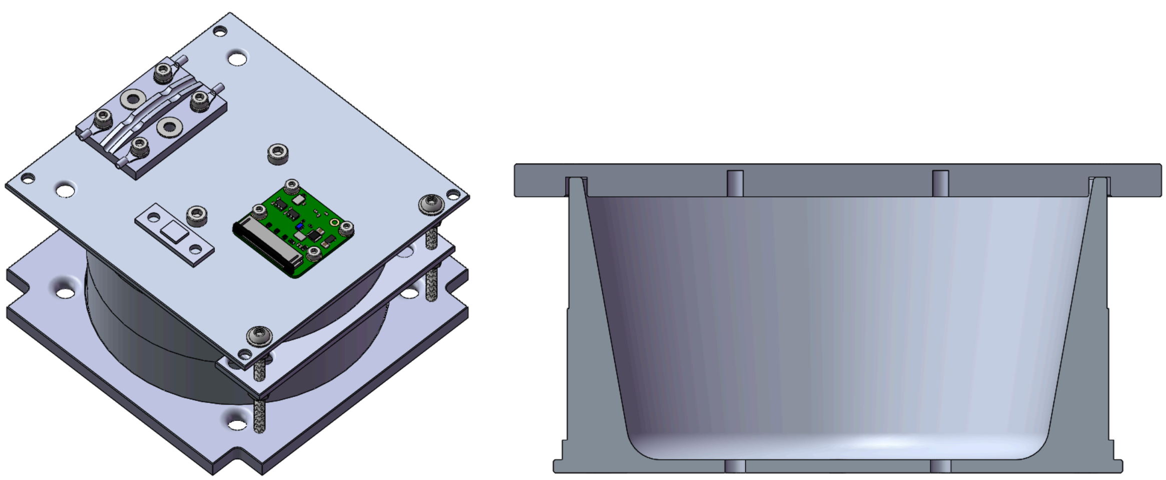


Figure 24 and Figure 25. Baseplate of AeroBoom Box and section view of AeroBoom Box and endplate, demonstrating a light prevention method

To prevent ultraviolet light from leaking into the AeroBoom Box, and thus curing the AeroBoom prematurely, three methods of light control are used. First, the solid storage structure completely surrounds the AeroBoom preventing any light from reaching the resin. Second, the endplate features a 3mm deep slot for the edge of the AeroBoom Box to fit in, preventing light from getting into the AeroBoom Box (See Figures 23 and 25). The final method of light control is the control of holes into the AeroBoom Box. Care was taken during the design process to ensure there are no through-holes into the AeroBoom Box through the endplate. The only through-holes into the AeroBoom Box are through the baseplate, which is acceptable because the amount of light that the interior of the satellite is exposed to is very small. Each side of the CubeSat has a component that blocks light from reaching the interior, whether it is the solar panels, UHF antenna, or the AeroBoom endplate. Additionally, these holes are completely covered either with the camera, UV sensor, or bolts. As a final precaution, the AeroBoom box will be exposed to UV light after it is assembled, and the UV sensor will detect if any stray light is reaching the interior.

3.8 Contamination Control

The AeroBoom does not have any flight heritage, which makes it the most significant contamination risk of the mission. The AeroBoom contamination control plan addresses this risk with two measures. First, low outgassing materials that have been subject to a thermal vacuum bake out will be used to assemble the AeroBoom. Second, the AeroBoom payload is contained within the storage structure, embedded in the CubeSat structure, preventing the payload from being directly exposed to space. In addition, this configuration reduces the chance of a resin contamination leak in the event of catastrophic failure of the outer FEP layer. NanoRacks has stated that since the 6-621 resin will be completely and hermetically sealed inside of the outer FEP layer, the resin will not have to pass the normal outgassing tests and will be safe to fly to the ISS.

3.9 Sensor Array and Electronic Interface Board

The AeroBoom payload will include three electronic accessories. The camera, UV sensor, and NCWC system will all be housed on the bottom of the baseplate of the AeroBoom Box. Each of these directly contribute to the primary mission objectives. The NCWC system will facilitate melting the restraint line. The camera will have a clear view of the AeroBoom once it is deployed, similar to figure (29) below. A picture will be taken after deployment and transmitted to our ground station to verify successful deployment. The UV sensor will be used both as an additional deployment indicator and, if deployment were to be unsuccessful, to determine if any UV light entered into the AeroBoom storage bay before deployment. A full description of the electronic interfaces between the AeroBoom and the GASPACS CubeSat is available [8].

3.10 Changes from Preliminary Design

The AeroBoom Storage Structure has undergone significant changes since GASPACS' Preliminary Design Review. Most notably, the baseplate and storage space have been combined. This increases the simplicity of the design, makes it easier to construct the AeroBoom payload, and saves 2mm of vertical space.

Other significant changes include the loss of a deployment switch and the addition of a groove for the endplate. The deployment switch was removed from the design because of the difficulty of finding and installing a switch small enough for the space. A 3mm groove was added to the endplate to help with light control.

4.0 Construction

To ensure that the AeroBoom payload produced for the flight article will function correctly, construction procedures for each part of the payload have been developed and functionally tested. These procedures consist of:

- AeroBoom Construction Procedure
- AeroBoom Payload Machining Notes
- AeroBoom Payload Assembly Procedure (Including Tensioning Procedure and Folding Procedure)

These procedures cover the construction of an AeroBoom payload, from start to finish. This ensures consistency and thus maximal chances for success with every AeroBoom payload.

4.1 AeroBoom Construction Procedure

The AeroBoom Construction Procedure contains exact procedures for the start-to-finish construction of the AeroBoom. It consists of two parts: Inner Boom Construction and Outer Boom Construction.

The Inner Boom Construction section consists of the procedures to construct an inner boom. First, a section of PVDF plastic is cut, and heat-sealed at one end. Then, it is placed in a vacuum chamber and carefully filled to an internal pressure of 2.2psi. After being heat sealed on the other end, it is submersion-tested for leaks.

The Outer Boom Construction section consists of the procedures to place the fiberglass around the inner boom, impregnate the fiberglass with the UV Resin, and cover the fiberglass with a sealed layer of FEP plastic. First, a length of fiberglass is stretched over the completed inner boom. Then, 10mL of Dymax 6-621 resin is spread evenly on both sides of the fiberglass. A length of FEP plastic is cut and pulled over the resin-impregnated fiberglass. The two clamps that attach to the AeroBoom Box and endplate are slid onto the FEP plastic, and a clamp disk is slid into one end of the FEP. The FEP is sealed on either side of the disk, ensuring that the clamp disk remains in place and keeping the FEP closed tight. Another disk is placed in the other end of the Outer Boom, and the Outer Boom is placed in the vacuum chamber, vacuuming all air out of the FEP/fiberglass portion. This ensures that the pressure in the AeroBoom is regulated and standardized. The Outer Boom is removed, and the FEP is heat sealed on either side of the second disk. That completes the construction of an AeroBoom.

4.2 AeroBoom Payload Machining Procedure

The completed AeroBoom Payload consists of eight CNC machined parts. Seven of the parts are machined from 6061-T6 billet aluminum, and the other is machined from MACOR, a machinable ceramic material. In addition to these components, a set of machinable “soft jaws” was milled and used to hold several of the round components. This brings the total number of machined pieces to ten.

The process started with CAD models that were created in Solidworks, and verified by the Mechanical team both through 3D printed prototypes and review of the models. The models were then exported to Autodesk Fusion 360 in order to create the CAM toolpaths. Each toolpath was meticulously prepared and checked to ensure the desired finish was achieved and the machine would not crash. The stock size needed was determined and notes were created for machining each part, as seen in [14]. The aluminum was ordered from Online Metals, and the MACOR from Amazon.com.

The machining was performed on a Tormach PCNC 770, owned by Danos. The majority of the milling was done using standard two flute endmills, between 1/16” and 3/8“ in diameter, however ball endmills sizes 1/16” to 1/4“ were used on the 3D contoured surfaces, such as the 10° sloped internal wall of the AeroBoom Box. Additionally, a #4 threadmill was used to create the M2.5 and M3 threads in the components. The exported CAM files are specific to this machine and tool set, and it is recommended that if students desire to reproduce the machined components after Danos has graduated, a professional service should be used.

4.3 AeroBoom Folding Procedure

In previous testing, certain folding methods have been shown to not only make the AeroBoom Box more difficult to close and tension properly, but also to hinder deployment and increase the amount of force exerted on the endplate before deployment. To ensure secure storage and a smooth deployment, a folding procedure for the AeroBoom inside the AeroBoom Box has been created and documented in text, photos, and videos.

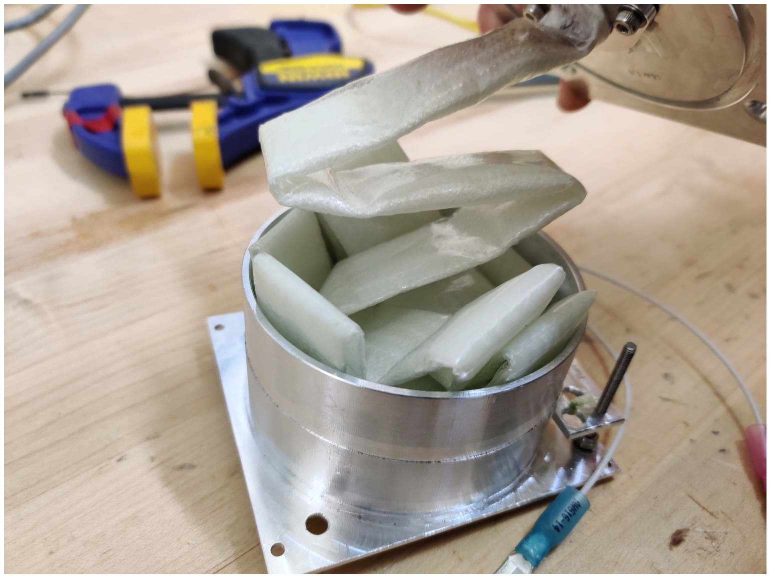


Figure 26: AeroBoom folded into AeroBoom Box using Folding Procedure

The folding procedure uses a folding pattern that resembles flower petals, which will allow the AeroBoom to unfold out of the AeroBoom Box easily. Three to four Z-folds are used at the end of the fold to fit the AeroBoom into the AeroBoom Box (See Fig. 26). This folding method has been tested numerous times to deploy successfully, and has not caused a single failed deployment.

4.4 AeroBoom Box Tensioning Procedure

Once the payload is assembled, with the AeroBoom folded into the AeroBoom Box, it must be tensioned. The AeroBoom Box Tensioning Procedure establishes a standardized method to do this securely, so that the tension in the restraining fishing line is within a pre-set range each time.

First, a 55cm section of Dyneema fishing line is cut from the spool, and one end is tied to one side of the tension bar with an improved clinch knot. The fishing line is fed through the filleted holes in the endplate and baseplate, ensuring that it runs over the MACOR spacer. Then, it is tied to the other end of the tension bar, again with a clinch knot. The exact route of the fishing line can be seen in figures (17) and (18).

The tension bar is placed on the screws attached to the baseplate, and an allen key is used to tighten the screws, pulling the tension bar down and increasing the tension in the restraining fishing line. The tension in the fishing line is then measured by pulling the fishing line with a spring scale, measuring the deflection, and calculating the tension in the fishing line from the deflection.

If the tension in the restraining fishing line is within the pre-set range, the procedure is successful. If not, the fishing line is either tightened or loosened, and then re-measured, until it is in the appropriate range.

Figure 27. Fishing line tension measurement process

4.5 AeroBoom Payload Assembly Procedure

A procedure has been carefully prepared to test payload components and assemble them together into a completed payload. First, the machined components are tested for tolerances with CAD Drawings. Then, the UV sensor and Raspberry Pi Camera are integrated with the AeroBoom Box, and the MACOR spacer is attached to the baseplate. The AeroBoom clamps, which are already on the assembled AeroBoom per **4.1**, are then bolted to the AeroBoom Box and the endplate. The wire cutters are set up by bolting down nichrome wire and ring terminals to the MACOR spacer. The nichrome wires run across the MACOR spacer, and the ring terminals attach to wires that lead to the electrical board. The AeroBoom is then folded per **4.3** and the AeroBoom Box is tensioned per **4.4**. At this point, the AeroBoom payload is completely assembled.

The AeroBoom payload is then placed in the vacuum chamber, and a deployment test is run. If deployment is successful, the AeroBoom is re-folded, the AeroBoom Box is re-tensioned, and the AeroBoom payload is marked as completed and tested.

5.0 Testing

The AeroBoom payload has been tested extensively for the purposes of concept verification and ensuring mission success. Upcoming testing, post-Critical Design Review, includes extensive testing on flight components as well as thermal/vacuum testing, and vibration testing courtesy of NanoRacks.

5.1 High Altitude Balloon Testing

The first proof of concept tests were conducted using high altitude balloons. The GAS Team has conducted 6 fully documented [9] high altitude balloon launches, each testing different aspects of the AeroBoom, see figure (28).

Figure 28. High altitude balloon launch.

From these tests we have concluded that an inflatable with the structure described previously in this paper is capable of deploying and inflating [9]. Figure (29) shows a picture taken during a high altitude balloon test on July 29, 2017. Table (2) lists the conditions the AeroBoom experienced during this test.

Figure 29. Picture of a deployed Aeroboom from a high altitude balloon flight

Table 2. July 29, 2017 High Altitude Balloon Conditions

Temperature at Time of Deployment	23° C
Minimum Recorded Temperature	-29° C
Maximum Recorded Temperature	45.6° C
Atmospheric Pressure at Time of Deployment	29.83 mbar
Altitude at Time of Deployment	71,074 ft
Minimum Recorded Atmospheric Pressure	6.38 mbar
Maximum Recorded Altitude	89,986 ft

5.2 Deployment Testing in Vacuum Chamber

Many AeroBoom Deployment tests have been conducted in the GAS Labs using a vacuum chamber. As part of the AeroBoom Payload Assembly/Testing procedures, each payload is deployed at least once. A video of a recent deployment test is available here.

5.3 Permeation Testing

One possible failure point for the AeroBoom Payload is that, in the vacuum of space, the air contained in the PVDF plastic permeates out of the AeroBoom, reducing the pressure inside the AeroBoom. This could easily cause a failure of the primary mission.

To reduce the likelihood of this happening, PVDF plastic was chosen as it has a very low permeation constant. To verify that the PVDF inner boom would not permeate significantly, long-term permeation testing was conducted. In September 2019, various sealed lengths of PVDF plastic with different volumes of air were placed in a vacuum chamber. The permeation loss from each of the sections was measured on occasion, and then finally when the test was completed and the vacuum chamber was repressurized in May 2020.

The full results of the test are available here. The full-size section of PVDF, replicating an inner boom, lost only 2.3% of its air to permeation over a period of 2 months. Over a period of 6 months, the test inner boom lost 22.3% of its air volume. Were the AeroBoom to be deployed after losing 22.3% of its air volume, its internal pressure would be 1.76 psi, placing it within 10% of maximum inflation, as per Figure 6.

The time from when GASPACS is brought outside the ISS, to when the boom deploys, is, at maximum, 6 days. This short period of time in vacuum, combined with the results of the permeation test, indicate that the AeroBoom will not fail from lack of internal pressure due to permeation.

6.0 Requirements

This section documents all of the NanoRacks and GASPACS requirements that pertain to the AeroBoom payload, and also documents the method by which the GASPACS payload complies with them. The NanoRacks requirements that are met by EnduroSat specifications are not included in this document.

The NanoRacks requirements are available as a part of the NanoRacks IDD [11]. The GASPACS requirements are available as a spreadsheet [12].

6.1 NanoRacks Requirements

4.1.1-9: Requirement met by inspection. CAD models of GASPACS meet this requirement for the design.

4.1.5-1: Requirement met by inspection. The restraint system for the AeroBoom Payload is described in section **3.3**

4.4.8: Requirement met by inspection. The internal pressure of the AeroBoom is 2.2psi.

4.4.10-1: Requirement met by inspection. No materials that are stress corrosion susceptible are present in the AeroBoom Payload, nor are any materials from Table II or Table III present in the AeroBoom Payload

4.4.10-3: Requirement met by inspection. Aside from the Dymax 6-621 UV-Curable resin, all materials present in the AeroBoom Payload comply with NASA guidelines for selecting low-outgassing materials. NanoRacks has approved the Dymax 6-621 UV-Curable resin since it is hermetically sealed inside the AeroBoom

6.2 GASPACS Requirements

1.1.1-5: Requirement met by design. All of the materials used in the AeroBoom Payload comply with NanoRacks requirements. The resin has been specifically approved by NanoRacks.

1.1.2-2: Requirement met by design. All of the components and mounting strategies used in the AeroBoom Payload are capable of withstanding any additional acceleration that could be generated by the centripetal acceleration provided by a 5 rpm/axis rotation.

1.1.3-2: Requirement met by design. All of the components involved with the AeroBoom Payload are capable of withstanding 100 Celcius, which is higher than the upper bound of the temperatures found in the Solidworks Thermal Simulation (see System Critical Design Document).

1.1.5-1: Requirement met by design and testing. All of the components incorporated in the AeroBoom Payload are capable of withstanding vacuum, and the Payload has been tested to function in vacuum.

1.1.5-2: Requirement met by design and testing. All of the components incorporated in the AeroBoom Payload are not susceptible to failure during a thermal bakeout, and will be subjected to bakeout after Critical Design Review.

1.2.1-1: Requirement met by testing and inspection. The AeroBoom Box, including the endplate, was designed to withstand the pressure of the AeroBoom without deformation. This has been verified through testing.

1.2.1-2: Requirement met by testing and inspection. The AeroBoom Payload endplate has been designed and measured to fit within this thickness.

1.2.1-3: Requirement covered above, in NanoRacks Requirement 4.1.5-1

1.2.1-4: Requirement met by testing and inspection. The tension mechanism is described in sections **3.3** and **4.4**

1.2.1-5: Requirement met by testing and inspection. Stray light control is described in section **3.7**

1.2.1-6: Requirement met by testing and inspection. AeroBoom Box contains mounting locations for the system camera and the UV sensor, and their respective placements and views have been verified. The system camera and UV sensor placement are visible in figure **24**

1.2.1-7: Requirement met by testing and inspection. AeroBoom Box has holes for the system camera, and its view has been tested for clear sight out of the AeroBoom Box.

1.2.1-8: Requirement met by design and inspection. The AeroBoom Box is mounted using 4 mounting holes in the baseplate that will slide onto the Endurosat structural rails.

1.2.2-1: Requirement met by design. The NCWC system has two lines of nickel-chromium wire that ensures a single fault tolerance.

1.2.2-3: Requirement met by design and inspection. The design of the AeroBoom Box and endplate will not impede deployment upon activation of the wire cutters. The deployment of the AeroBoom has also been tested multiple times, with no deployment impedance.

1.2.2-5: Requirement met by design, construction, and testing. The AeroBoom Construction Procedure ensures that each AeroBoom contains 2.2 +- 0.05 PSI when it is constructed, and the permeation testing performed and described in **5.3** ensures that at least 1.9PSI will be present in the AeroBoom upon deployment.

7.0 Conclusion

The deployable AeroBoom payload system has completed its design phase, and it has been extensively tested to validate the design and development concepts. Formalized procedures have been developed around the design of the AeroBoom payload to standardize construction. At this point the AeroBoom payload is ready to be integrated into the GASPACS satellite. Further development of the AeroBoom payload will be limited solely to environmental and long-term testing, and preparation for manufacturing the flight unit.

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Nomenclature

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Abbreviations

AWG	American Wire Gauge
EPS	Electric Power System
FEP	Fluorinated Ethylene Propylene (non-reactive, high UV transmitting polymer)
G10	A Type of High Pressure Fiberglass Composite Material
GASPACS	Get Away Special Passive Attitude Control Satellite
ISS	International Space Station
LEO	Low Earth Orbit
MATLAB	Matrix Laboratory (The name of a numerical scripting programming tool)
NASA	National Aeronautics and Space Administration
NCWC	Nickel Chromium Wire Cutter
NRCSD	NanoRacks CubeSat Deployer
PSI	Pounds per Square Inch
PVDF	Polyvinylidene Difluoride (highly non-reactive thermoplastic fluoropolymer)
STP	Standard Temperature and Pressure
UHF	UltraHigh Frequency
UV	Ultra Violet (light)

Symbols

$-\nabla f$	Pressure Gradient
ρ	Gas Density
ΔP	Change in Pressure
Δx	Thickness of Membrane Wall
P	Pressure
V	Volume
N	Number of Moles of Substance
R	Gas Constant (8.314 J/mol)
T	Temperature in Kelvin
C	Temperature Celcius