Deployable Antenna for CubeSat

Final Design Review

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Statement of Disclaimer

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Executive Summary

This project is a proof-of-concept ground model of a large deployable antenna designed for the small space requirements of CubeSats. This small deployment module is designed to fit a 2 m by 1 m reflective antenna inside a storage volume of with the dimensions 20 cm by 20 cm x 40 cm. The reflector will be deployed to a parabolic shape with the goal of modeling the reflector necessary for high frequency communication. Because this module is designed as a proof-of-concept for the deployable parabolic reflector specifically, no electrical components will be incorporated and will just focus on the deployment mechanism and will not be space grade. Because this module is designed as a first iteration, it has the potential to be built upon and improved by other groups in the future.

Chapter 1: Introduction

1.1 Sponsor Background and Needs

Stellar Exploration, Inc., is a small business focused on creating innovative low-cost aerospace and space exploration projects. As the demand for communications and surveillance satellites increases and the complexity of these devices requires larger structures, it is desirable to launch these products in smaller volume units to reduce transportation costs. In an effort to enter the niche aerospace market of low-cost space radar and surveillance technology, Stellar Exploration, Inc., needs the ability to deploy large, accurate antennas from small CubeSat volumes.

1.2 Problem Definition

Competitors have successfully deployed antennas from CubeSats, but the transportation package volume has limited the size of the antenna. Our challenge is to develop a mechanism that can be packaged in a CubeSat and successfully deploy a larger antenna than those in the current market without losing accuracy or range. Completion of our project will be a joint effort between our team, Stellar Exploration, Inc., our sponsor, Dr. Tomas Svitek, and our project advisor, Professor Rossman. Our goal is to have a fully-functioning prototype to test by May 2017.

1.3 Objectives

The overall goal of this project is to design the deployment of an impressively large parabolic antenna from a small CubeSat, and to provide Stellar Exploration, Inc., with a tested prototype which the company can then use to continue to test and develop for future implementation. The prototype will serve as a proof-of-concept for the antenna deployment but is not intended to go into space.

The prototype delivered by our team will be a ground model aiming to show the feasibility of a technique for deploying a parabolic antenna from a CubeSat, on the order of a few meters long and capable of communicating in the S-band frequency range. The prototype will not be required to be able to send and receive signals itself, but rather have the appropriate shape to do so.

As seen in the boundary sketch below, the scope of our project only includes the deployment module, consisting of the antenna reflector, supporting booms, antenna feed mount, and the housing for this unit. None of the electronics beyond any motors or actuators used are part of the scope of this project. The feed itself is also not in the scope, only the mount and input for the feed.

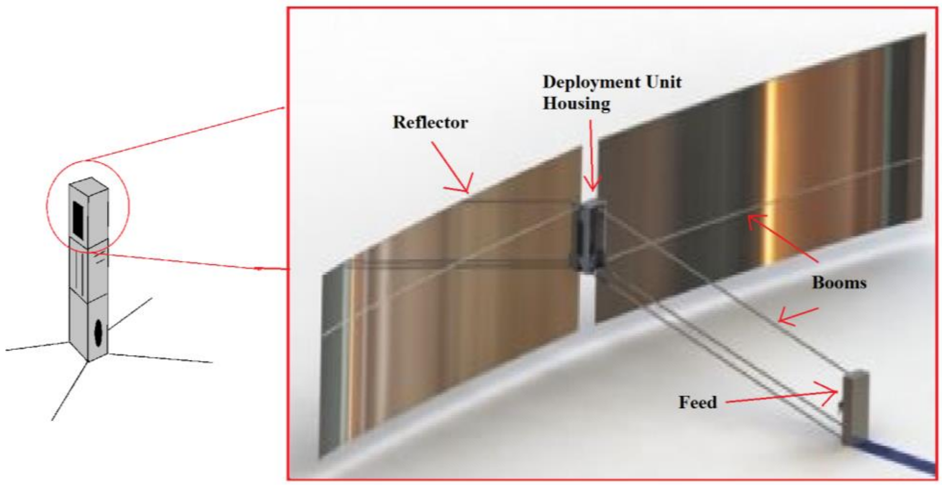

Figure 1. Boundary sketch showing scope of the project. The antenna deployment unit of the CubeSat is circled and enlarged to show the details of fully-deployed antenna. Image of antenna provided by Stellar Exploration, Inc.

In order to ensure that the prototype our team produces meets the customer's requirements as best as possible, the "Quality Function Deployment" method, shown in Appendix A, was used to create a "House of Quality." This tool matches each customer need with an engineering specification suited to meet that need, and then weighs each need to compare its relative importance. The diagram also compares the team's goals for the final product against existing ideas from other competitors. Upon completing the "House of Quality" and examining the importance of and relationships between all requirements, a set of engineering specifications was developed and can be seen in the Table 1 below. The table provides clear definitions of the targets and will be used to determine how well the team's design matches up with the customer requirements. The "Risk" column displays the level of risk associated with being able to meet each requirement, with (H) indicating a high risk, (M) a medium risk, and (L) a low risk. The compliance column indicates how the design specification will be verified, with (A) for analysis, (T) for test, (S) for similarity to existing designs, and (I) for inspection.

Table 1. Engineering Specifications

Spec. #	Parameter Description	Requirement	Tolerance	Risk	Compliance
1	Size (one side)	2m x 1m (LxW)	Min.	M	S, I
2	Tolerance of Parabolic Reflector Shape*	$\lambda/20$ (0.5cm for a 3GHz signal)	Max.	H	A, T, S, I
3	Deployment Power Consumption	10 W	Max.	L	A, T
4	Stored Volume*	20 x 20 x 40 cm	Max.	H	A, T, I
5	Communication Capability*	S-band (3 GHz)	± 1 GHz	M	A, T, I
6	Type of Suppliers & Materials*	0 customization	Max.	L	I
7	Weight	50 lbs	Max.	L	T, I
8	Resistance to Forces & Vibrations*	50G acceleration	Min.	M	A , T
9	Operating Temperature Range	20°C	+40°C -80°C	M	A, T
10	Budget / Cost	$3000	Max.	L	I

* Denotes a requirement that has since been relaxed or adjusted in some way due to the overall complexity of the project, which became more apparent in detailed design. See Chapter 4 Section 7 "Deviation from Required Specifications" for details.

Each engineering specification is important to the success of the project. The size of the antenna, 2 m x 1 m is meant to be for one side of the antenna. Figure 7 shows both sides of the antenna for a total of 4 m x 1 m of reflector area. We are only responsible for designing one side because the opposite side is the exact same. The tolerance of the parabolic reflector shape determines the accuracy of the signal that the antenna can receive. For many satellites and CubeSats, power consumption is very important, so the power consumption of our antenna has been limited to 10W. The storage volume is the available volume allowed for the entire antenna system to fit in when stored. Communication capability is the types of signals the antenna will be able to pick up. S-band is a stretch goal because of the tight tolerance required to achieve a good S-band satellite, yet it remains a goal due to the vast amount of applications that it can be used for. Ideally, this project would use exclusively commercial off the shelf components, which is the reason for the goal of zero customization. Because CubeSat launches are not dependent on weight, and instead depend on volume, the specification of weight has been given a large value of 50 lbs. There are many forces that the antenna must endure during launch, so it is important to make sure that it can resist these forces and still function correctly. The operating temperature range has been set at room temperature. We need to make sure that the antenna functions at room temperature for the ground model test, but we also need to analyze what happens at temperature up to + 60°C and down to - 60°C. The budget given to us by our sponsor is $3000.

The team listed the tolerance of the parabolic shape of the reflector as well as the antenna's stored volume as high risk requirements. The tolerance on the shape of the reflector means that, looking at the reflector in one direction at a time (length and width), the orthogonal distance between a point on the ideal parabolic curve and its corresponding point on the actual reflector curve must be within that tolerance. The shape tolerance of $\lambda/20$ for a target frequency of 3GHz is 0.5cm, which is a small tolerance for such a large reflector, and currently the team is not fully confident of how accurate of a shape it can produce. The team will continually assess the attainability of this goal as we strive to meet it. The stored volume was marked as high risk because of the difficult challenge presented in fitting a 2m x 1m reflector into 20 x 20 x 40cm of space.

To verify that our final design meets the specifications put forth in the above table, the following tests and/or evaluations will be performed.

- The size of the reflector will simply be measured along its width and length.
- The tolerance of the parabolic shape, as well as the feed mount position, will be determined using the parabolic equation and an evaluation of the actual curvature, most likely via a 3-D scanning rig.
- The power consumed during deployment will be calculated using the technical specifications of the datasheet for the motors/actuators used, and also measured electrically with a power meter.
- The stored volume will simply be measured along the length, width, and height.
- The communication capabilities of the antenna will be predicted by achieved size, shape, and shape tolerance of the reflector.
- The team will review whether or not any custom parts have to be used.
- The prototype will be weighed with a standard household scale.
- The resistance to forces and vibrations will be calculated from the geometry and material properties with a stress analysis. If possible, a shake table may be used to test the prototype.

- The prototype will be designed (based on heat transfer analysis and material properties) for 20°C or room temperature. The behavior of the prototype will then be analyzed for other temperatures.
- The team will keep track of all expenses and check the total against the $3000 limit.

1.4 Project Management

Several roles have been established in order to delegate responsibilities for each team member. In doing so we make sure that all responsibilities do not fall on one person, and that all team member have their fair share of duties.

David Galvez will be the team communications officer. This position requires facilitating all contact between the team, the sponsor, and the advisor. Additional responsibilities include scheduling meeting with the project sponsor and enforcing deadlines imposed by the advisor and/or sponsor.

Caleb Barber will act as the team secretary. The purpose of this role is to maintain the information repository for the team, i.e. team binder, Google Docs, references. Also, Caleb is in charge of the maintenance of important documents. These documents can include but are not limited to: parts drawings, sketches, and reports.

Mack Lennon is tasked with the role of team treasurer. This position puts him in charge of all financial responsibility. In the unlikely chance that the team must travel, the treasurer will maintain the team travel budget. In addition, once the purchase of materials becomes necessary, Mack will maintain the budget for anything purchased as well as obtain and file all receipts associated with materials or travel. Mack will also be responsible for filing any paperwork regarding the team's finances.

In addition to these administrative duties, each team member will be primarily responsible as the lead for certain technical aspects of the design. David, the analysis lead, is responsible for reviewing and approving on any analysis done to avoid miscalculation and error that are potentially detrimental to the project. Caleb, the CAD lead, is responsible for inspecting and approving all Solidworks models or drawing to make sure that no drawing errors are made, the BOM is up to date and correct, and that the design is functioning correctly. Mack, the manufacturing lead, is responsible for maintaining and overseeing the manufacturability of the design and the build phase of the project. It is important to make sure all parts of the design are possible and within our reach to be either purchased or fabricated in on-campus machine shops.

Although we each have our own designated roles within the senior project team, all major decisions and design ideas shall be generated and completed as a group. All members were active in the design process by developing a long list of potential ideas. Together, a Pugh matrix and decision matrix were created and used to narrow our ideas down to a final design. Furthermore, throughout the course of this project, specific deliverables will be provided for the sponsor and advisor. There many tasks that must be completed before the final product comes to fruition. At this point, the ideation phase has been completed and detail design and analysis will begin. A list of tasks that need to be completed, and when they will be completed, can be seen in the Gantt chart in Appendix B. These tasks are essential to the success of this project and, unless unforeseen circumstances occur, they will be completed on schedule. Further design analysis and project solidification will lead to the Critical Design Report (CDR) due on Feb. 7, 2017. Parts will need to be ordered and manufacturing will begin after the CDR. A project update report and a project hardware safety demo will take place on March 16, 2017 and May 2, 2017 respectively. Following these will be project testing and finally the Final Design Report (FDR) and Senior Design Project Expo will be due/take place on June 2, 2017.

Chapter 2: Background

In 1999, Professor Jordi Puig-Suari at California Polytechnic State University (Cal Poly) and Professor Bob Twiggs at Stanford University developed the specifications for the first CubeSats. A standard CubeSat unit, 1U, is 10 cm x 10 cm x 10 cm with a mass less than 1.33 kg. In many cases, actual CubeSats are multiples of 1U. Since the emergence of CubeSats, Cal Poly has played a pivotal role in developing standards and codes for academic development of CubeSats, and the popularity of these small satellites has continued to grow [1]. Although the emergence of the CubeSat has been relatively new, scientists and engineers have developed several antenna deployment mechanisms for satellites since the beginning of spaceflight. The examination of technology used in these larger, older antennas is valuable when developing technology for smaller satellites such as CubeSats.

An industry search initiated in 1969 explored several concepts for antenna deployment designs that would allow for highly efficient communication and reflector shape reliability. Starkey [2] explored three different antenna designs which included an antenna flex-rib design, an expandable-truss antenna design, and a radial rib antenna design. The antenna flex-rib design was folded by wrapping the carpenter-tape-shaped ribs and the mesh circumferentially around the hub. The extendable-truss design utilized many triangular, deep-truss modules that were hinged and fastened together with spider joints. Starkey determined that these two designs would require extensive developmental effort to satisfy outer-planet requirements, so he focused his analysis on the radial rib antenna design. Starkey analyzed the Jet Propulsion Laboratory (JPL) radial rib antenna-reflector that used aluminum ribs and he determined that the structure was feasible for outer planet communication. Since this study, many companies and organizations have expanded on the technology available in the radial-rib structures. Figure 2 shows a 1999 design by Harris Corporation [3] that illustrates the general contour of the radial-rib structure.

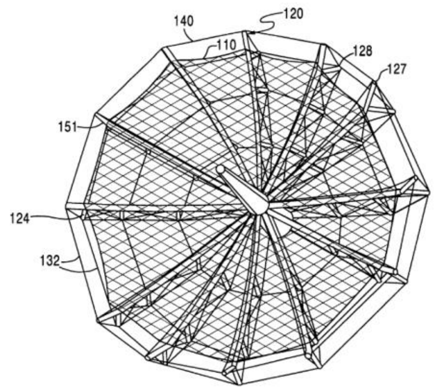

Figure 2. Radial Truss Support Structure Designed by Harris Corporation (US6219009 B1) [3].

Under the direction of NASA in 1979, Leavy et al. developed a telescoping antenna deployment mechanism for use with spacecraft. Figure 3 shows the diagram of the telescoping antenna. The mechanism used a series of telescoping tubes which were nested one within the other when the antenna was in a retracted, stowed position. A dual motor driven cable, which started in the wound position on a drum at the lower end of the antenna, drove the pulleys which were attached to successively large tubes of the antenna until it was fully extended. The ability of the tubes to collapse into each other allowed the antenna to be deployed from a relatively small package. [4] Since the development of the telescoping antenna, rare progress has been made in this field as most space-oriented companies have preferred circular reflectors rather than cylindrical antennas.

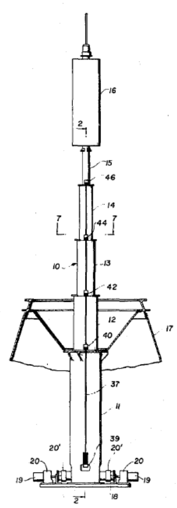

Figure 3. Diagram of Deployable Telescoping Antenna (US4176360 A) [4].

As briefly mentioned earlier, foldable truss structures are often used to deploy space antennas. Depending on the exact design of the trusses, the joints can either be multiple degree of freedom joints or simple hinges requiring a single degree of freedom. Figure 4 shows a synchronous deployable double fold beam and planar truss structure designed by Rhodes et al. under the direction of NASA. This figure illustrates the basic design of most collapsible truss structures used in space applications. Rhodes et al. note that foldable truss structures are often used for large antennas to avoid complex deployment mechanisms [5].

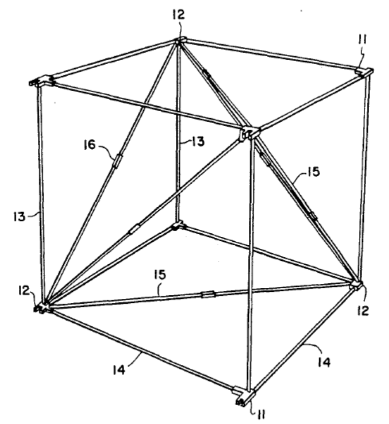

Figure 4. Synchronous Deployable Double Fold Beam and Planar Truss Structure [5].

A branch off the planar truss structure is the lattice truss that can be coiled. AEC-Able Engineering Company, Inc. (ABLE) developed what is known as the carousel deployment which uses a motor to drive a turntable at the base of a structure which uncoils and extends the mast. This deployment mechanism is shown below in Figure 5. Warden et al. discusses the feasibility of this design which could potentially decrease the overall package size of a truss structure [6].

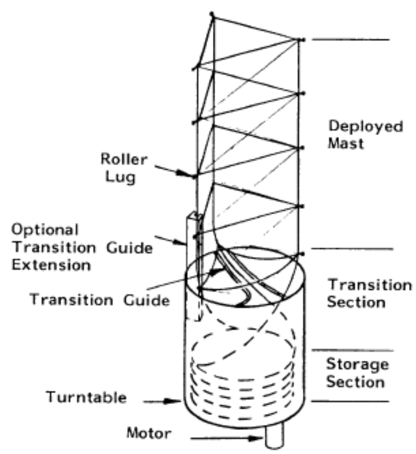

Figure 5. Carousel Deployment Mechanism for Coilable Lattice Truss (US5016418 A) [6].

A few other designs have been considered that neglect conventional deployment techniques. Researchers at Massachusetts Institute of Technology (MIT) explored an inflatable antenna technique from their design that uses powder that turns into gas to deploy an antenna from a CubeSat [7]. These unconventional methods inspire out-of-the-box thinking that can also yield feasible deployable antenna designs.

Other schools and organizations have attempted to deploy antennas from CubeSats. A team at University of Southern California (USC) worked on the Aeneas nanosatellite, which had an antenna with a circular ribbed mesh. The antenna has been functioning well in the S-band range for several years now; however, the dish is quite small (0.5 m diameter) and as such does not have an impressive size (>2m x 1m) [8]. The details of these specifications will be discussed at the end of this section.

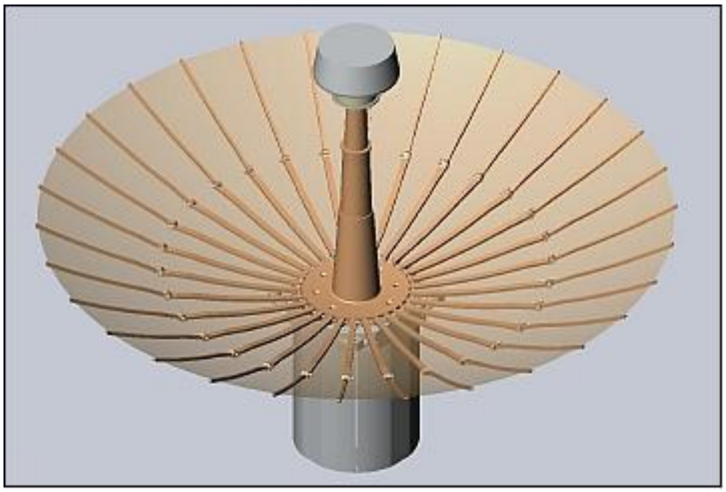

Figure 6. USC's Aeneas Satellite Antenna, Circular Ribbed Mesh Design [8].

Northrop Grumman's AstroMesh family of satellites boast large deployments (anywhere from 3-50m), but the packaged volume is substantial (on the order of a few meters), and is too large for most CubeSats [9]. The ISIS (Innovative Solutions in Space) deployable dipole antenna system is small (~0.5-1m) but packs into a small volume (> 1U). It has the advantage of using little power and being composed of only commercial off-the-shelf (COTS) components [10]. High-Performance Space Structure Systems use a similar design to Northrop Grumman, which is a circular truss that expands to a very large size (5-20m) and holds the reflector mesh like a trampoline. As with Northrop Grumman, however, its storage volume is too big for the CubeSat class of satellites (> 6U) [11].

Modern antenna deployment techniques use elastically deformable booms to extend and accurately support antenna reflectors. These types of booms are capable of being stored around a spool and as the booms unroll, they stiffen, extend, and ultimately support large structures. In 1971, NASA published a paper on tubular spacecraft booms that are extendible and reel-stored. These booms assume tubular shapes on deployment [12]. Mechanisms utilizing this technology have advanced since then which can be seen in the innovative escapement-based mechanism for micro-antenna boom deployment developed by the Polish BRITE-PL [13]. Alternates to the tubular shaped booms are found in the triangular rollable and collapsible (TRAC) booms which were developed by Murphey et al. under the direction of the U.S. Air Force Research Laboratory. These booms resemble measuring tape in their shape and rollability but are much stronger due to the carbon fiber reinforced polymer that composes their structure. [14] The TRAC booms appear to be one of the most advanced options for supporting large antenna reflectors and rolling them in a small CubeSat volume.

In addition to requiring effective deployment mechanisms, CubeSat antennas aim to operate at target radio frequencies. In order for an antenna to effectively detect a given frequency, the size of the antenna must be much larger than the wavelength of the radio waves captured. In the case of an antenna reflector, which is used in satellite dishes and space parabolic reflectors, the shape directs the signal to a feed that ultimately captures the signal.

The size of the parabolic reflector is directly related to the gain of the antenna, which is a measure of how powerful the antenna receives and transmits a signal. The tolerance of these parabolic/dish shapes is especially important when attempting to capture high frequency signals since the wavelengths are much shorter and more susceptible to noise or distortion if the reflector shape is incorrect. This sensitivity to surface tolerance is due to the superposition of waves that are reflected from the antenna to the focal point of the parabola, which is where the feed is located.

A phase difference between two signals of $\lambda/2$ (where λ is the wavelength of the signal) results in destructive interference since the peak of one wave negates the trough of the other wave. A phase difference results when one signal travels further than another due to distortions of the parabolic shape.

By minimizing variations between a reflector and a true parabolic curve, we maximize the constructive interference by reducing the phase delay so that the feed receives a clear signal. A rule of thumb for antenna reflectors is to keep the tolerance below $\lambda/20$. In general, the higher the target frequency, the more precise the tolerance must be on the parabolic shape that reflects the signals to the feed.

Common signal designations, with their associated frequency ranges, used in satellite communications are UHF (0.3 to 1 GHz), L-Band (1 to 2 GHz), S-Band (2 to 4 GHz), C-Band (4 to 8 GHz) and X-Band (8 to 12 GHz). Most CubeSats launched by academic institutions have been only capable of UHF and L-Band communications. CubeSat antennas are limited by the size of the refector they can deploy and the tolerance of the reflector shape they are able to achieve upon deployment.

Conducting a thorough patent search allowed us to collect some useful information. The purpose of this patent search was not only for idea generation purposes, but also to make sure we are not treading on someone else's ideas. Many of the concepts and products found in the patent search are antennas used in much larger "full-scale" satellite applications as opposed to CubeSat applications.

There were a couple ideas found in our patent search that are specifically designed for CubeSat applications. The first is the deployable helical antenna for nano-satellites shown below in Figure 7**.**

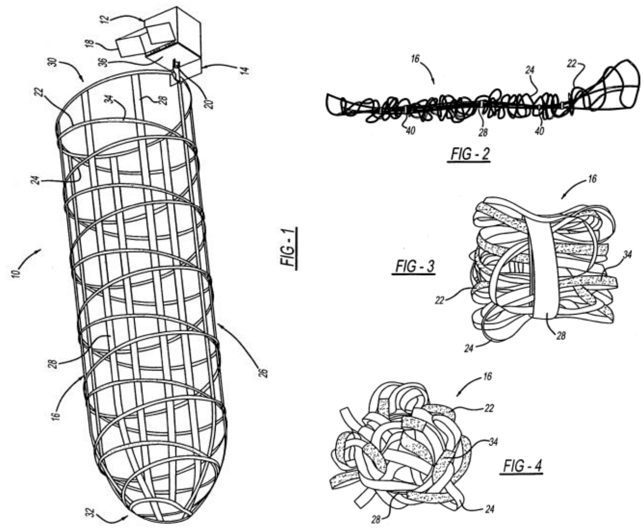

Figure 7. Deployable Helical Antenna for Nanosatellite (EP2693563 B1).

Many known satellites make use of helical antennas. This antenna is especially good for fitting into small spaces, but is quite small and does not achieve a very high antenna gain.

An additional patent was found using tape measure booms (US8770522 B1). This idea is one that we have explored deeply because of its many applications. These antennas are constructed by using storable tubular extendible member (STEM) structures. These members or "booms" are generally made from spring steel or carbon fiber reinforced plastic. This idea seemed very promising for us to recreate and improve. This patented invention is designed so that the extendible structures or roll out linearly and unfurl the antenna reflector in an unconstrained, flat fashion. However, a parabolic shape, rather than a linear "flat" shape, allows for better antenna gain and more accurate signals.

Chapter 3: Design Development

3.1 Design Process

In order to properly start the design process, the problem was understood and defined by our team. Existing solutions to the aforementioned problem were researched to avoid "reinventing the wheel." This research consisted of figuring out why the problem needs a solution, how the problem has been handled before, and technical research involving what is needed in order to create a proper solution.

Once the preliminary research was done, then the customer requirements were established. These requirements were confirmed by the project sponsor during the initial meeting with the team. These customer requirements were used to develop engineering specifications. To prepare the specification list, we used the QFD method as shown in Appendix A. The QFD method includes the “House of Quality”, which is a matrix used for defining and analyzing the relationships between customer requirements and engineering specifications. This matrix was used to determine the importance of each of the requirements/specifications and how the competition compares to the what is feasible for our project.

When all the engineering specifications were prioritized, the design process continued with ideation and brainstorming possible solutions. Ideation began with the generation of as many ideas and concepts as possible without judgment, which promoted creativity and solutions never thought possible. Many of these ideas and concepts are shown in the concept generation section. Once enough ideas had been presented, the best solutions were narrowed down to several general designs and then compared using basic analysis. Next, we determined the best possible design that not only solved the problem but was the most viable, efficient, and innovative product.

Extensive analysis and evaluation was performed once a final concept was selected. This assessment included but was not limited to: stress analysis, material selection, and parabola and focal point definition. Many issues are sure to arise causing the need for iteration, but once a final design is determined and analyzed, we will move forward with the manufacturing of a functioning prototype.

Prototyping inevitably leads to issues and new iterations. Obtaining all the necessary parts and materials is the next step. Some components may need to be modified or machined. Any modifications on iterations will be reflected into our final design. Also, reanalyzing components that have changed will also be necessary. A final product will be deemed finished when all possible analysis is complete, testing is done, and a final, functioning prototype is created. These steps have been simplified and shown in Figure 8 below.

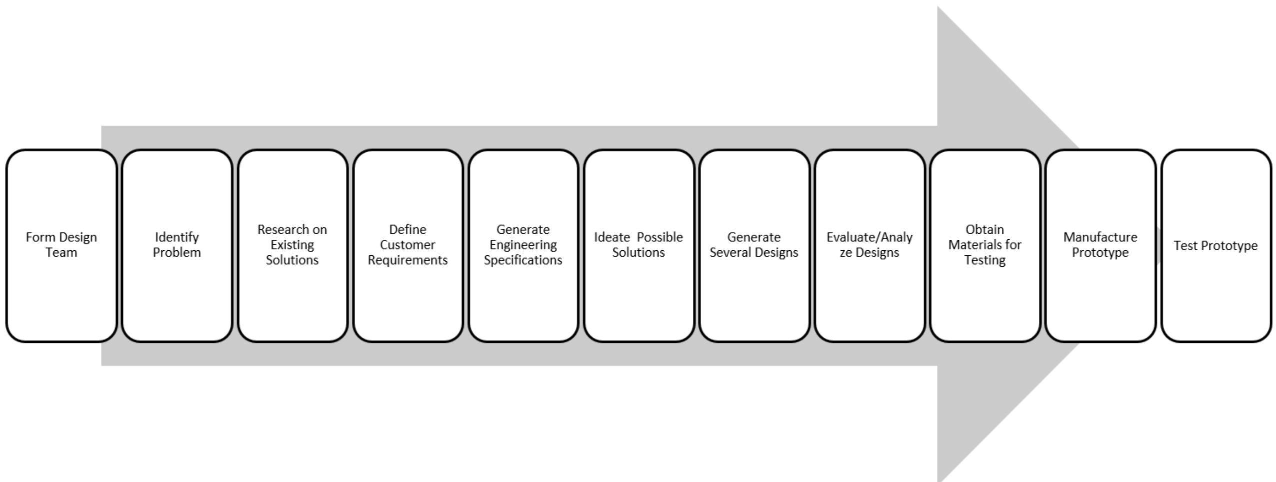

Figure 8. Design Process for Deployable Antenna.

3.2 Concept Generation

Several methods of ideation and concept development were utilized to generate possible solutions to the problem presented. Ideation is the process of generating different ideas for the overall scope of the project as well as specific functions. The methods used include: function identification, brainwriting, brainstorming, SCAMPER, and concept modeling. Some of the more promising concepts generated are described in more detail below.

Brainwriting is a form of ideation where each member writes down as many possible ideas or sketches as they possibly can. These ideas were then shared and built upon by each team member to help create even more ideas. This process goes on for several "rounds" which provides a sufficient amount ideas. Using the brainwriting technique, our team developed the concepts for the double boom roller and linked plate for achieving a parabolically shaped reflector. Sketches for these ideas are shown in Figure 9. The double roller is very similar to a single tape measure boom, but instead has two booms rolled together inside that, when extending, split into two different directions. This double-spooling minimizes the space needed and allows for a larger reflector. However, it was thought that getting each boom to split into different directions and maintain the correct shape would prove to be a difficult task. The linked plate concept is essentially a stack of linked plates that are hinged and extend around into a circular and parabolic shape. This idea was disregarded because the actuation needed to accomplish this would be highly complex.

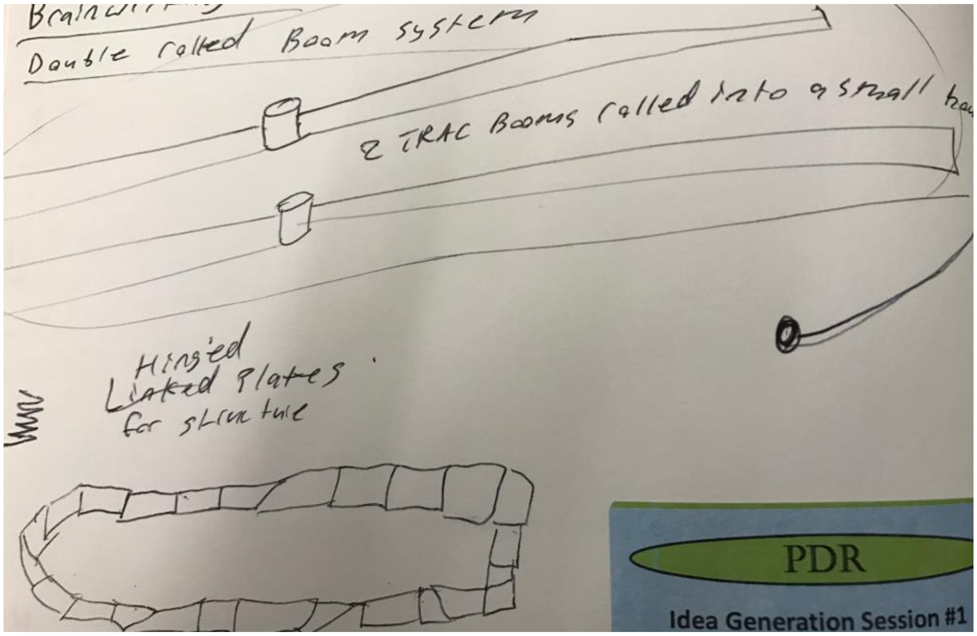

Figure 9. Brainwriting Example Sketches.

Brainstorming was used to build upon these initial brainwriting ideas to produces newer or more well-thought-out concepts. Our group discussed the feasibility, the functions, and the changes in the concepts we originally produced in brainwriting. These new concepts were more realistic but no bad judgment was imposed on any idea.

All ideas were open to discussion, modification, or addition. For example, the accordion truss shown below in Figure 10 is a concept that uses material similar to the helical antenna for nano-satellites shown in Figure 6. The expandable truss is attached to a boom deployer and expands as it is pulled out of storage. The parabolic reflector is mounted at strategic points on the truss to ensure that it comes out as a parabolic shape.

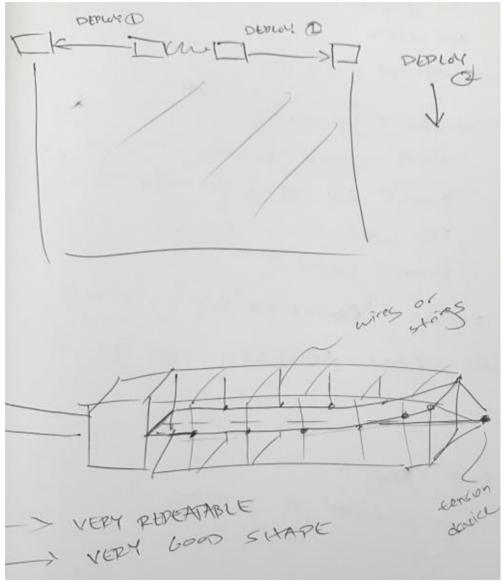

Figure 10. Building on Ideas During Brainstorming.

Another ideation process we used was brainwriting but focusing on a specific function, in which the group picked one function of the project and expanded on as many possible ideas as we could. The function development for shape of the reflector is shown below in Figure 11.

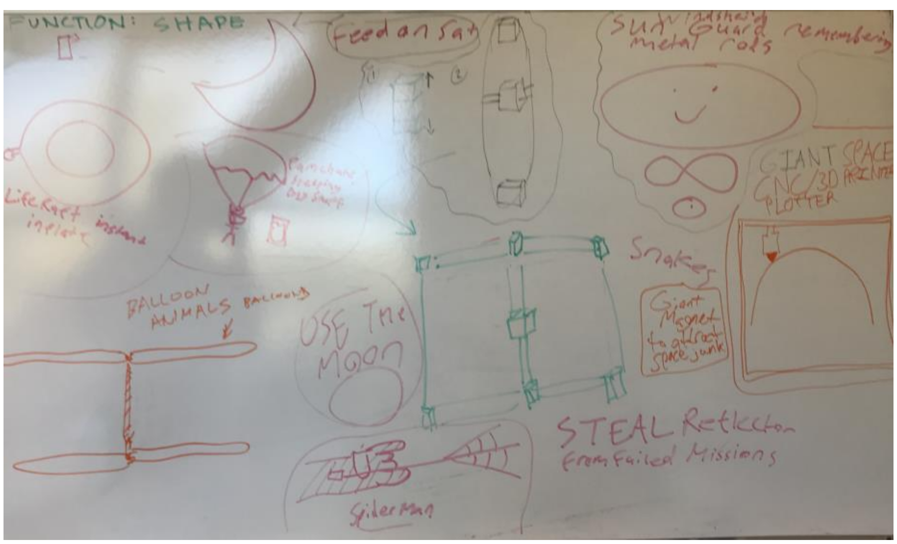

Figure 11. Developing the Shape of the Antenna.

In addition to sketching on paper or on a whiteboard, our team also built various concept models which allowed us to visualize our ideas and prove that some ideas are not physically possible. We also used concept modeling to give us an idea as to the size of reflector needed and how much space we had to work with. Figure 12 shows the goal for actual size of reflector, 2 m x 1 m, demonstrated with aluminum foil.

Figure 12. Actual Size of a 2 m x 1 m Reflector Using Aluminum Foil.

Other concept models were creating using household material such as popsicle sticks, construction paper, and tape. The concept model below in Figure 13 shows the stored volume and the deployed hinged boom system and folding reflector. This model was not very rigid and had very complicated actuation.

Figure 13. Hinged Boom Concept Model Folded and Deployed.

After exploring solutions during our ideation sessions, we gathered what we thought were the concepts and functions with the most potential. These concepts shown and described below were used in the idea selection processes, as described in detail in the concept evaluation section.

We split the generated concepts into groups based on their function. The first group shown below, is a system level group showing concepts that display exactly how the reflector is going to be expanded out.

3.3 System Development

In order to develop our ideas on a full-system level, we generated various concepts based on the knowledge we gained through background research and benchmarking. After making a decision on the system level concept, our group developed ideas for the individual components that are crucial to the design. The expanding truss idea, shown below in Figure 14, is one that has been previously used by aerospace corporations such as Northrop Grumman.

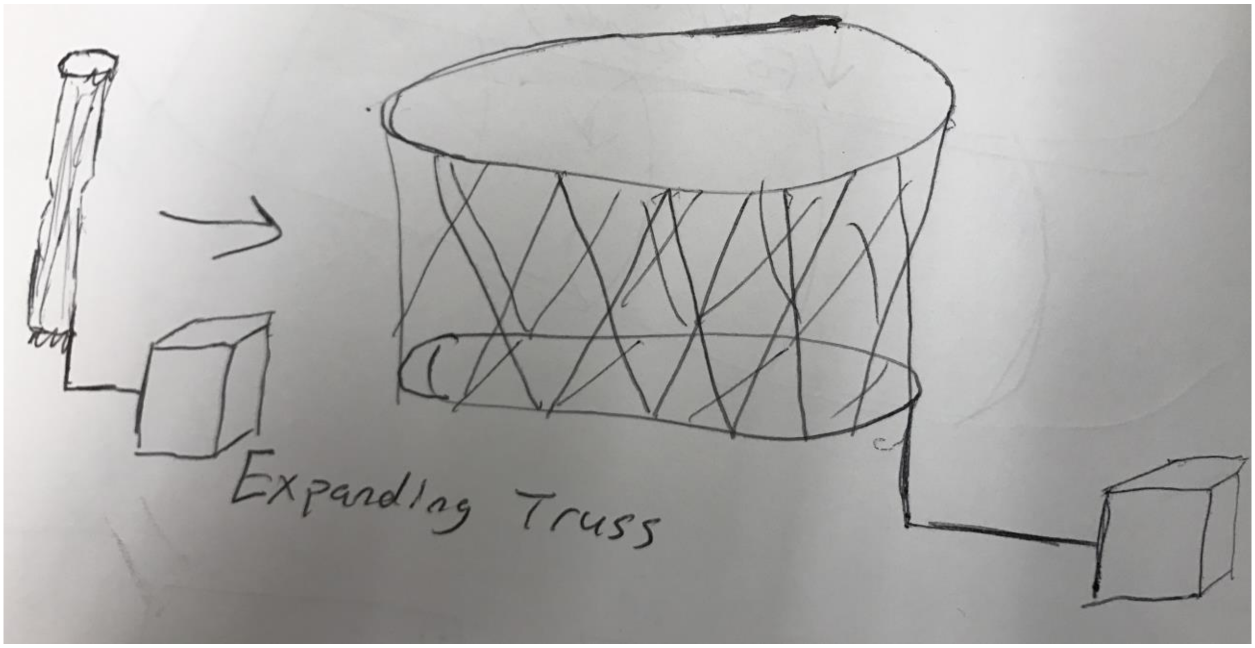

Figure 14. Expanding Truss.

This structure utilizes an expanding cage of two-force members that can be expanded from a small diameter to a very large diameter. The idea was used in a previous senior project and proved to be quite complicated with many small, high-precision parts.

The telescoping umbrella concept shown above is very much like an umbrella in that it uses a collar and hinged supports to expand out a circular umbrella surface. For this application, the umbrella "handle" would be a telescoping boom that deploys away from the CubeSat and then allows for the umbrella to open up by actuating a collar to move further out along the boom and push the hinged supports. This concept also has many small precise parts that are hinged and fold on themselves just as a regular umbrella does. It seems challenging to actuate a collar sliding over a telescoped boom.

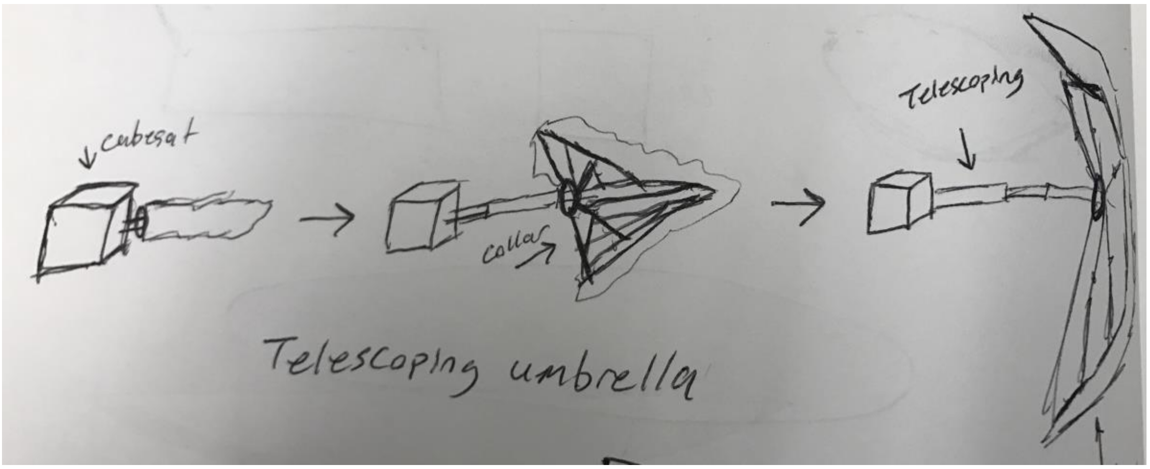

Figure 15. Telescoping Umbrella.

One of the more popular and most used systems is the tape measure deployer method shown below in Figure 16. This concept uses motorized rolls of boom material, usually mild steel or carbon reinforced plastic, that unrolls into a rigid boom.

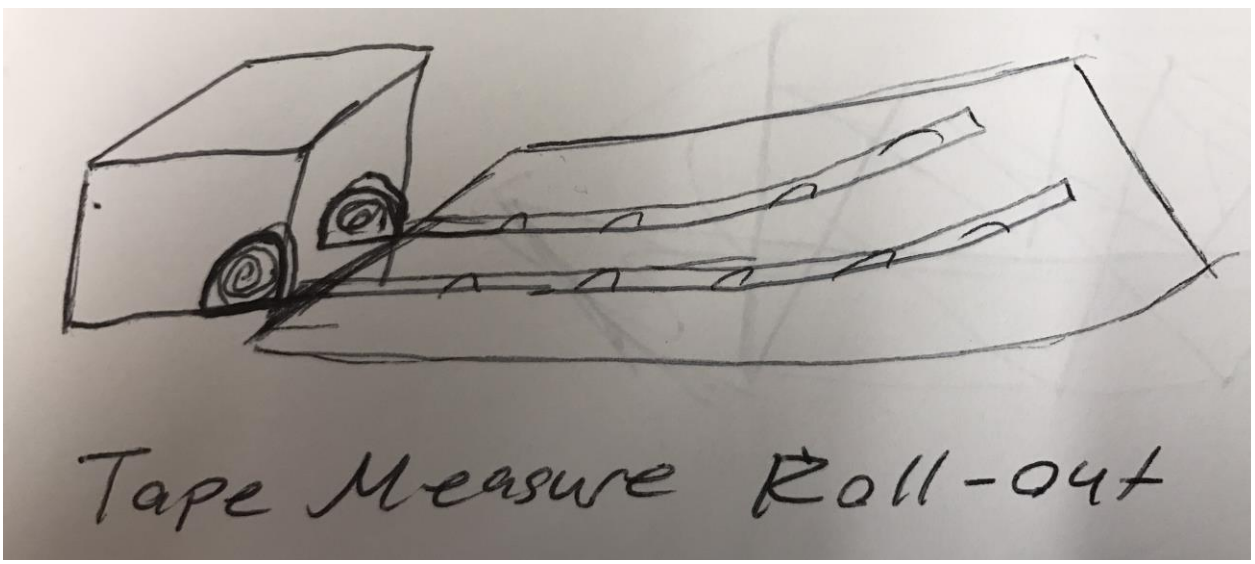

Figure 16. Tape Measure “Rollout”.

This concept is exemplified by a tape measure being rolled out in a linear fashion. The reflector material would either be bunched up in front of these rolls or rolled inside of them. Many groups have used this concept for structures such as solar sails and flat antennas, but not for parabolic antennas. The benefits of this concept are its simplicity and lack of many small intricate supports. This idea would likely use multiple rolls of boom material to help form the parabolic shaper of the reflector.

Another concept developed through our ideations sessions was the scissor-lift accordion shown below in Figure 17. This concept utilizes scissor lift supports that extend out from each side of the CubeSat. The scissor-lifts can collapse can expand fairly easily.

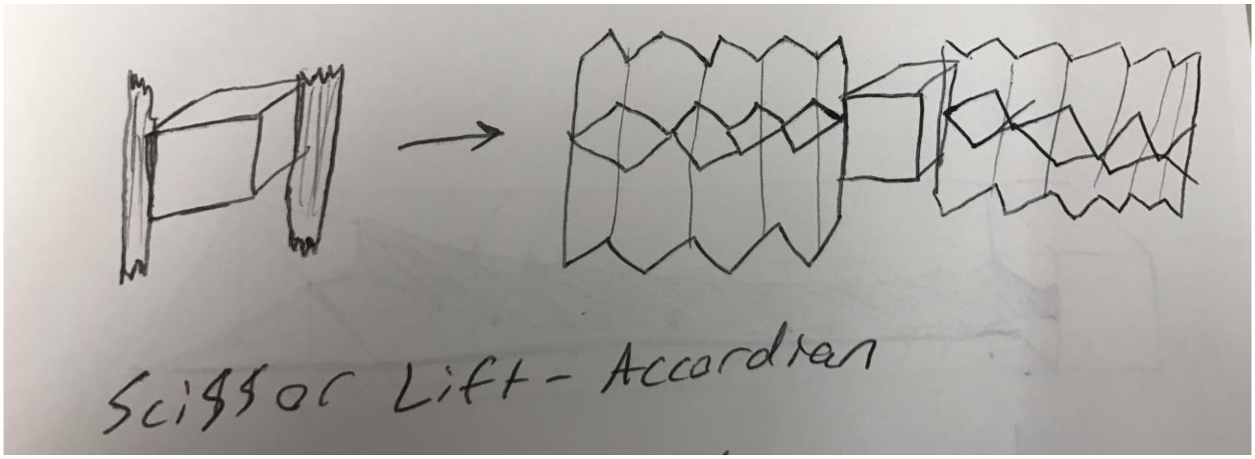

Figure 17. Scissor Lift Accordion.

The reflector would be folded "accordion style" and attached to the scissor-lifts in a way that the reflector expands as the accordion does. The scissor-lift also requires many small precise supports that are hinged and folded on top of each other in intricate ways.

One of the more interesting ideas was the parachute idea shown in Figure 18 below. On Earth, a parachute is packed into a small space and shot out when a person is falling. The air fills the parachute giving it a specific shape that allows for the person to fall safely.

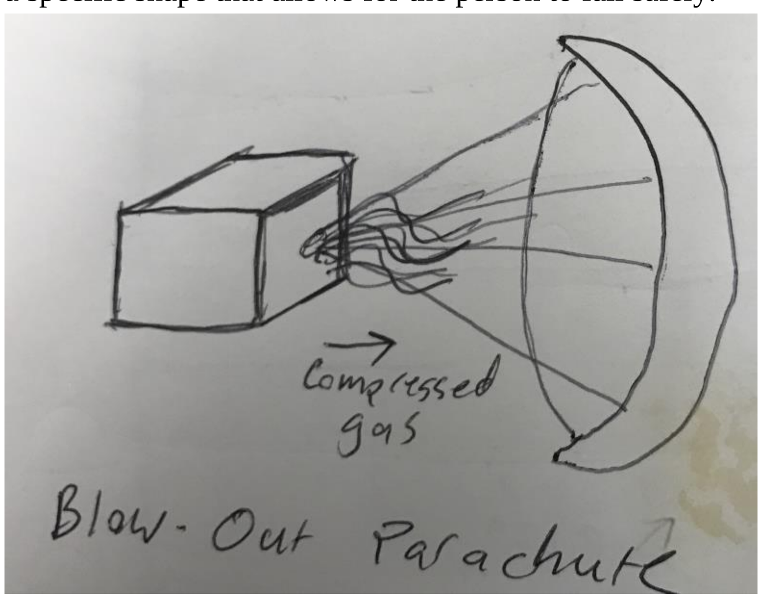

Figure 18. "Blow-Out" Parachute.

This concept has the parachute repurposed as an antenna reflector. The reflector is bunched up into a small space and shot out. Then compressed gas is blown into the reflector to make it more rigid and in the parabolic shape desired. There are various problems associated with sending compressed gas into space, so this concept may not be useful at all.

The system-level concepts were collected and evaluated in a process (detailed further in the Concept Evaluation and Selection section) that led the team to choose tape measure-style boom deployment. After the system-level concept that we wanted to use was chosen, we were able to focus on generating ideas for the specific functions that the antenna needs to accomplish, the main one being that the reflector needs to be parabolic in two directions. We will call those directions the longitudinal and latitudinal directions. Longitudinal is the direction perpendicular to the face of the CubeSat and latitudinal is the direction parallel to the face of the CubeSat. We focused on various concepts in order to achieve the parabolic shape we need in the longitudinal directions first.

3.4 Direction-Specific Deployment and Curvature Concept Development

The first way to achieve a parabolic shape in the longitudinal direction is to heat treat the mild steel or carbon fiber reinforced plastic booms to a point where they are able to be naturally parabolic-shaped, but still be able to be rolled inside the deployer without any issues. This concept is shown below in Figure 19. This will take a lot of materials research as well as a large enough and hot enough oven to heat treat a 2 m long boom.

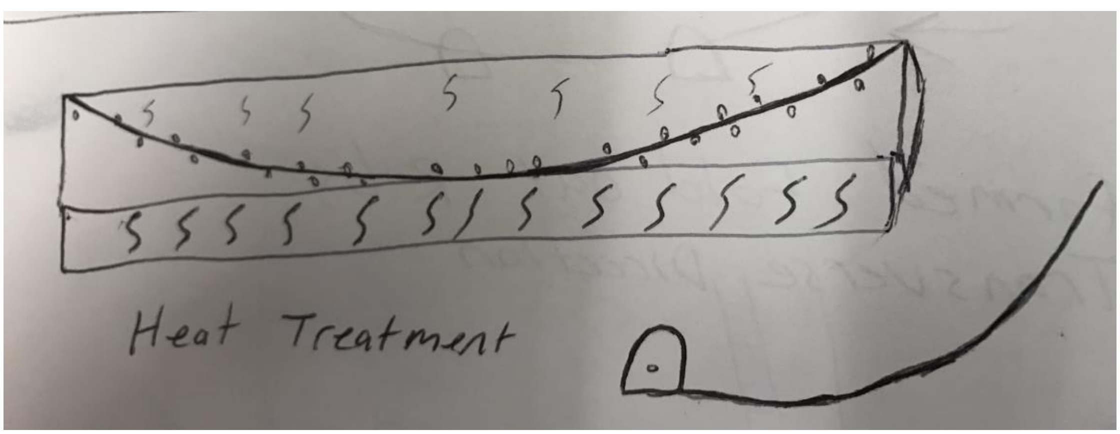

Figure 19. Heat Treated Tape Measure Boom.

The next concept for achieving a parabolic shape in the longitudinal direction, shown below in Figure 20, is similar to the previous one but instead of heat treating the booms, smaller, more flexible ribs would be embedded in the reflector to allow it to be rigid in the correct shape, but also still be rolled or bunched into the allotted storage space. The ribbed reflector could be mounted on tape measure booms, but these booms don't have to be curved.

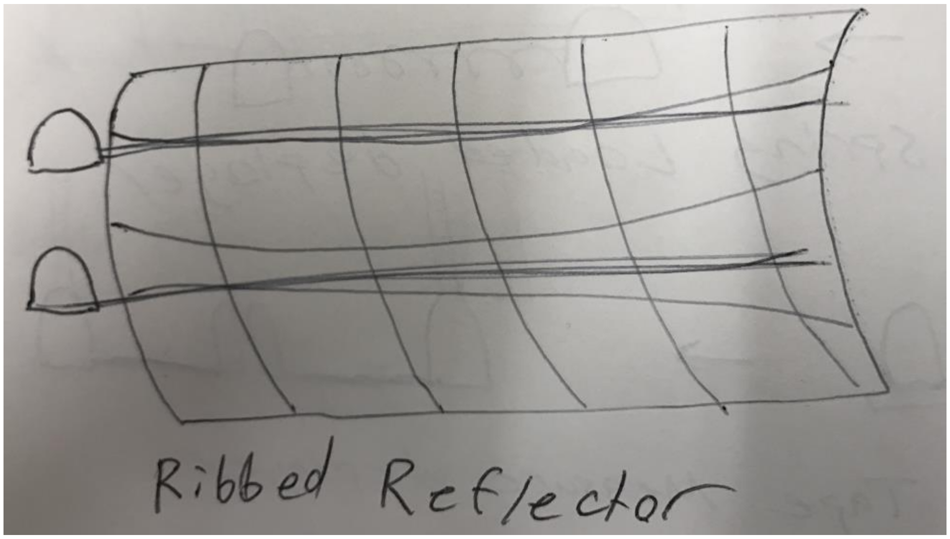

Figure 20. Linear Boom, Ribbed Reflector.

Cold-rolling the boom, shown below in Figure 21, in the longitudinal direction is a different method to form the boom but accomplishes the same task as heat treating. The boom would still naturally be parabolic but ideally still be able to be rolled up like a tape measure.

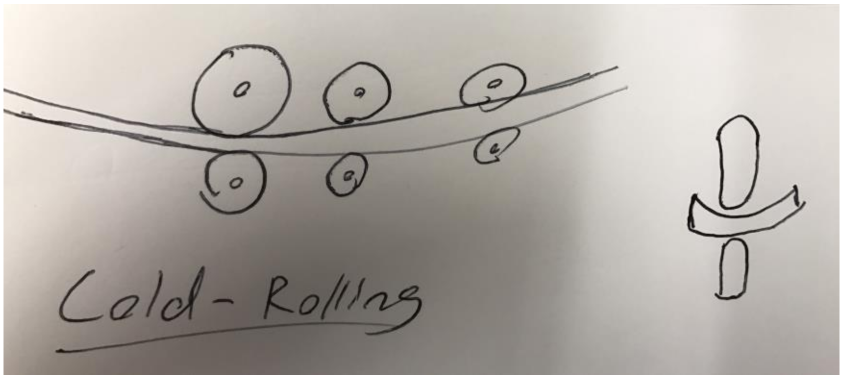

Figure 21. Cold Rolled Longitudinal Boom.

Our final concept of achieving a parabolic shape in the longitudinal direction is through the use of tensioned cables or string that, as the boom is rolled out, pull the boom upwards into the correct shape. This concept is shown below in Figure 22.

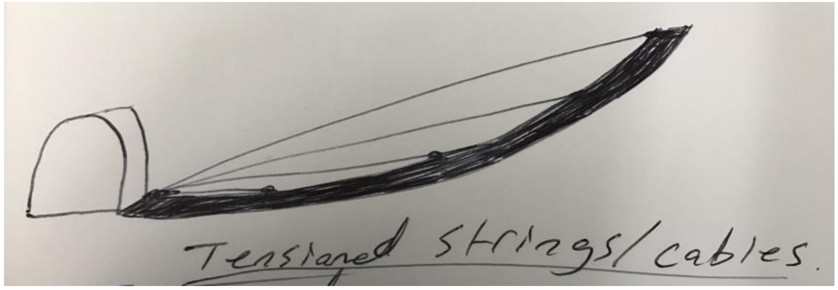

Figure 22. Tensioned Springs and Cables.

These cables would be cut to a specific length and attached in strategic positions that pull up as the linear tape measure boom is rolled out. This idea has great potential because it has no need for heat treating or cold rolling.

In addition to being parabolically shaped in the longitudinal direction, the reflector must also be parabolic in the latitudinal direction to be able to direct the signal to a specific focus point. Some concept generated for this are shown below.

The first concept to be further evaluated for achieving parabolic shape in the latitudinal direction is the preformed fold out ribs concept shown below in Figure 23. Since the reflector has to be 1 m wide and the available storage space is at max 40 cm, the reflector must be able to expand in the latitudinal direction.

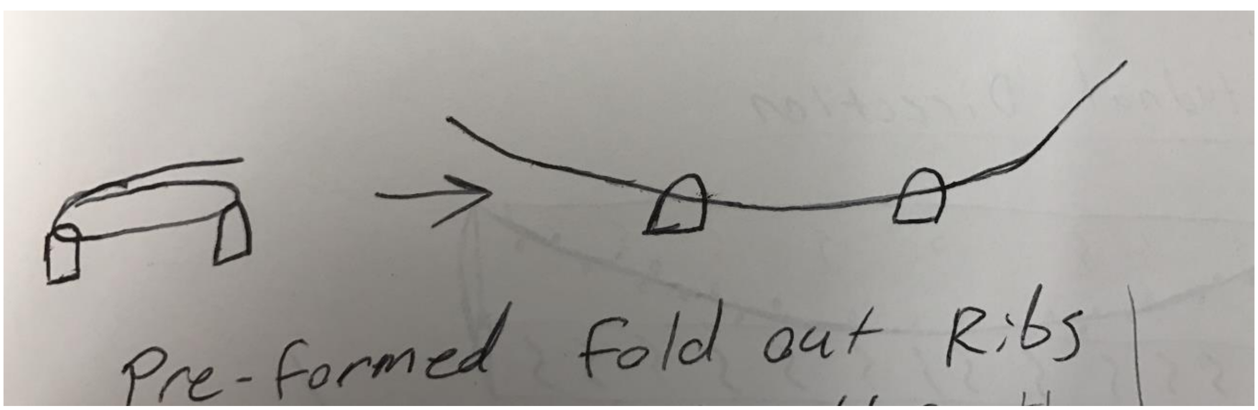

Figure 23. Preformed Fold-Out Ribs.

These preformed ribs would line the reflector material to make it rigid and parabolic and could be folded or rolled back on top of each other for a more compact storage.

Figure 24 and 25 both show latitudinal deployers that are slightly different but accomplish the same goal. These deployers would be stored 40 cm away from each other but would be able to be extended to the 1 m width that we need. Figure 24 shows a spring loaded deployer that allows for for the reflector material to be stretched via a large spring to the correct width. Similarly, Figure

25 shows the same concept, but instead of a spring-loaded extension, it uses addition tape measure deployers to push out the reflector material to the correct shape and width.

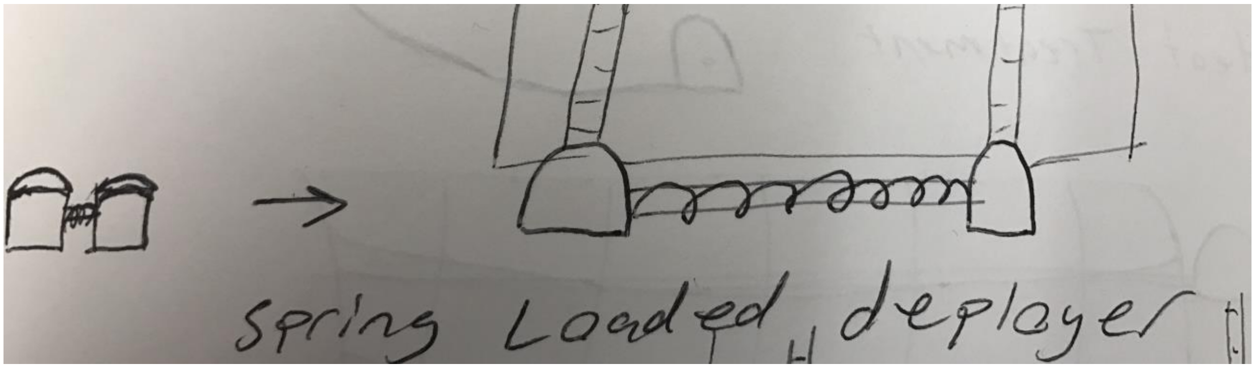

Figure 24. Spring Loaded Latitudinal Deployer.

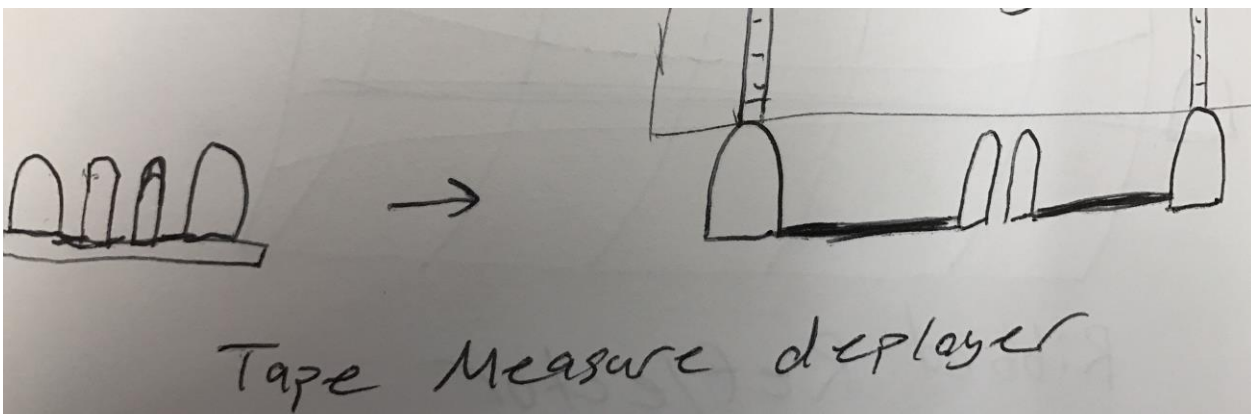

Figure 25. Tape Measure Boom Latitudinal Deployer.

Finally, the last concept evaluated is one that was previously described below in Figure 26 and is also very similar to the deployable helical antenna. The accordion truss is an expandable and collapsible truss that uses a tape measure-like mast to draw out the structure. The reflector mesh is fixed in strategic places on that truss structure, which is made of thin cables or wires, to give it a parabolic shape in both the longitudinal and latitudinal directions. This design could allow for very accurate surface definition, but would require a lot of cabling. Each of the concepts and functions above are evaluated and narrowed down in the Concept Evaluation and Selection section below.

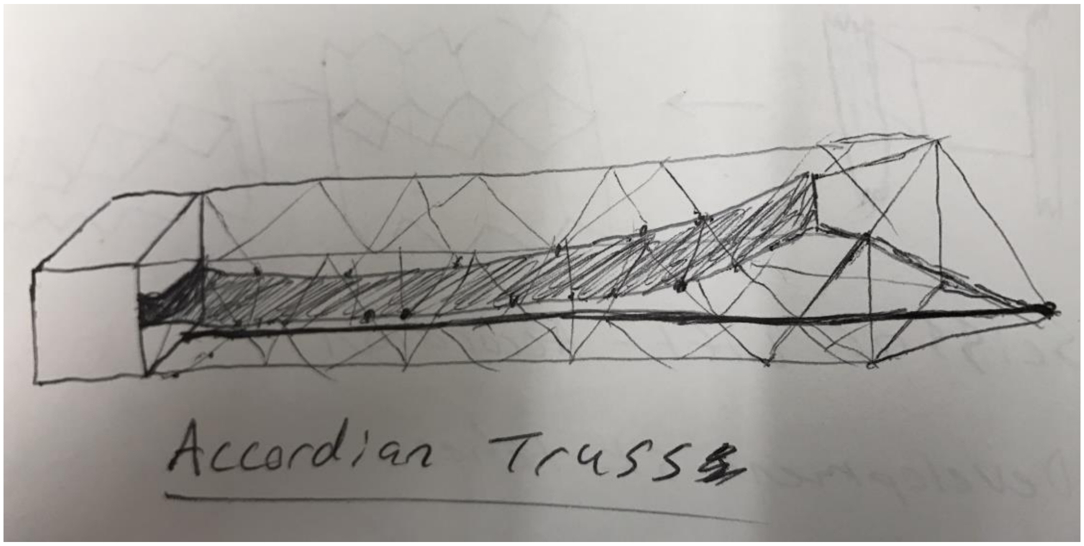

Figure 26. Accordion Truss.

3.5 Concept Evaluation and Selection

While our team came up with a number of interesting and creative design ideas, a lead concept had to be chosen so that the team could move forward on the project. Several of the more far-fetched ideas were eliminated out of a brief observation that, for one reason or another, they would not work. Collecting the remaining possible concepts, the team used a Pugh-style matrix to narrow down the system level concepts. This matrix can be seen in Table 2 below.

A Pugh matrix is a design tool used for comparing function-level ideas with the intent of generating new ideas by suggesting a best idea, and then attempting to incorporate the advantages from other ideas to fill in the selected idea's negatives. Pugh matrices compare each function idea as better or worse than the idea chosen to be the datum, across each design criteria category. The following matrix started out as a Pugh matrix evaluating how well each idea could fulfill the function of deploying the booms of the antenna structure with the given criteria. Eventually, it became the basis for our initial decisions regarding our main system level concepts because the team realized that, due to the scope of the project, each system level idea still left room for several variations on how that design was to be carried out. Due to time constraints, the team had to move forward with an overall system concept to then develop and evaluate implementation ideas. As such, the above Pugh matrix became something of a decision matrix. A decision matrix is a tool used primarily for final concept selection, and ranks each idea numerically for each criterion. Each criterion is given a weight, so that a weighted total score can be produced for each idea, and the strongest concept should have the highest score. A true decision matrix was used later to select the final concept for the project.

Table 2. Pugh Matrix for Evaluating Boom Deployment Ideas (used for making comparisons between system-level concepts).

	Concepts				
Criteria	Expanding Truss	Telescoping Umbrella	Tape Measure "Rollout"	Scissor-Lift / Accordian	Blow-Out Parachute
Deployable to 2x1m	+	+	D	S	+
Achieve Accurate Parabolic Shape	+	-		-	-
Can be stowed in 20x20x40cm	-	-	A	-	S
Use COTS parts, low cost	-	-		S	S
Endure Launch Vibrations	-	-	T	-	-
Operate in Temperature Range	S	S		S	-
Simplicity	-	-	U	-	+
Σ+	2	1		0	2
Σ-	4	5	M	4	3
ΣS	1	1		3	2

In this initial matrix, the Expanding Truss idea scored well for deploying to a large size and achieving an accurate parabolic shape because we saw these properties demonstrated in the Northrop Grumman Astromesh products. However, this idea scored poorly compared to the Tape Measure “Rollout” for storage volume and simplicity. Our team only found successful implementations of this design for much larger-scale satellites and knew it would be difficult to scale down the design for our needs. The Telescoping Umbrella idea was a popular one at first but it was decided that it required too many separate movements that would be difficult to achieve, requiring a collar that slides over a telescopic boom to push the folded ribs out. The Scissor-Lift/Accordion idea had would likely result in too much wrinkling of the reflector mesh and showed no real advantages over the Rollout design. The Blow-Out Parachute idea seemed to very simple; however, the team thought the complications of bringing a fluid (some compressed gas) into space for the sake of deployment would negate that apparent simplicity. The results of this decision matrix, the precedence for using tape measure-style booms for similar purposes found in our research, as well as input from Stellar Exploration, Inc., gave the team confidence that the Tape Measure “Rollout” idea was the direction to pursue.

Having decided to develop a tape measure-style deployment, the team then examined different concepts for achieving the deployment module's two main functions: deploying an antenna with parabolic curvature 2m in the length direction, and deploying an antenna with parabolic curvature 1m in the width direction. The Pugh matrices for each are shown in Table 3 and 4 below.

Table 3. Pugh Matrix for Deployment of Parabolic Curvature in Length Direction (2m).

	Concepts			
Criteria	Preformed Heat Treated	Several Lengthwise Booms / Ribs	Preformed Cold-Rolling	String Tensioners
Achieve Accurate Parabolic Shape	D	-	S	-
"Rollability"	A	+	+	+
Simplicity / Feasability	T	-	S	+
Cost	U	S	S	+
Σ+	M	1	1	3
Σ-		2	0	1
ΣS		3	3	0

Table 4. Pugh Matrix for Deployment of Parabolic Curvature in Width Direction (1m).

	Concepts		
Criteria	Fold-Out Ribs	Pop-Out Deployers	Accordian Truss
Achieve Accurate Parabolic Shape	D	S	+
Extend from 40cm to 1m	A	S	-
Simplicity / Feasability	T	-	-
Cost	U	S	S
Σ+	M	0	1
Σ-		1	2
ΣS		3	1

The Pugh matrix for lengthwise deployment used the idea of heat-treating the tape measure booms to unroll into a parabolic shape as the datum. Using several lengthwise ribs (which would probably end up being small preformed booms or support wires) was thought to be easy to roll up with the tape measure booms but would not be as effective at achieving the desired shape and might be difficult to implement. Using rollers to pre-form the booms was thought to be similar to using heat treatment, except that it might roll into the deployer better since the preforming technique involves rolling. The string tensioners concept seemed very attractive for its utter simplicity but it seemed like it would be a challenge to achieve the tight tolerance required on the parabolic shape and may require a lot of strings to do so.

The Pugh matrix for widthwise deployment used the idea of embedding flexible support ribs into the reflector material that fold out as the datum. The pop-out deployers concept, involving the use of either spring-loaded tracks or two, stiffer tape measure booms that push the main deployers out to a 1m width, ranked similarly to the unfolding ribs, except for being somewhat more complicated since it would require a second form of actuation. The accordion truss idea would excel at defining a very accurate parabolic shape but had the challenge of attaching the reflector to the supporting structure at so many locations and also requiring a lot of support strings/wires that would have to be stowed in the module and then pull out to the proper width. From this matrix, the fold out ribs looked like the most attractive idea.

Table 5. Weighted Decision Matrix Evaluating Top Concepts.

		Criteria							
		Achieve Accurate Parabolic Shape	Use COTS Parts, Low Cost	Endure Launch Vibrations	Simplicity and Manufacturability	Operate in Temperature Range	Can Be Stowed in Storage Volume	"Rollability"	Total
Concepts	Weight	30%	10%	5%	15%	5%	20%	15%	100%
Pre-Shaped Booms with Fold-Out Ribs	Rating	9	6	8	5	5	9	6	
	Wt. Rtg.	2.7	0.6	0.4	0.75	0.25	1.8	0.9	7.4
String-Tensioned Booms with Fold-Out Ribs	Rating	8	7	7	8	5	8	4	
	Wt. Rtg.	2.4	0.7	0.35	1.2	0.25	1.6	0.6	7.1
String-Tensioned Booms with Pop-Out Deployers	Rating	8	5	6	5	4	7	5	
	Wt. Rtg.	2.4	0.5	0.3	0.75	0.2	1.4	0.75	6.3
Accordion Truss	Rating	9	3	6	2	4	6	7	
	Wt. Rtg.	2.7	0.3	0.3	0.3	0.2	1.2	1.05	6.05

The team then developed a final weighted decision matrix (Table 2) to evaluate and compare the top four concepts combining ideas for both lengthwise and widthwise deployment. The first concept was to pre-shape the booms to be naturally parabolic (using either heat treatment, cold rolling, or some combination of the two) and then use flexible support ribs that fold out as the booms deploy. The second concept kept the idea of using the fold-out ribs but instead of pre-shaping the booms, they would be pulled into shape by strings. The third concept used the string tensioners with deployers that push out from the sides of the CubeSat (using either a spring-loaded mechanism or stiffer booms to do so). The final concept was the accordion truss idea described earlier, which uses a central boom to pull the entire material into shape in both directions using lots of tensioning strings/cables.

The criteria were weighted according to their relative importance as determined by the team using engineering judgment, research, and input from Stellar Exploration, Inc. Using the decision matrix as a tool, the team decided that it would intend on implementing the idea to heat treat the booms to be pre-curved, but that if upon further investigation it becomes apparent that this technique has too many problems (such as the steel cannot actually be rolled up well after heat treatment, it loses its curve shape, or is beyond our ability/access to utilize), the string tensioners would then be used as a backup. In either case, fold-out ribs would be used to achieve the widthwise deployment. For all concepts, including the top concept, it was decided that the reflector material would be attached to the booms with sleeves that are fixed to the material and slide over the booms. The sleeve on the end of the boom would be fixed to both the material and the boom so that the material would slide out with the boom.

Chapter 4: Final Design

4.1 Design Overview

The designs chosen as the leading concepts involve the use of two tape measure-style booms that are driven by motorized spools to uncoil and deploy the length of the reflector, along with flexible cross-ribs that are embedded into the reflector mesh and deploy the width of the reflector as the booms push the antenna out from the deployment module. The fully deployed system is shown below in Figure 27.

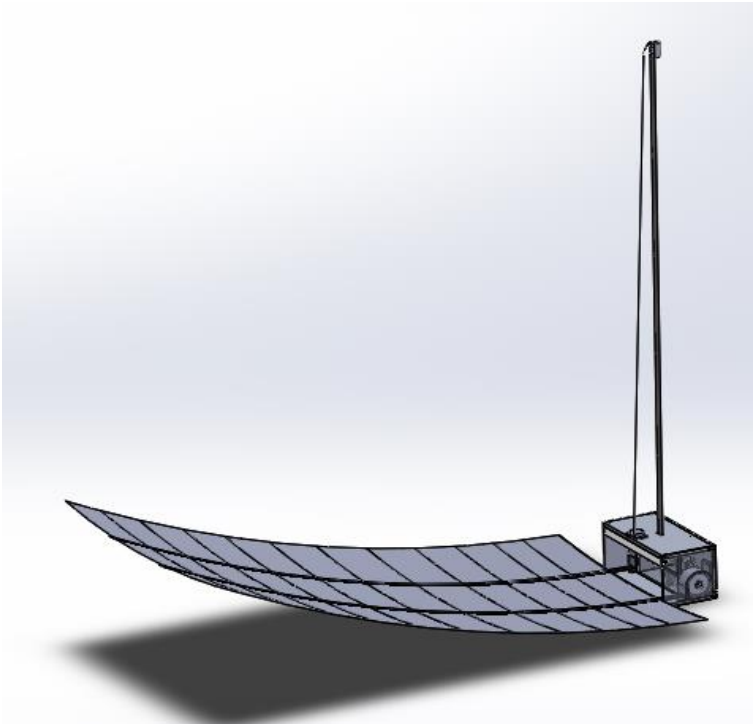

Figure 27. Fully Deployed Reflector and Feed.

These features and their driving mechanisms must be initially stored in the 20 cm x 20 cm x 40 cm module housing which is illustrated below in Figure 28.

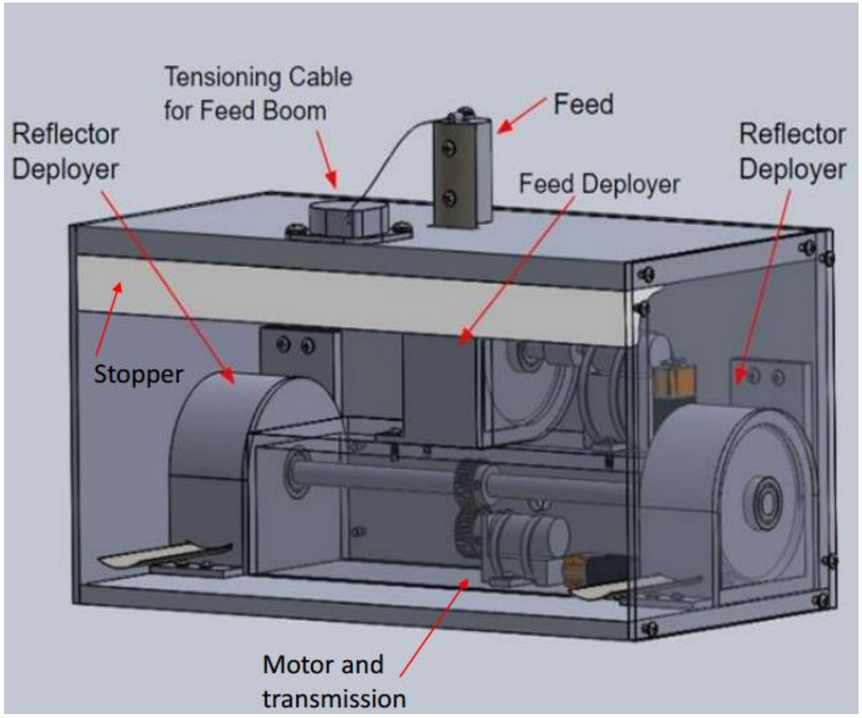

Figure 28. Deployment Module Assembly

4.2 Lengthwise Curvature Designs

After the critical design phase, our final design originally had two variations which we were considering pursuing. These two distinct options only differed in the method for achieving the lengthwise curvature of the booms. The designs for the deployment module housing, the ribs and reflector arrangement, the motor and shaft specifications, and the feed deployer were all exactly the same between the two options. The preferred option for achieving lengthwise curvature was to heat-treat the booms such that they uncoil into the desired parabolic curvature. It was thought that using a heat-treatment process to pre-shape the booms could be a convenient method for achieving a highly accurate shape. However, the success of this method was not guaranteed, given that in all of our benchmarking and conversations with experts, we could not find a precedent for using heat-treatment to achieve the properties we were looking for (i.e. the ability to coil up and then uncoil and still retain the preset curvature), nor did anyone tell us that it was impossible. Our backup method for achieving the parabolic shape along the boom was to fix the end of each boom to an anchor point on the housing with some sort of cable that would be cut to a length such that when the boom is fully extended it would be constrained by the cable and tensioned into a curved shape. While a seemingly simple solution, our team was unsure of how accurate of a shape could be achieved with this method. Therefore, the heat-treatment option was pursued first. Unfortunately, due to an issue with vendor communication, this method was eventually dropped and the string-tensioner option was applied to the final prototype. The following two sub-sections detail our team’s pursuit of both methods for the lengthwise curvature. The difference between the two variations of our design can be seen below in Figure 28.

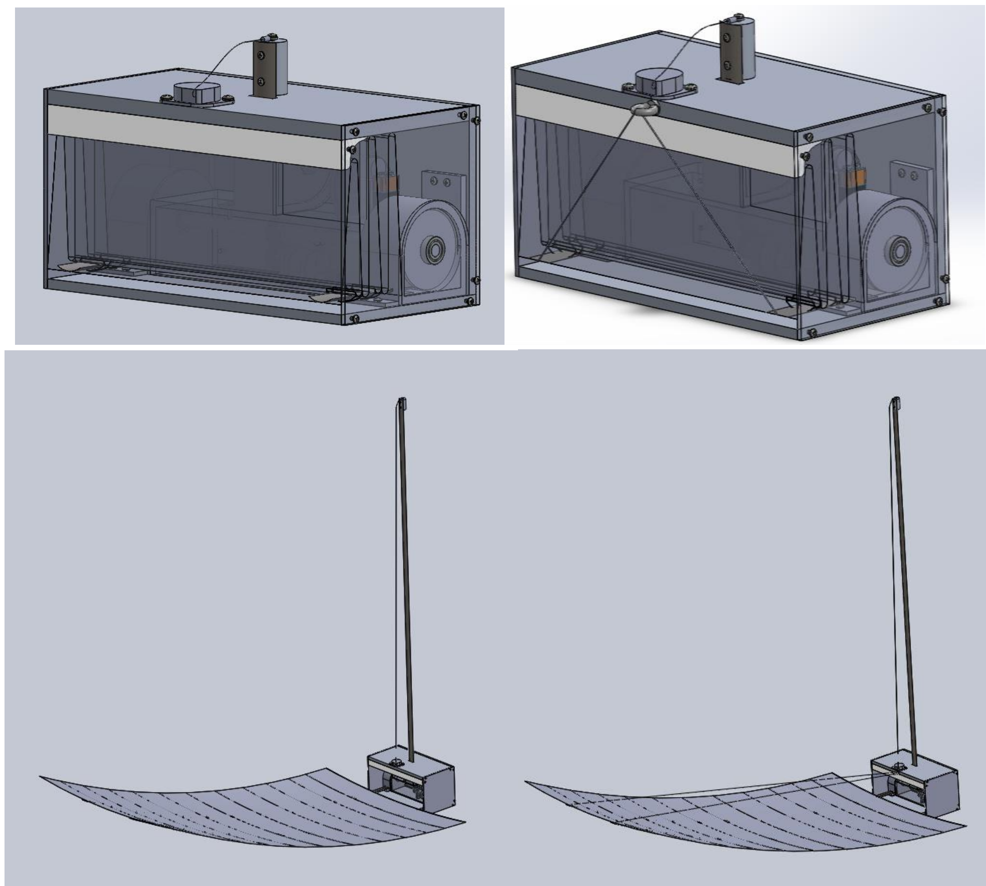

Figure 29. Side-by-side Comparison of Final Design Variations in Their Stowed and Unfolded Configurations

4.2.1 Heat Treatment Design

Our first and more preferred method for obtaining the lengthwise parabolic shape of the booms was to heat treat steel into the parabolic shape so that it would maintain the shape after being rolled in the spool and then deployed. We designed the heat treated booms to have both the required parabolic curve and an axial curve to add stiffness to the length. Figure 30 shows the geometry of the booms with both curves.

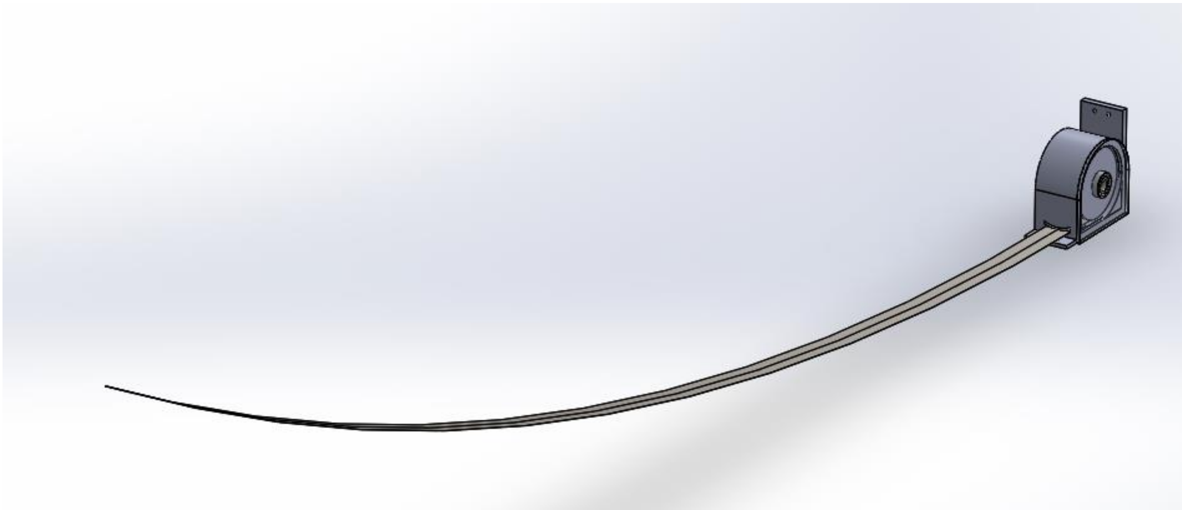

Figure 30. CAD Model of the Boom Geometry.

Having little to no expertise in the field of heat treatment, we sought assistance from the Materials Engineering Consulting Group at Cal Poly, where a materials engineering graduate student, David Otsu, agreed to help us. After describing our project and design specifications, he researched viable materials that could be potential candidates. His full report, shown in Appendix E, provided us with a good starting point for materials to evaluate and vendors to purchase them from. We used this data and reached out to companies that would be willing to provide us with the materials and options to treat those materials. Unfortunately, we came across an unexpected number of obstacles when attempting to find companies or facilities capable of helping us. Our initial design centered around heat treating 0.010 inch 1074/1075 spring steel since its untreated form is very elastic and coilable. Unfortunately, 1074/1075 spring steel requires oil quenching after heat treating due to the instability of the carbon in the steel, which would burn off if not oil-quenched. The burnout of carbon would cause the spring steel to lose its elasticity and would ultimately make it useless to us. We contacted several heat treatment facilities throughout California, but none of them had oil quench heat treatment facilities large enough to fit two 2-meter long spring steel strips. This is mostly because most applications of spring steel require that it spring back to a position that is relatively small in volume which requires the steel gets heat treated in that small volume position. Our project calls for the opposite of the typical spring steel treatment: we want the booms to spring back to the long parabolic shape from a temporarily small storage volume, which would require that it gets heat treated in the long shape, and we found no facilities capable of supporting that.

We discovered that 17-7 stainless steel can be precipitation hardened in large furnaces and does not necessarily require oil quenching. 17-7 stainless steel has high strength and elasticity, and can be easily formed into complex shapes. This material was our best heat treatment option since many heat treatment facilities have furnaces large enough to shape the 17-7 steel. One company in particular, Burbank Steel Treating, Inc., offered to help us attempt to parabolically shape the steel and test if it could roll up in a spool and still maintain its shape afterwards. They offered to perform a few iterations of different heat treatment methods to see if we could accomplish our design specifications. However, some unfortunate miscommunication occurred between our team and Burbank Steel, and eventually we learned that they only had facilities to heat-treat objects under 4 feet long, which was not long enough to meet our needs. Due to the lack of time and resources to pursue another heat-treatment specialist, our team decided that it was time to abandon the heat-treatment idea for our project and move on to our backup method of using string tensioners.

4.2.2 String Tensioner Design

The string tensioner design that was ultimately implemented utilizes the natural tension caused by the motor pushing the booms against a fishing line that is tied to anchor points on the top of the module housing. The fishing line is cut to a length of around 2.02 meters which pulls the tip of the boom upward as it gets deployed outward. The model of the deployed booms with the strings tensioning the boom tips is shows below in Figure 31. It was thought that this method would not work with axially curved booms, as the metal would want to fold rather than curve, so we designed the booms for the string tensioner design as flat booms rolled around the spool. However, the flat 1074/1075 spring steel strips we attempted to use would uncoil out and push against the deployer casing walls so much that the motors could not deploy them. So, the choice was made to use actual tape measure for the booms. Because we knew that the tape measure booms would snap under tension, they were flipped upside down such that the axial curvature opens downward, resulting in a fairly good combination of stiffness and flexibility to where they do not snap as easily when tensioned.

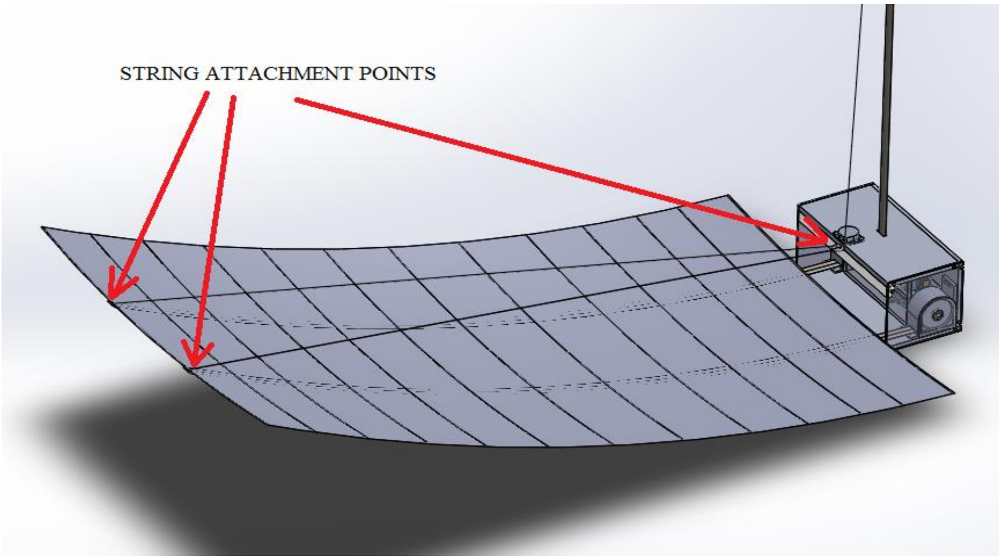

Figure 31. CAD Model of the Deployed String Tensioner Design.

4.3 Deployment Module

This section details the design of the module housing, the shaft and motor specifications, the feed deployment, and the ribs and reflector arrangement.

The module housing, shown below in Figure 32, consists of four aluminum 6061 plates fastened together with several M4 screws. The bottom plate has several holes used for the attachment of the motor, deployer casings, and feed support. The top plate has a slot to allow for the exit of the tape measure used to support the feed. There are also holes on the top plate to allow for the attachment of the constant-force retractable reel used to support the feed tape measure.

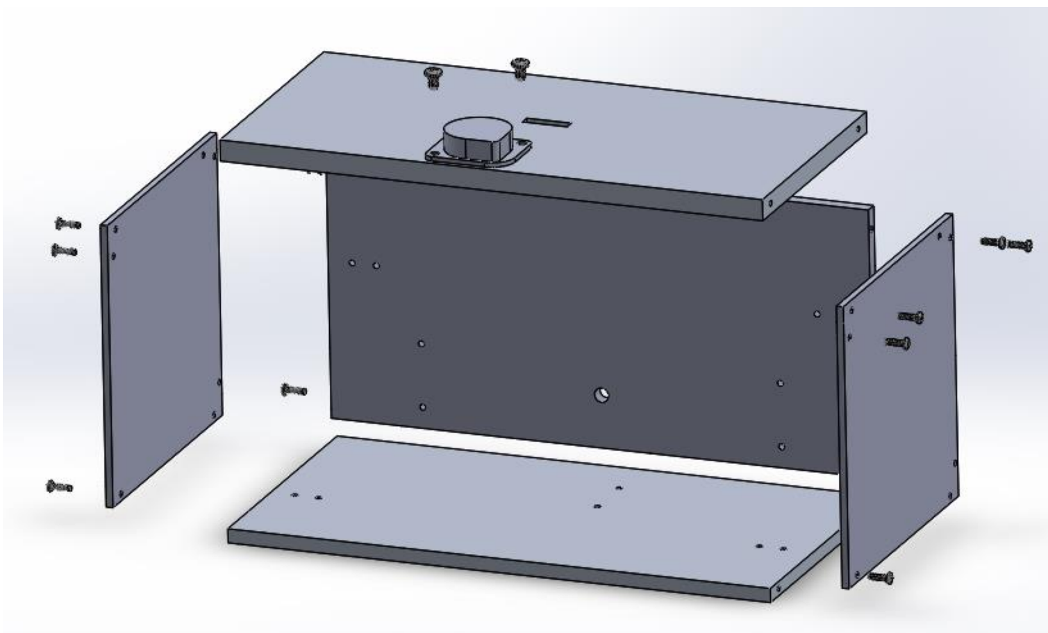

Figure 32. Exploded View of Module Housing Detailed Model.

We designed the deployment mechanism with a steel 12 mm shaft diameter based on the torque requirement calculation seen in Appendix H. A simple DC motor drives the shaft. The selected motor is the 26 rpm Mini Econ gear motor from ServoCity which has fairly high torque capability for its size, as well as a low speed, which is desirable to ensure the deployment occurs smoothly. This DC motor is has a power rating of 6V - 18V which can be supplied through a battery pack with an on/off switch. This motor contains a 4mm shaft that will drive the 12 mm main shaft with a 1:1 gear ratio. These gears are made from a high-load metal gear rod stock with a 20° pressure angle found on McMaster-Carr. The gears are cut to a face width of .5 inches, an outer diameter of 1 inch, and an inner diameter corresponding to the shaft they are located on. The use of English units for these gears is because the stock chosen is in English units. The gears are mounted to their respective shafts using small set screws with a size of M5 6mm long. The power transmission components are shown below in Figure 33.

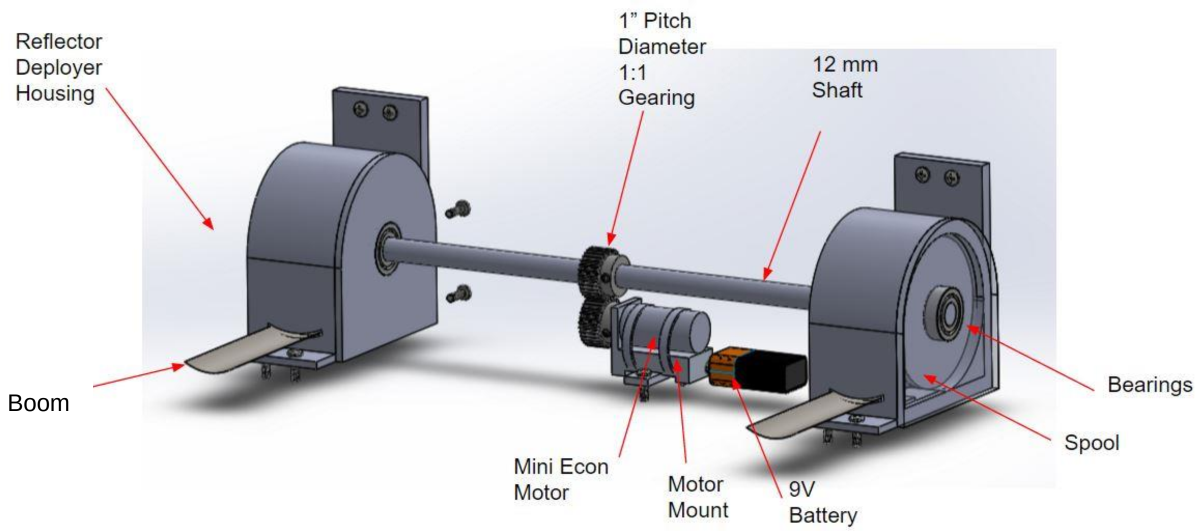

Figure 33. CAD Model of Power Transmission Components.

The feed deployment mechanism sits on top of the feed support which also houses the motor and gears. A separate motor is used to drive the feed deployment mechanism. The torque requirement for this motor is shown in Appendix H. We selected the same motor used for the deployment of the reflector, the 26 rpm Mini Econ Gear motor, for this application because of its high torque output and low rpm. The feed itself will be modeled with a 100-gram cylindrical mass of aluminum. This cylinder will not count towards our allocated 20 cm x 20 cm x 40 cm volume and will be a component that rests on top of the housing when "stowed." Due to the one-sided stiffness of a tape measure caused by its axial curvature, we will install a constant-force retractable reel to tension the tip of the tape measure and keep it from buckling in its weak direction during and after deployment. This retractable reel will also stay outside of the housing and does not contribute towards our allocated volume. This retractable reel applies a constant 0.5 lb force to help stiffen the feed boom. Although this dramatic buckling of the feed boom would not actually occur in a zero-gravity space environment, the reel is necessary to balance the weight of the cylindrical mass during our ground test. During deployment, the tape measure will slide through a slot located on the top plate of the housing while pushing the cylindrical mass upwards to its proper position. The solid model of the feed deployment system is illustrated in Figure 34.

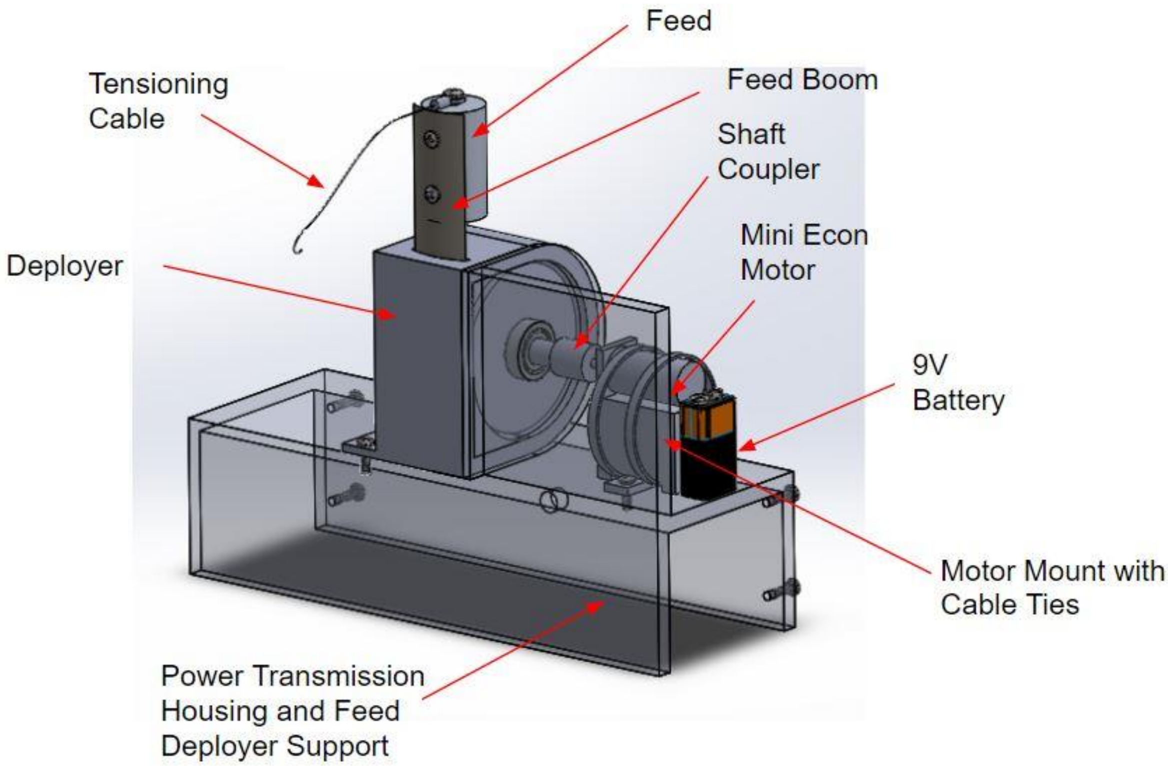

Figure 34. CAD Model of the Feed Deployment System.

For the reflector itself, Mylar was chosen as the material to be used in order to mimic common antenna reflector designs. The ribs deploy in the widthwise direction, perpendicular to the lengthwise booms, and are responsible for the widthwise parabolic shape. Since the target size of the widthwise curvature is 1 m and the housing module has a maximum width of approximately 40 cm, in order for the reflector to be stored in the housing before deployment, it must be stowed in a tri-fold manner. The booms are separated by 34 cm and the Nitinol ribs are folded around the booms and over themselves making the reflector have three sections. The largest section in the middle will be 34 cm, as defined by the distance between the booms, and the outer sections will be 33 cm each. As discussed in section 7.2 and detailed in Appendix H, the exact curvature of each rib would gradually flatten out as its location lies further from the module housing since the rib's vertex moves further away from the focal point. However, this would require customization for every rib which is not feasible for our prototype. Therefore, with acknowledgement from Stellar Exploration, Inc, we are relaxing the exact parabolic tolerance in the widthwise direction and using the same parabolic curvature for every rib. In order for the length of the reflector to fit in the housing module, we are also folding it along its length, after being tri-folded in the widthwise direction. We designed the spacing of the ribs to have 12 segments of Mylar so that the segment length can fit in the module opening, and these segments would fold over each other in an accordion-style fold. The Mylar is embedded with 13 ribs spaced out evenly throughout its length by placing the ribs against the Mylar and gluing separate strips of Mylar over the ribs to keep them in place. 2 mm diameter Nitinol rods are used for the ribs since they are capable of bending through very small radii, and can maintain their elasticity and shape after large deformations. After our team obtained small samples of Nitinol wire, we were confident in its ability to perform as elastic ribs. Figure 35 below shows a visual representation of the Mylar reflector embedded with the Nitinol rods.

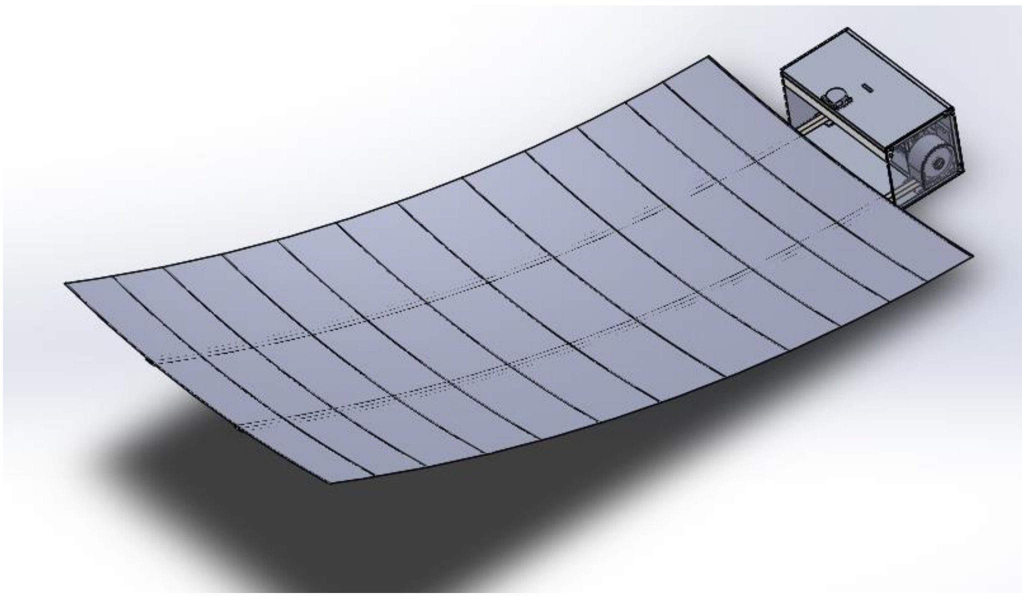

Figure 35. CAD Model of the Mylar Reflector Embedded with Nitinol Ribs.

Two Mylar pockets are placed at the far end of the reflector for each boom to fit in. These pockets serve as the primary attachment points between the reflector and the booms. As the booms begin to unroll during deployment, the booms push on the Mylar pockets and begin the unfolding process of the reflector. As this occurs, the Nitinol in the Mylar reflector will unfold one segment at a time. The booms will run through Mylar collars attached to the reflectors to ensure that the reflector pulls out into shape during deployment. To help restrain the reflector from popping out of the housing while it is being stowed, the top plate of the housing has a curved lip at the exit that will keep the segments of reflector inside until the booms deploy. A side view of the lip at the housing exit is shown in Figure 36. The red circle in the figure indicates the location of the lip with respect to the rest of the module components.

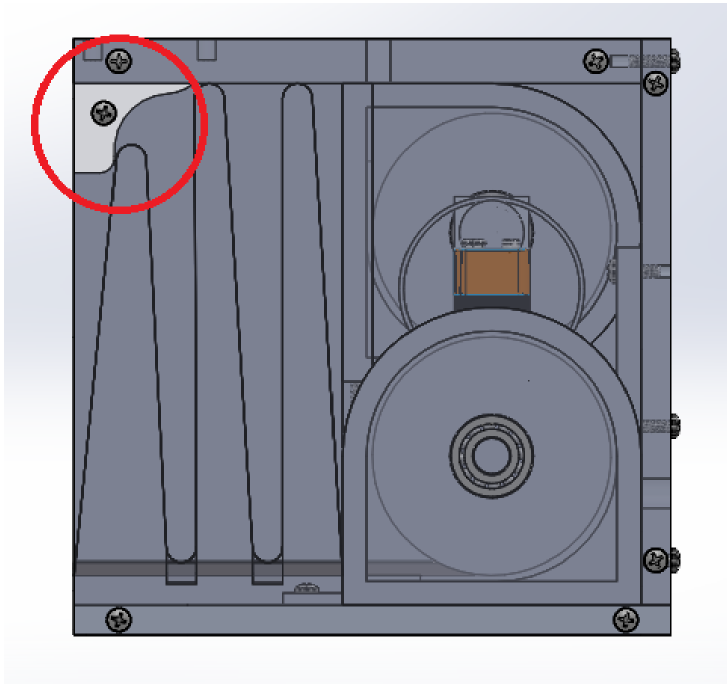

Figure 36. CAD Model of the Lip Located at the Top of the Housing Exit.

4.4 Design Assessment

We performed several calculations regarding stress, deflection, and geometric consistencies to ensure feasibility of our final designs. The most probable mode of failure lies in either excessive stress or deflection of the tape measure boom when supporting the reflector material in a 1G acceleration field. We simplified the analysis of a curved boom by modeling it as a cantilever beam under a distributed load. Using Mylar as a common material for antenna reflectors and assuming a common thickness of the Mylar to be 50.8 micrometers (2 mil), we determined the distributed load to be about 0.36 N/m for each boom. Under this distributed load, the maximum stress at the fixed end of the cantilever beam is approximately 2.85 GPa, which would yield a straight rectangular boom, but would be safe for an axially curved boom with a stronger area moment of inertia. The exact materials used for tape measures vary by manufacturer, but the most common materials used are a combination of steel, fiberglass, and plastic. As a feasible approximation, we used the properties of stainless steel for further analysis, but also considered the effects of varying properties for the sake of thoroughness. Considering the modulus of elasticity of stainless steel, we determined the maximum deflection of the boom to be 8 mm, and the maximum deflections of less stiff materials such as reinforced plastic approached 2 cm.

Understanding that the accuracy of the mathematical analysis is dependent on the accuracy of the physical properties considered, we tested the actual response of a measuring tape under a simulated load to validate our results. We simulated the Mylar material load by extending a measuring tape 2 meters out and distributing 1.4 N of quarters along the length. This load is approximately twice the load that we would expect from the weight of the Mylar, but we doubled the load to ensure a reasonable factor of safety. Although the measuring tape deflected more than the predicted 1.2 cm, it did not yield under the load. This test validated our mathematical analysis and allowed us to further pursue the tape measure design idea. The analysis for this test is shown in Appendix H. It is important to account for the predicted deflection in order to ensure that the parabolic reflector meets the required tolerance. It is also worth considering that the tape measures will deflect differently during our 1G test on Earth than when it actually deploys in space. This analysis will need to be thorough in the final design.

Figure 37. Static Test of Actual Tape Measure Deflection Using Coins as Distributed Load.

It is important to note that the stress and deflection analysis was performed for straight booms. Our design will utilize curved booms which will certainly change the results of stress and deflection. There is also the added benefit that heat treating the booms will increase their stiffness values.

A crucial aspect to antenna reflector design is ensuring the ability for the reflector to effectively direct incoming signals to the feed. The ability of our reflector to do this relies heavily on its accordance with the target 3D paraboloid shape. We mathematically mapped the 3D parabolic shape and created a surface plot of the effective shape using MATLAB. Appendix H shows the derivation of the 3D parabolic definition and Figure 38 shows the 3D plot of the entire antenna. As mentioned previously, although we have defined the exact parabolic shape that the reflector should follow, we are using a constant rib shape for manufacturing purposes which will result in an inexact paraboloid shape. These differences are noted and the accuracy of the final prototype will be compared to the modified shape.

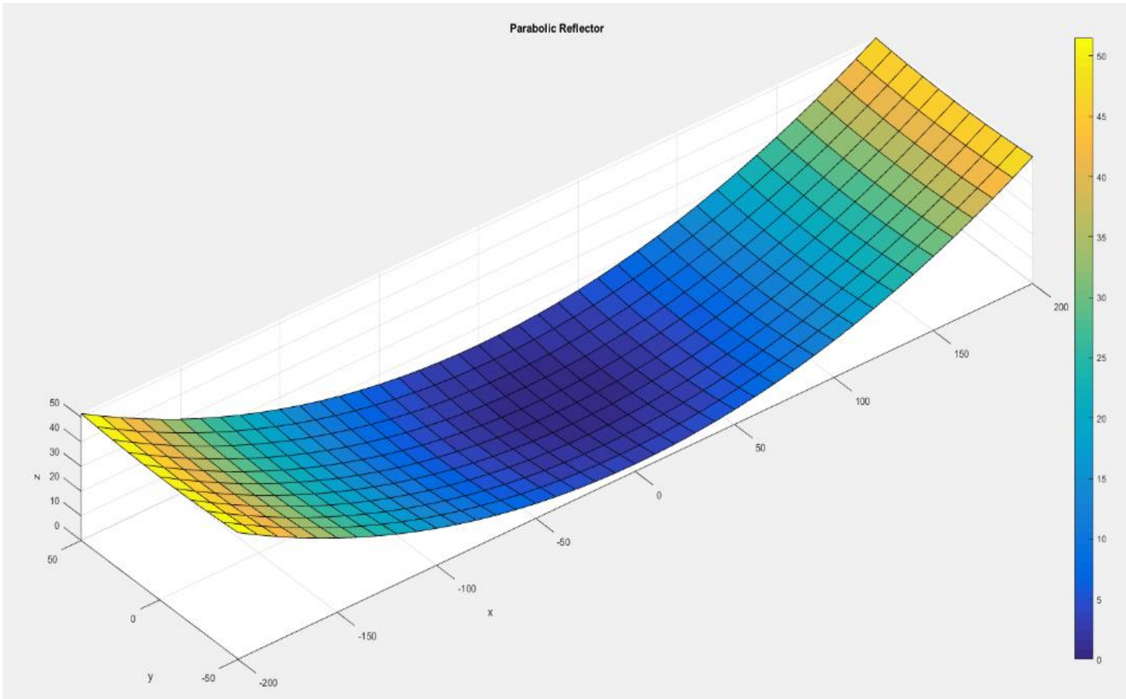

Figure 38. MATLAB 3D Surface Plot of Overall Antenna Shape.

4. 5 Power Transmission and Motor Selection Assessment

In order to drive the deployer mechanisms, we selected appropriate motors that will overcome the resistance in the deployers due to the unfolding of the reflector and the deployment of the feed. For our purposes, a high torque, low speed motor was selected based on the torque generated from unrolling a tape measure with or without added weight.

In order to find the resistance to rotational motion of the tape measure, the force to lift the 150 g feed vertically while attached to the feed boom was measured. Although the target mass of the feed will be 100 g, we analyzed the torque for 150 g to give a factor of safety. Additionally, the force to unroll a tape measure horizontally was measured and then doubled for both of the reflector deployers. These forces were found fastening a spring with a calibrated spring constant to the end of the tape measure and pulling while measuring the deflection of the spring. The spring constant was found by hanging known masses off of the spring and measuring the deflection to find the spring constant k. Using the spring deflection equation, the force required to pull two tape measures out horizontally, and one tape measure with added feed mass vertically, was found. This force was used to find the resistance to rotational motion for each case which is the torque need to overcome this resistance. Knowing the torque needed and the relative rotational speed needed of the motor, we were able to calculate the required motor power. The power required is approximately is less than 1/10th horsepower for each case. The stall torque for the motors we expect need to be above 4.54 kgfcm for the horizontal deployers and 3.98 kgfcm for the vertical deployment of the feed. A note of advice from our sponsor was to quadruple the estimated torque needed by your motors as a safety precaution. Luckily, we were able find low speed, high torque motors easily. The motor we chose is from Servocity, and runs at a speed of 26 rpm which is slow enough for our needs and has a maximum stall torque of 46.8 kgfcm, which is well above our estimated torque needed, even when quadrupled. This motor will be used for both the horizontal deployment of the reflector and the vertical deployment of the feed. The motor has a power requirement of 6 -18 V which can easily be achieved with the use of batteries and will be controlled by an on/off switch located on the battery pack. Calculations and supporting evidence is located in Appendix H.

Figure 39. 26 RPM Mini Econ Gear Motor from Servocity.

Knowing the motor specifications, we needed to figure out how to transmit the power from the motor to the shaft located between the two deployers. We initially considering using a dual shaft motor that would be mounted directly between the two deployers. However, dual shaft motors that have the required maximum stall torque needed were far too large to make fit into our storage volume. So a smaller single shaft motor using two gears with a 1:1 gear ratio would help maintain our compact space requirements, and will allow us to mount our motor off center of the shaft. The motor placement for the vertical feed deployment is a much simpler task because there is enough space for the motor to be mounted in line the deployer and directly power the deployer without any gearing.

As for the power transmission to the horizontal deployment of the reflector, shaft sizes must be determined in order to size the gears. The minimum diameter of the shaft was found using the known torque, speed, and power that the motor is generating. These calculations can be seen in Appendix H. The minimum shaft diameter was found to be 2.1 mm. The selected motor has a shaft size of 4 mm so we can expect that not to have any deflection. The shaft between the two deployers was chosen to be 12 mm. This was chosen because it is less than the inner diameter of the spool located inside the deployers, it is large enough to fit a keyway into and drive the deployers, and it is above the calculated minimum diameter. This shaft is also a standard size to make it easy to fit bearings and gears.

Knowing both the size of the shaft located on the motor as well as the size of the shaft driving the deployers, we were able to size gears accordingly. Because the diameter of the motor is approximately 1 in or 12 mm, we needed to size the gears to not interfere with the motor housing or any other components. So, gears with a pitch diameter of 1 in were chosen because they do not interfere with the motor housing. In order to ensure that the selected gears would be strong enough, calculations were done in Appendix H. These calculations show that when using steel gears, the maximum allowable stress for our case is almost 6000 psi. This value is well over anything that this gear will see and in fact has a safety factor of over 1000. This solidified our gear selection with a 32-tooth steel gear with a diametral pitch of 1 in and a face width of 0.5 in. Because we need multiple of the same gear, but with different inner diameters we decided to select a 1 ft rod of gear stock so the inner diameter can easily be machined and we will have enough stock for many gears in the case of damage, incorrect machining, or any other problem that we may occur. McMaster-Carr sells this stock in English units only; which is why these gear calculations were done with English units as opposed to metric. These gears will be fastened onto the corresponding shafts using set screws. Figure 40 below shows the CAD model of the boom deployer motor and gear system.

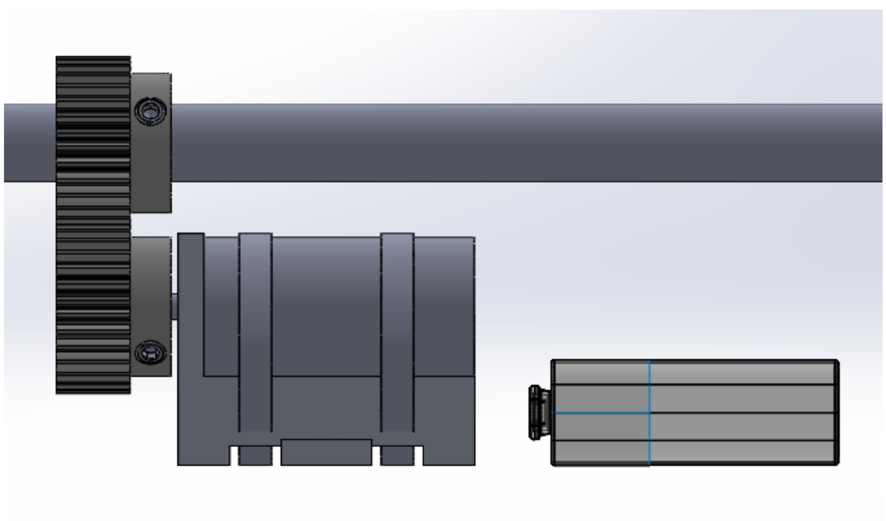

Figure 40. CAD Model of the Boom Deployer Motor and Gear System

As stated earlier, power transmission to the feed deployer is much simpler. The motor is going to be mounted directly next to the feed deployer and power it via a 4 mm to 12 mm shaft coupler. This shaft coupler is a standard size also found at Servocity. The motor shaft drives the coupler, which drives the deployer shaft, which drives the spool inside the deployer via a keyway in the 12 mm shaft. Because this motor is driving less load more simply than the reflector deployer transmission, it can be assumed that the strength of these shafts and components will suffice.

4.6 Deployer Assessment

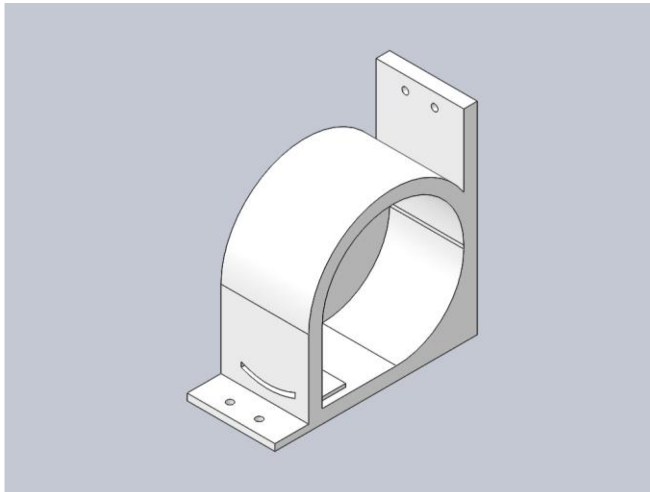

Figure 41. Deployer Casing

The deployer casing size was determined by a simple tape roll diameter calculation provided by www.giangrandi.ch. The calculation determines what the outer diameter a roll of tape material will be if you input the length and thickness of the stretched-out configuration of that same material. This calculation showed us that the booms, with a thickness of 0.010 in and length of 2.15 m, can theoretically be rolled into a small diameter of 4.9 cm. We chose to nearly double this estimate, however, because the calculation was intended for tape-like materials, which are much more elastic than the steel we will be using. To ensure that the booms can indeed be coiled onto the spool, we designed the outer diameter of the spool casing to be 8 cm, and assumed an inner diameter of 2cm.

The bearings from McMaster-Carr were selected primarily for the size compatibility. Since our shaft is not subject to high torque or a large number of cycles, we determined that we do not need extensive calculations to prove the yield strength or fatigue resistance of the bearings. The relatively mild conditions that our power transmission system resides in allowed us to have freedom in the type of bearings we chose. Because of the low speed and torque required of our power transmission, we do not expect any significant amount of stress or wear on our bearings.

Similar to the bearings, we selected the fasteners for our design completely based on size and compatibility with the thin components we are using. Since the aluminum plates used for the housing vary in thickness from 0.5 cm to 1.5 cm, the fastener size that was most suitable for all applications was the metric size of 4 mm. This corresponds to the ISO metric M4 standard fastener which is what we are using for most of our fastener. Since our deployment module prototype is not subject to any excessive static or dynamic loads, there is no need to perform extensive analysis on the structural integrity of the fasteners. However, the design of the actual model that will be sent to space should consider the dynamic loads of the rocket launch to ensure that the fasteners and structures will not fail.

4.7 Deviation from Required Specifications

In order to move forward with less emphasis on theoretical design and more emphasis on a physical prototype, we have relaxed a few required specifications that we were originally constrained by. The first relaxed specification, which we have already mentioned, involves a deviation from the exact three-dimensional paraboloid shape. This is due to the higher cost and larger lead time of forming individualized parabolic shapes for the ribs. In theory, each rib would be a different parabolic shape and a subsequent iteration of this design should include exact rib parabolas. As it stands, the non-standard nature of parabolic booms and Nitinol wires require custom ordering. Thus, we have also relaxed the requirement that we would only use commercial, off-the-shelf parts. Also, the original storage volume specification of all components fitting inside a 20 cm x 20 cm x 40 cm box has been relaxed since both the feed cylinder and the constant-force reel will be located on top of our housing. Another constraint that we relaxed is the requirement that our prototype withstand a simulated rocket launch load with either a 50g static load or shaker table test. We do not find it reasonable to focus too much on the structural integrity of our design as we wish to focus our attention on obtaining the parabolic reflector shape. Our primary objective is to obtain the $\lambda/20$ tolerance of 0.5 cm, but our ability to accomplish this is completely dependent on the success of our heat treatment or string tensioning designs. We want to emphasize that we have designed our module to have the opportunity to succeed, we just need to perform several trials during the building phase.

Chapter 5: Product Realization

After completing the detailed design phase is complete and agreeing upon a final design and parts list, we have completed manufacturing and testing. Our team has composed a detailed list of the parts used, the suppliers for the stock parts or the commercial off-the-shelf products used, as well as an analysis of the costs that have occurred. Many of the less complex parts have been manufactured at the Cal Poly machine shops; however, certain parts needed more specialty attention. A Design Safety Identification Checklist, shown in Appendix C, has been completed to ensure the safety of all the team members as well as those present during project demonstration. A detailed plan for how each component has been manufactured is presented in this section. Timing for each manufacturing phase is outlined in the Gantt Chart in Appendix B. A drawing packet has been included in Appendix G that shows a wide range of drawings from exploded assembly views to individual dimensioned part drawings.

5.1 Manufacturing of Booms

As mentioned above, certain parts such as the tape measure booms were going to be formed using heat treatment or cold working methods. Heat treatment consists of pinning or molding the boom material and then heating it up in a large oven until the boom's natural shape is the correct parabolic shape previously determined through analysis. For our 2 m long booms, we have selected 17-7 stainless steel strips that would have been performed by Burbank Steel Treating Inc. These booms will be approximately 2.15 m long and have an axial bend similar to that of a tape measure. They will also be curved parabolically fitting the shape discussed in earlier sections. The benefit to Using 17-7 stainless steel strips is that when heat treating, there is no need for an oil quench and no loss of carbon content in the steel, which allows it to maintain its elasticity. These 17-7 steel strips will be purchased from Precision Steel Warehouse, Inc. and will sent directly to our contact at Burbank Steel Treating Inc. The lead time and estimate of the timing of this exchange is outlined in the Gantt Chart in Appendix B. However due to the extended lead time and a potential cost of thousands of dollars, we chose to go with our back up plan of using string tensioners to get our parabolic deployment.

Since this version of our project does not require heat treatment, there was no need for the axial bend in the boom. This allows for the flat boom to be pulled up by our fishing line tensioners. The material used for this boom was going to be 1045 spring steel purchased from McMaster-Carr and would not be sent to Burbank Steel Treating, Inc. for heat treatment. The fishing line tensioners will be fixed to the endpoint of the boom through a hole. What was actually used was tape measure material cut from a 35 foot Dewalt tape measure. This tape measure is installed with the axial bend facing down so the boom is fairly rigid, can be pulled parabolically by tensioners, and can still be rolled up.

This method has been tested and seen in Figure 42 below. The tensioner pulls on the upside down tape measure material until it is curved to a parabolic shape.

Figure 42. Testing tape measure curvature capabilities.

Both booms are fixed to our spool at one end using two M2 x 0.4 mm screws. The holes for which were made using a drill press located at the Cal Poly Machine Shops.

The feed boom, rather than be parabolically shaped, needed to be perfectly shaped and rounded axially for stiffness. It is made of the same tape measure material as the horizontal booms. It has the same holes drilled in for attachment to the spool but will also have holes for attachment of the feed at the opposite end. These booms can be seen in Figure 43 below.

Figure 43. Tape measure booms used for vertical and horizontal deployment.

5.2 Manufacturing of Ribs

The material chosen for the ribs of the ribbed reflector are nitinol rods because of its elasticity. Because this material is very difficult to work with, our ribs will be purchased pre-formed from Fort Wayne Metals in Fort Wayne, IN. They will heat treat the nitinol to make sure its natural resting position is the parabolic shape that we require. While ideally, these ribs would be perfect shape and have the correct focal point, that would require each individual rib to have a different focal length and therefore a different shape. This is because as the ribs go up the lengthwise parabolic booms, the distance they are away from the focal point changes. For the purposes of our prototype and our limited budget requirements, we ordered and received 25 ribs that are all the same shape. We also expected these ribs to have a long lead time, possibly more than a month. So they were ordered right away. The correct shape for the extended nitinol ribs is shown below in Figure 44.

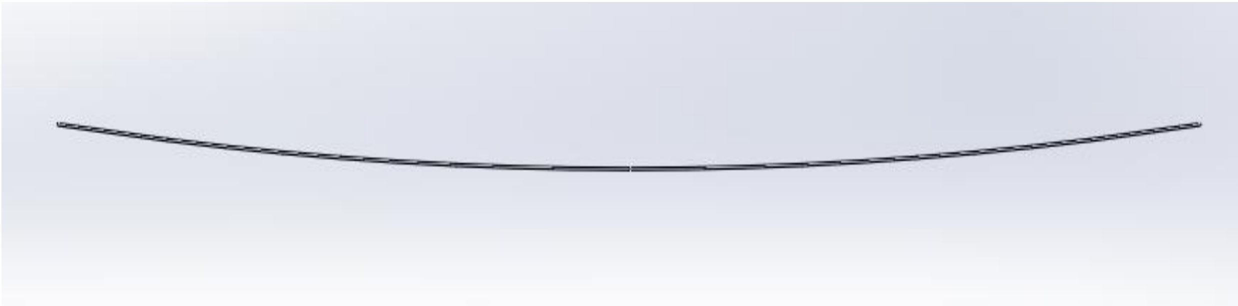

Figure 44. CAD Model of the Nitinol Rod Used as the Reflector Ribs.

Unfortunately, Fort Wayne could not produce 1 meter long ribs and could only send us a maximum length of 24 inches. So because of this, our team embedded two ribs, side-by-side to reach the full length of the reflector. The actual ribs purchased are shown below in Figure 44.

As mentioned in earlier sections, these ribs were embedded in the Mylar reflector material by taping and sandwiching the ribs onto the Mylar reflector.

The entire reflector will be mounted to the lengthwise booms once all the ribs are fully embedded. This can be seen below in Figure 45.

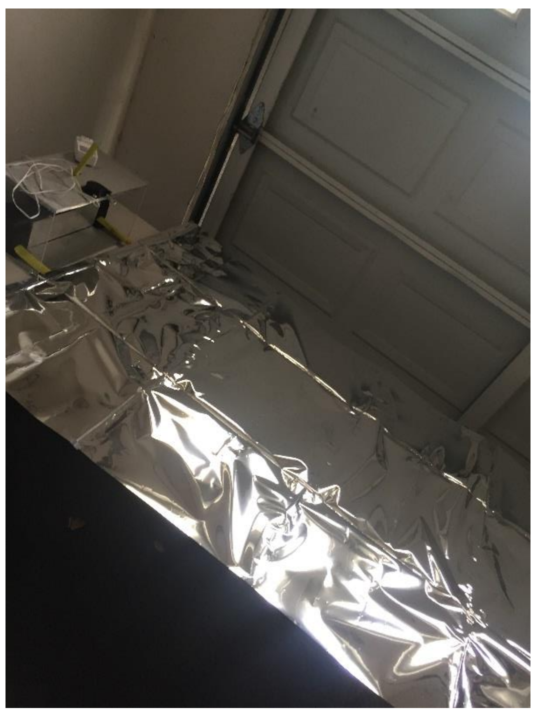

Figure 45. Assembled Mylar reflector.

The mounts consist of small Mylar collars glued onto the reflector. This allows for the booms to slide in and out of the reflector. These collars can be seen in Figure 46 below.


Figure 46. Mylar Collars

This assembly did not need the use of any technical equipment was done in a place large enough for the entire unfolded reflector to be spread.

5.3 Manufacturing of Antenna Housing

The manufacturing of the antenna housing was one of the first things we assembled. This helped us get an understanding of our space requirements and allow us to adjust as we completed the other sub-assemblies.

The storage volume consists of five, 10 mm thick 6061 aluminum stock plates cut to the correct dimensions as seen in the drawing list in Appendix G. Only five sides are closed with the front of the storage volume being open for the deployment of the reflector. The dimensions of this storage volume is 20 cm x 20 cm x 40 cm as required by our engineering specifications. The stock aluminum were purchased from Metals Depot and were cut and assembled in the Cal Poly machine shops using a vertical band saw shown in Figure 47 below.

Figure 47. Manufacturing of housing plates.

The antenna housing needed various holes in it for mounting positions of other components so those holes will be drilled by our team using a drill press. The storage volume was bolted together using M4 x 0.7 mm sized fasteners. This antenna housing assembly is shown below in Figure 48. A slot will be cut in the top plate of the storage volume where the feed deployer can pass through.

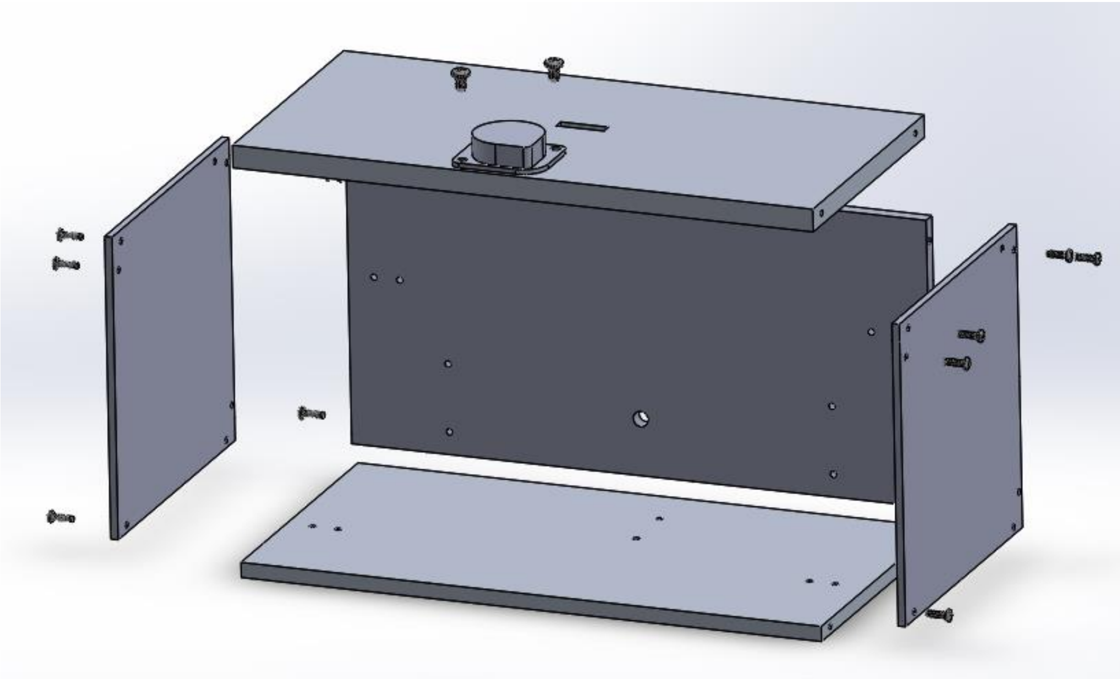

Figure 48. Exploded View of Storage Volume

The storage volume also contains a 3D printed stopper to help contain the folded reflector. It was 3D printed by our sponsor, Stellar Exploration, Inc. The polycarbonate plastic stopper will be mounted to the storage volume using size M4 x 0.7 mm fasteners. We expect the storage volume to take up to 2 weeks including the 3D printed stopper. It was decided to make the side plates of the housing out of 3/16th thick clear acrylic sheet as to be able to see the internal components. The full Housing including the 3D printed stopper can be seen below in Figure 49.

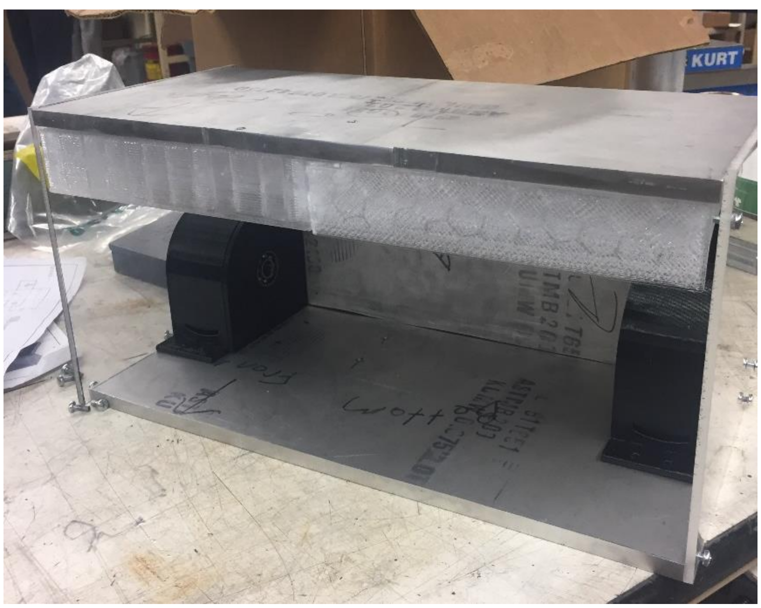

Figure 49. Manufactured housing and stopper

5.4 Manufacturing of Various Deployer Housings

The deployer housings, because of their complicated shape and complex slot, was rapidly prototyped via 3D printing. Stellar Exploration Inc., was our main point of contact for access to the 3D printers. The material used in these 3D printer is polycarbonate plastic and was strong enough for our purposes. These printers took about to a day or two each, and was given a total of a week to be finished. The difficulty with using other manufacturing methods for this part is that each deployer housing is slightly different because of space constraints. Also, the curved parabolic slot on the front of the deployers would be almost impossible to cut using other tools. This is why 3D printing is the best choice.

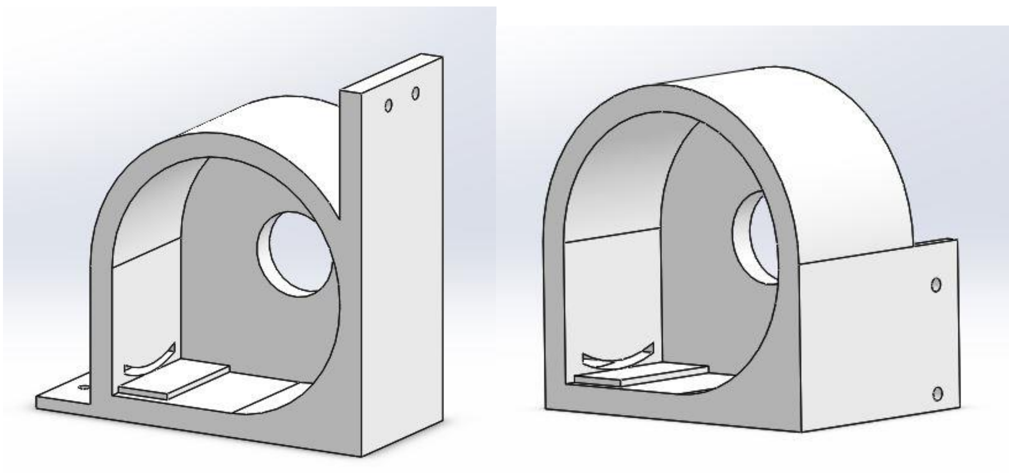

Figure 50. Side-by-side Comparison of Reflector Deployer Housing and Feed Deployer Housing

The reflector deployers are mounted using holes located on the flanges of the deployers and will be fastened to the storage volume using M4 x 0.7 mm bolts and nuts into the corresponding position. The deployers are mounted to the very back of the storage volume to increase the amount of space inside for the folded reflector. The feed deployer is mounted to the motor and power transmission housing using the same screws. The completed 3D printed deployer housings are shown below in Figure 51. In order to accommodate our change in boom material the front slots of the deployer housings were opened up using a Dremel.

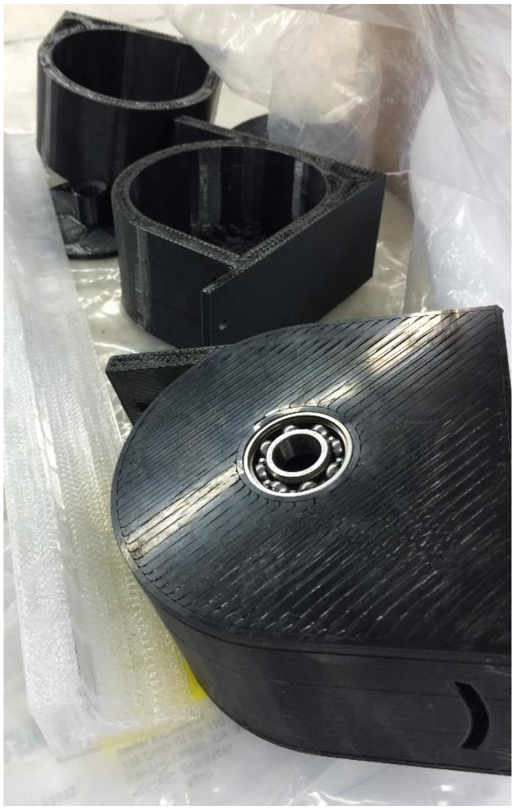

Figure 51. 3D printed deployer housings

The fully assembled deployers inside the housing can be seen in Figure 52 below. This shows both horizontal deployers and the vertical feed deployer mounted inside the housing.

Figure 52. Mounted horizontal and vertical deployers.

5.5 Manufacturing of Spool

The horizontal deployer spools were made of a 6061 aluminum 40 mm cylindrical stock. In order to make this stock our spool, we used the Cal Poly Machine Shops. All members of our group are yellow tag certified which allows us to use lathes. The aluminum stock pieces were turned down to the outside diameter of 80 mm and then turned down in the middle to 20 mm create the spool. The center of the spool contains a 12 mm hole drilled out with a keyway allowing for the shaft to turn the spool when the motor is on. Both spools for each horizontal deployer were cut from the same piece of 40 mm, 1 ft long cylindrical stock which is found on McMaster-Carr. The spool also contains small M2 x 0.4 mm sized threaded holes on its inner diameter for the booms to be bolted to. An exploded model of the deployer spool is shown below in Figure 53.

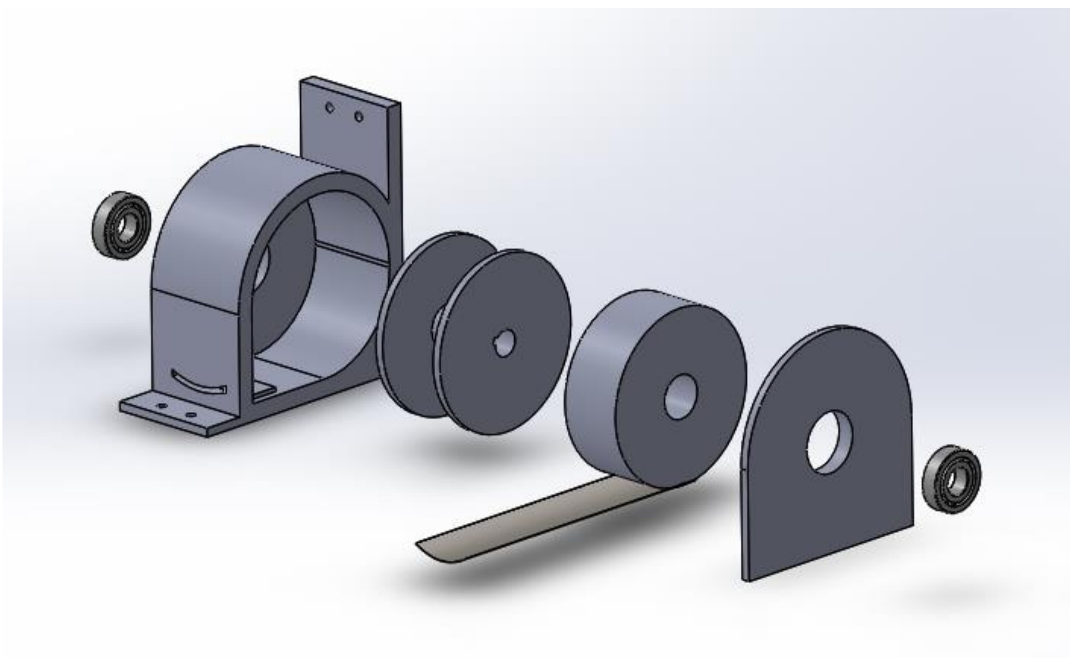

Figure 53. Exploded CAD Model of the Deployer Casing and Spool.

This part turned out to be much more difficult than we expected and required the help of the Cal Poly Machine shop techs to operate the CNC lathe to turn down the inner diameter and out flanges of the spool. Figure 54 below shows the spool being turned down on a manual lathe prior to being turned in the CNC lathe.

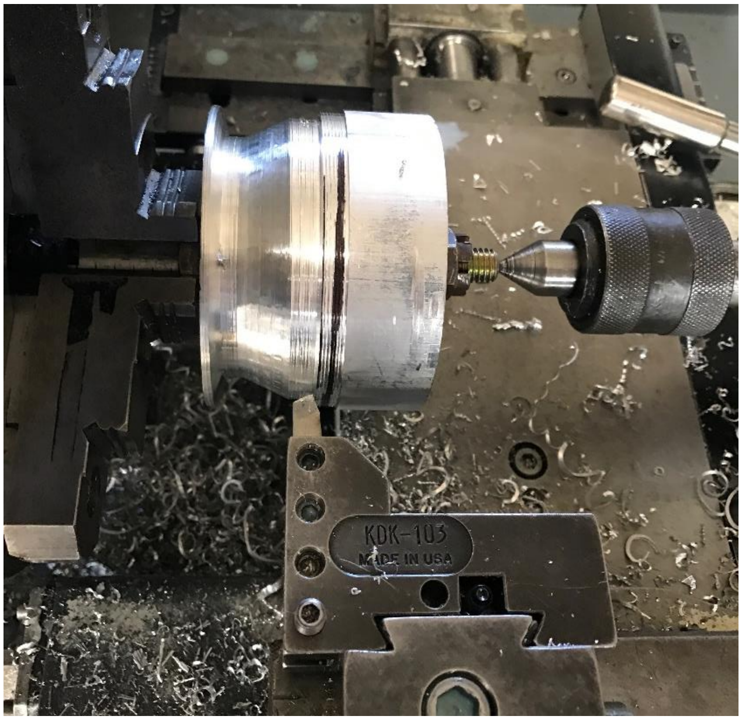

Figure 54. Turning spool on a manual lathe

The following figure shows the finished aluminum 6061 spool after being turned on the CNC lathe.


Figure 55. Completed Spool

For the vertical feed deployer spool, we decided to try a 3D printed spool printed by Stellar Exploration Inc. Because the vertical feed deployer requires less torque overall, the 3D printed spool is fine for the vertical feed deployment. The 3D printed spool can be seen in Figure 56 below.

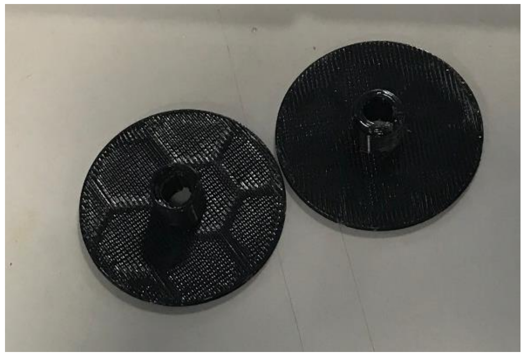

Figure 56. 3D Polycarbonate spool

5.6 Manufacturing of Shafts

The shaft is a very simple design. It is made from a small 12 mm diameter steel rotary shaft found on McMaster-Carr. The shaft comes keyed which allows for us to mount and power our gears and spools. The material is a 1045 carbon steel used for rotary purposes. This shaft will not take very much time to manufacture because all that need to be done to it is cut to right length and mount gears, spools, and bearings to it. Because McMaster is so fast and reliable we do not expect a long lead time for any of the parts ordered from them. Once the shaft is obtained we can expect to have the shaft within a day. Many of these parts will be made in conjunction with one another or made by different people. This is outlined in the manufacturing schedule in the Gantt Chart in Appendix B.

After cutting the shaft in the chop saw, the rough edges had to be ground down the make sure the shafts could fit into our bearings. One shaft is the larger main shaft which is approximately 40 cm long and the small shaft is to transmit power to the feed deployer and is approximately 8 cm long. Each shaft as a key in it that is 4 mm that allows for power transmission to the spools. The figure below shows the grinding down of the shaft edges.

Figure 57. Grinding of the main shaft.

The completed main shaft and feed shaft can be seen below in Figure 58. Each shaft is made from 1045 steel to guarantee there is now way for bending or torsion to occur.

Figure 58. Completed main and feed shaft.

5.7 Manufacturing of Gears

The gears were from a high-load metal gear rod stock with a 20 degree pressure angle, a pitch of 32, with 32 teeth. The pitch diameter of this gear stock is 1 inch. This stock was1 ft long and provided us with enough material for multiple sets of our gears.

The gears will be cut to allow for a face width of 0.5 inches and a small set screw, size M5 6 mm long drilled directly into the gear. This differs from our design because there is now now smoothed out section for the set screw. The smooth rounded sections for the set screw were going to be turned and smoothed out using a lathe before cutting the gear off the stock. However, with the advice of the shop techs, we just drilled and tapped the hole for the set screw directly into the teeth of the gear. The set screw allows for a rigid attachment of the gear to the shaft. Figure 59 below shows the gear rod stock we plan to purchase from McMaster-Carr.

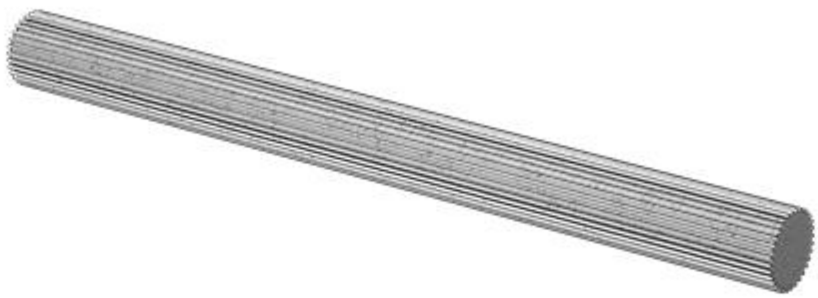

Figure 59. Gear Rod Stock from McMaster-Carr.

The two gears we need for our design will be the exact same except for the inside diameter which will either be 12 mm for the deployer shaft or 4 mm for the motor shaft. They contain the same parameters and set screw location. In Figure 60 below, gears shaft is mounted in the lathe with a center-hole about to be drilled into it.

Figure 60. Using lathe to drill concentric 12 mm hole into gear shaft.

The long stock allows for us to have an abundance of extra gear material to account for mistakes and for us to make multiple sets. But we were able to cut, drill, and tap 2 gears within 1 day of manufacturing. Figure 61 below shows the completed gears used.

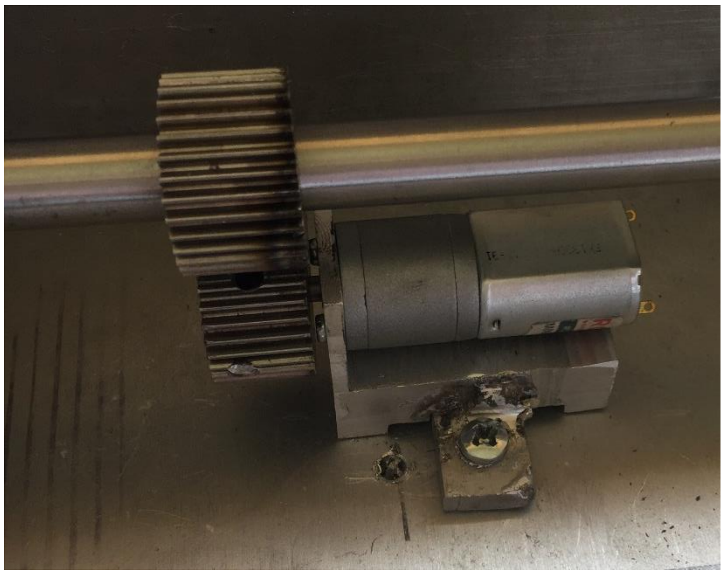

Figure 61. Completed gears mounted on main shaft and motor.

5.8 Mounting of Motors

The motors used are the 26 rpm Mini Econ motors purchased from ServoCity which required motor mounts to help attach them to the module housing. The mount is connected to the motor and then using the extra threaded holes on the motor mount, will be mounted to an aluminum 6061 angled motor mount that we manufactured in the Cal Poly machine shops using an end mill. The end mill was used because the angled mount has only flat surfaces perfect for milling. The assembly for the boom deployer motor mount is shown below in Figure 62.

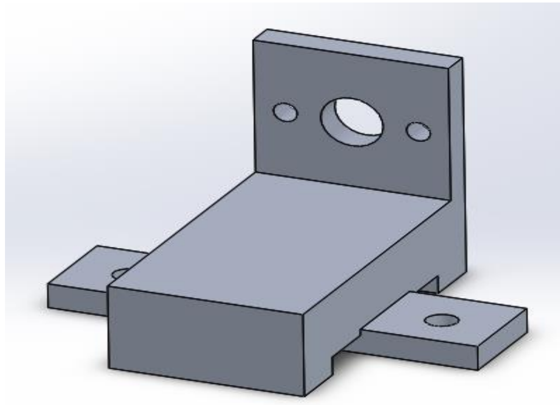

Figure 62. CAD Model of the Boom Deployer Motor Mount.

The completed motor mount can be seen in the previous section in Figure 61. It can be seen that the bottom plate is welded on. This was performed with the help of the Cal Poly Shop techs. Although because of the small nature of the motor mount and our inexperience with welding equipment, it was decided that for the feed motor mount below, we bolted the bottom plate onto the mount to avoid the unsightly nature of the welding job.

The motor for the feed deployer will be mounted in a similar fashion with an angled aluminum mount but instead is fastened to the power transmission housing. The power transmission housing will be manufactured using the same type of aluminum as the motor mounts using an end mill. The power transmission housing is then mounted to the back of the storage volume using threaded holes and M4 x 0.7 mm fasteners. The feed motor, shown below in Figure 63 is connected to the feed deployer via a 4mm to 12mm shaft coupler purchased from ServoCity.

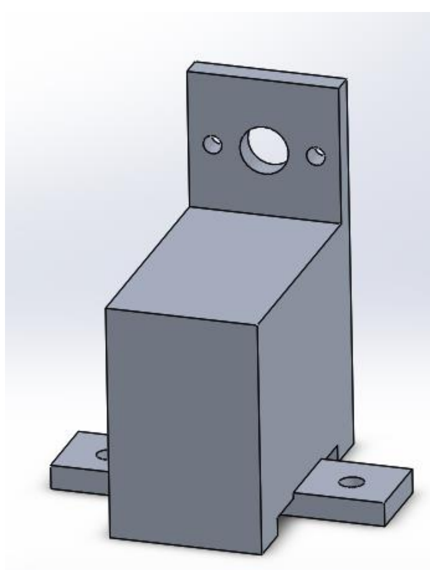

Figure 63. CAD Model of the Feed Deployer Motor Mount.

The timing for this mount assembly took an estimated 2 weeks to get fully assembled due to the high demand of the end mills. The completed feed motor mount can be seen in Figure 64 below.

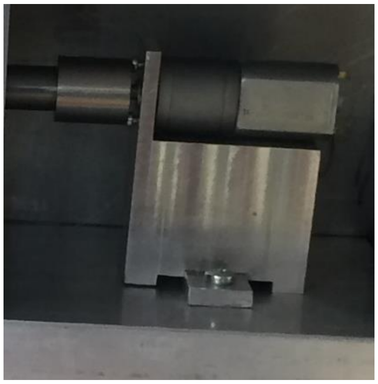

Figure 64. Completed feed motor mount

5.9 Manufacturing of Mylar Reflector

The Mylar reflector was purchased from Amazon due to the fast lead time and low cost. The Mylar sheet needed to be 2 m x 1m and is approximately 2 mils thick. Extra Mylar and tape was used to create the strips needed for embedding the ribs and for if the Mylar gets damaged. The sleeves needed for the booms were made from extra mylar attached to the bottom of the Mylar using tape.

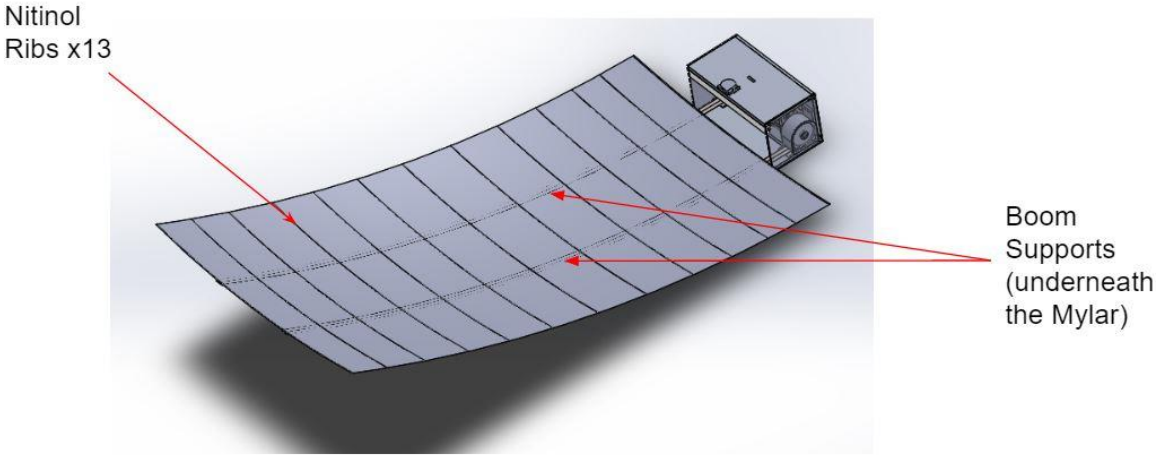

Figure 65. Rib and Boom position in Reflector

Construction of the Mylar reflector heavily depended on the lead time of the nitinol ribs, which arrived on May 23, 2017. Once the ribs were obtained, the construction of the Mylar reflector took less than a day. The completed reflector containing nitinol ribs is shown below in Figure 66. This reflector is not being tensioned in the lengthwise direction.

Figure 66. Completed nitinol reflector.

It can be seen from the image above that the horizontal curvature is slight even with the additions of the nitinol rods. While the curvature is very slight in the design. The weight of the reflector is weighing down the rods slightly.

5.10 Components and Fasteners

All the fasteners mentioned above will be purchased from McMaster-Carr and doubled in case they are lost or broken. The bearing for the deployers will also be purchased from McMaster-Carr. The bearings will be press fit onto the shaft in their correct location on the deployers.

5.11 Assembly

The antenna housing was the first to be assembled. This gave us a good idea of how much space we had to work with as well as all the mounting points need to put all the components together. The housing assembly including a 3d printed polycarbonate stopper, printed by Stellar Exploration, Inc. as well as the newly included acrylic side walls, is shown below in Figure 67.

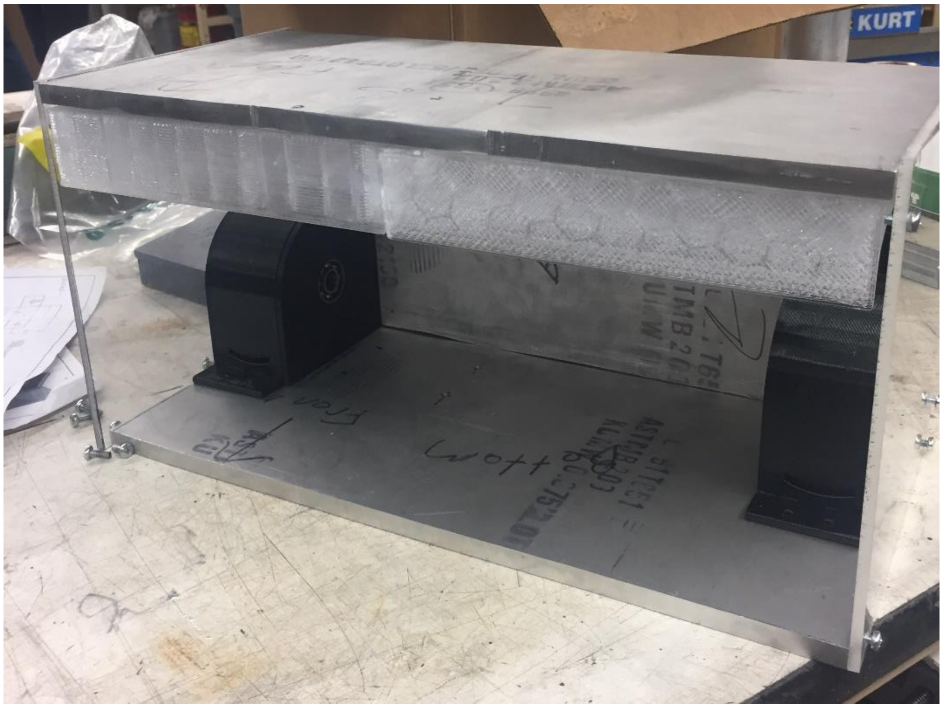

Figure 67. Completed housing assembly.

The reflector deployer assembly consists of the two horizontal reflector deployers, their spools, and their booms. The deployers and fully extended and tensioned booms can be seen in Figure 68.

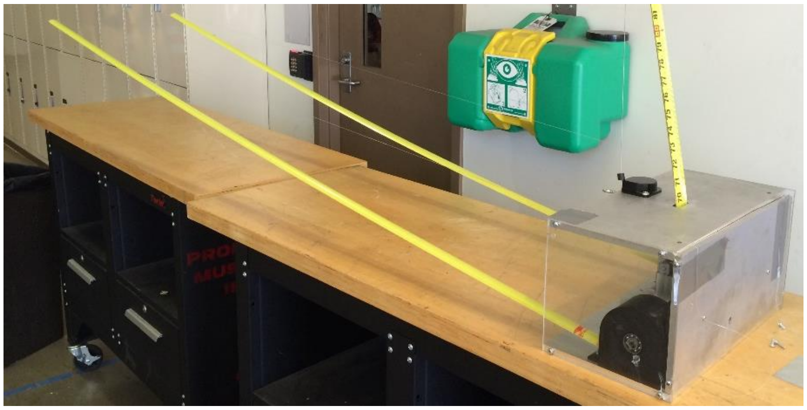

Figure 68. Fully extended deployer assembly with acylic plexiglass side walls and tape measure material booms.

The feed deployer assembly is put together and mounted to the top of the power transmission housing. This can be seen below in Figure 69 below.

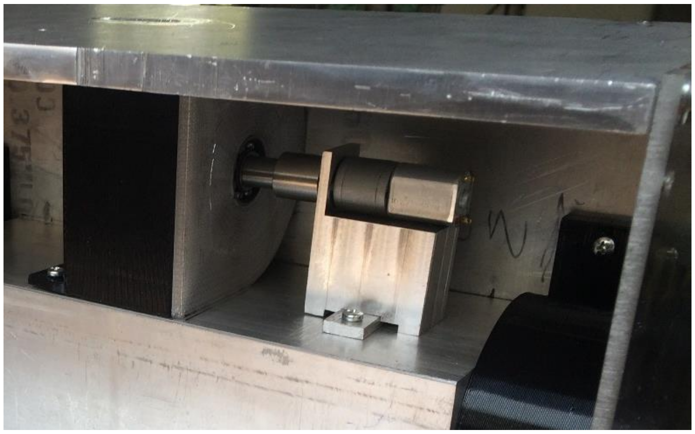

Figure 69. Feed deployer assembly.

The power transmission includes the main shaft, the main motor mount and motor, the gears, and the bearings used. This power transmission is used to drive the two main horizontal reflector deployers. The power transmission is covered by the power transmission housing which is mad of aluminum 6061 angle purchased from Mcmaster-Carr. The main motor is powered by a variable voltage power supply that is wired to the motor and connected to the wall outlet.The power transmission assembly, minus the housing, can be seen in Figure 70 below.

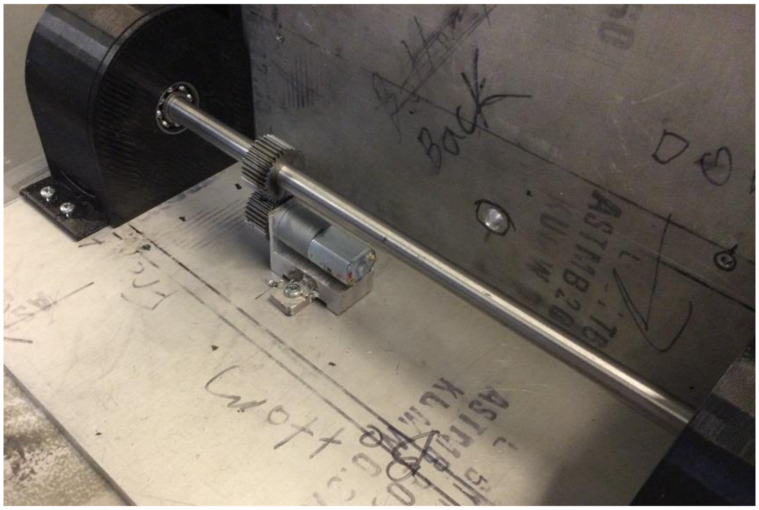

Figure 70. Power transmission to reflector deployers.

The reflector assembly containing the Mylar reflector material, the nitinol ribs, the boom collars and string tensioners and the fully manufactured prototype can be seen below in Figure 71.


Figure 71. Final manufactured reflector and deployer prototype.

5.12 Final Prototype

The final prototype differs from the planned design in ways that have been mentioned above and in some additional ways. The first way it differs is the use of acrylic side plates Instead of additional aluminum side plates. This was recommended by our sponsor and was intended to help see what was going on inside the module. This proved to be very beneficial in troubleshooting various problems.

Another way that the final prototype differs from the planned design is the use up upside-down tape measure material booms as opposed to heat-treated booms or flat spring steel booms. We noticed during testing that the tape measure material acts much more favorable when rolling up and deploying than spring steel does. It can also be pulled into a parabolic shape with tensioners much more easily than spring steel. Because of this change, the exit slots in the deployer casing needed to be widened.

When tensioning the horizontal booms, the tensioning points need to be in line with the booms as opposed to mounted in the middle using the eyebolt. So screws were mounted to the back of the module that alow the string tensioners to be tied around and remain in line with the booms. These changes can be seen in Figure 71 above.

Also, when considering how to power our motors, we thought it would be beneficial to use a variable voltage power supply that plugs into a wall outlet. This was to determine what voltage works best for our deployment module. The voltages range from13.5 V, to 18 V, and up to 30 V.

We tried up to 18 V but noticed we were breaking more motors at that high voltage and decided to keep it at 13.5 V.
Another difference is the amount of ribs used. When trying to maximize space we noticed that having the reflector folded as tightly as we could only allows for five ribs as opposed to the thirteen ribs we designed for. The ribs we received are also much shorter than design for, 24 inches rather than a meter, so they had to be doubled up. Doubling the ribs per fold would mean we would not have enough ribs if we decided to use 13 full length ribs.

Finally, when considering our feed deployment mechanism, we felt a constant force reel would help stabilize our feed boom but, it hindered it instead. So our prototype is unable to deploy right-side up. However, after removing the constant force reel, and deploying the feed upside-down (simulating no gravitational effects), the feed boom deploys straight down to its full length of 2 meters. The full prototype extended, and stowed can be see below in Figure 72.

Figure 72. Final Prototype (Extended and Stowed)

5.13 Cost Analysis

We performed a comprehensive cost analysis shown in Appendix F. The cost has been broken down by each sub-assembly for estimates for each manufacturing phase.

The antenna housing and all the stock components used to assemble it costs $155.91. The reflector deployer assembly will cost approximately $134.36. was a much higher estimate when considering heat treated booms, but has since drastically decreased in price from our use of booms made from tape measure material. The power transmission costs $281.97. The feed deployer will cost $58.57 and the reflector assembly will cost $821.95. This large price point is due to the custom ribs ordered from Fort Wayne Steel in order to shape our reflector. Additional fasteners, motors, manufacturing supplies, and simple components such as the microfilament fishing line and power supplies cost $174.92.

When including the cost of shipping to be approximately $93.82, we can estimate our total cost to be $1,627.85. This meets our engineering specification of being less than $3000.

5.14 Maintenance and Repair

There is little to no need for maintenance and repair of our prototype since our components will not undergo any large loads or excessive lifetime cycles. However, there have been a few cases of overexerting our motor and having to replace them. The motors are quite inexpensive so they are easy to replace. The only aspect of the design that we have repeatedly adjusted is the folding and storage of the Mylar reflector as well as after deployment since it will experience the most drastic movements from storage to deployment. In that sense, the reflector is most prone to fatigue and possible tear; thus, the Mylar will need to be replaced and the Nitinol rods and sleeves will need to be reinstalled accordingly. Since the cost of Mylar is relatively inexpensive and can be purchased in bulk quantities, maintenance and repair costs are low. Nitinol, our most expensive component is also our strongest and most resilient so it is doubtful that these will ever need replacing.

5.15 Safety Considerations

The main safety concern associated with our deployment module lies with the rotary motion of the gears and shaft. Possible safety hazards include getting body parts or hair caught in the rotating objects which can cause injury. To mitigate this safety hazard and limit potential interference with the reflector, we designed an inner housing to prevent accidental access to the rotating gears and shaft. Our project includes the use of highly elastic materials, such as stainless steel and Nitinol, which are prone to violent movements after being deflected and released. This causes the potential hazard of accidentally hitting people. To mitigate this risk, we will wear safety glasses when handling highly elastic objects. Another safety concern lies in the manufacturing and machining of our components. As we are responsible for the prototype to be built, it is impossible to completely avoid this risk. To limit the risk of injury, we will abide by all the rules set forth by the Cal Poly machine shop and always wear personal protective equipment (PPE) when operating machinery.

5.16 Resources and Timing

A list of resources is presented in Appendix F. This document is a list of all the supplier we will use over the course of the manufacturing of our deployable antenna. It also contains shop resources and personnel that are required for the completion of our project.

An additional schedule is located in the Gantt Chart in Appendix B that details our time estimates for each manufacturing phase. These phases include: ordering of long lead parts, storage volume assembly, reflector deployer assemblies, power transmission assembly, feed deployer assembly, reflector assembly, and full antenna deployer assembly. These phases may overlap in order to create a finished product by May 2017 and be ready for testing.

It should be noted that delays are very likely and that these time estimates are just a guide for us to maintain focus.

Chapter 6: Design Verification

The testing of our built prototype quantified how close our prototype met the original engineering specifications. While a deployable antenna for a CubeSat may be intended for space, our prototype was not, and we measured performance based on Earth's 1G gravity and at room temperature. This should be kept in mind when analyzing the results and assessing the effectiveness of our prototype. It is also worth noting that we originally planned to run tests such as a shake table test to simulate launch loads and temperature tests to simulate low-earth orbit temperatures. As mentioned previously, the shake table test and temperature tests were omitted since it was decided that we should focus on achieving a successful deployment rather than preparing for an actual launch.

One of the key components to a successful satellite, aside from the reflector, is the feed that the reflector bounces signals towards. Although we were not responsible for building a working feed, we still needed to simulate the mass of the feed by using a steel cylinder. Our original goal for the feed was to successfully be able to deploy the mass 2-meters in length straight up, and we attempted to accomplish this by using a constant force reel to balance the weight of our cylinder. When we tested this method, it proved to be successful up to about half of a meter. After half of a meter, the feed boom twisted and eventually buckled due to the constant force reel pulling the boom down in one direction. One possible solution to this would be to use more constant force reels to balance the load, but this seemed unnecessary since this would only solve the issue of deploying the feed in 1G, and would not be useful in actual space applications. Understanding that the original intent of the reel was to offset the effect of gravity, we performed another test by deploying the feed upside down, and the feed struggled to deploy with the constant force reel and deployed flawlessly without it. This confirmed our suspicions that gravity would have an enormous impact on our ability to deploy the feed from our prototype. This test can be seen in Figure 73 below.

Figure 73. Upside-down feed deployment test

We performed a number of tests to assess the ability of our prototype to deploy a curved shape for the parabolic reflector. We began by perfecting the deployment of straight booms before we added the strings to tension the booms into a curved shape. Figure 74 below shows the initial testing of our booms and string tensioners. In these tests, we had the booms initially start in their deployer housing, then turned them on to see them unwind into their shape. It took a lot of fine tuning of the strings before we decided by inspection that the deployed curvature was acceptable to add the Mylar reflector.

Figure 74. Initial testing of the booms with string tensioners.

After we successfully achieved an acceptable curvature with just the booms and strings, we added the Mylar reflector to the ribs. Since our order for the Nitinol that we used for the ribs took so long, we initially installed the Mylar reflector without ribs, and fastened them to the booms with several collars as detailed earlier in this report. This allowed us to test if our theoretical zig-zag folding method for the reflector would actually succeed. Figure 75 below shows that we were successfully able to fold the Mylar as originally planned which validated that our planned folding method would be effective.

Figure 75. Side view of folded Mylar reflector stored in housing.

We then tested the deployed shape of the reflector with metal wire rather than the Nitinol ribs, which initially gave the reflector an imperfect look, but still managed to simulate a similar load and stiffness to the actual ribs. This proved that the booms would be able to sustain the weight of the Mylar and the ribs in a 1G environment.

When we finally received the shipment for the Nitinol, we embedded them into the Mylar, and performed the deployed shape test again. This time, the shape was much more visually appealing and there looked to be potential for the geometry to be close to the theoretically exact shape. Finally, we attempted to run a full deployment by initially folding the reflector along with the embedded Nitinol ribs from the deployed position into the main housing. When it was fully stored in the housing, we attempted to run the deployment by starting the motors. Unfortunately, after several different attempts, the motors were unable to push the reflector out of the housing since the ribs expanded in the storage volume and created too much friction to exit as planned. We initially supplied the motors with 13.5 V, but after that failed a few times, we supplied the motor with 18 V. After several iterations of this, the motors finally burned out. Although the deployed shape proved to be parabolic as designed, the final tests of the entire prototype deployment ended up being a failure, and the recommendations to improve this for future designs are detailed in the next section.

Figure 76. 3-D scanning the reflector (spray painted black) to assess shape.

One of the highest risk engineering specifications was the parabolic tolerance of the reflector at its fully deployed position. This also had one of the most vulnerabilities towards skewness from Earth's gravity (aside from the feed), which would not be an issue if our prototype was in space. In order for the antenna feed to receive S-band communication signals, the reflector must be within 0.5 cm of the ideal shape at all points on the reflector. For us to measure the accuracy of the shape, our team used Cal Poly Innovation Sandbox's Microsoft Xbox Kinect to take a three-dimensional scan of our prototype. The three-dimensional scan was taken as a .stl file and we hoped to convert this to a .sldprt file in SolidWorks, for further analysis. However, the 3D scan was too fuzzy and we were not able to repair the scans we took enough since they had too many faces to import to SolidWorks. Instead, we used a measuring tape to measure the vertical height at 12 difference locations along our deployed reflector. From there, we compared it to the ideal meshed geometry which revealed heights at 5 cm intervals and exported these node locations to MATLAB. Our MATLAB code, shown in Appendix H.2, compares the measured points to the theoretical points and outputs an rms (root-mean-square) error using the calculation taken from www.navipedia.net:

$$\text{rms vertical error} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \Delta U_i^2}$$

where i is the index for each nodal location corresponding to a fixed location, n is the total number of nodes measured, and ΔU_i is the difference in vertical height from the ideal shape to the shape of our prototype at location i. This value is subject to the accuracy and precision of our tape measure value, which is why we only take into account nodes spaced 5 cm apart. Any more nodes would not necessarily yield a more accurate rms error.

We determined the rms error to be 15.2 cm which indicates that we were far from our original goal of 0.5 cm. We had expected a large error since we struggled obtaining the proper curvature throughout the project. A more qualitative assessment of the accuracy of our deployed reflector is shown below in Figure 77 where we placed the ideal shape next to the 3D scanned model. The inaccuracy is clear in this images.

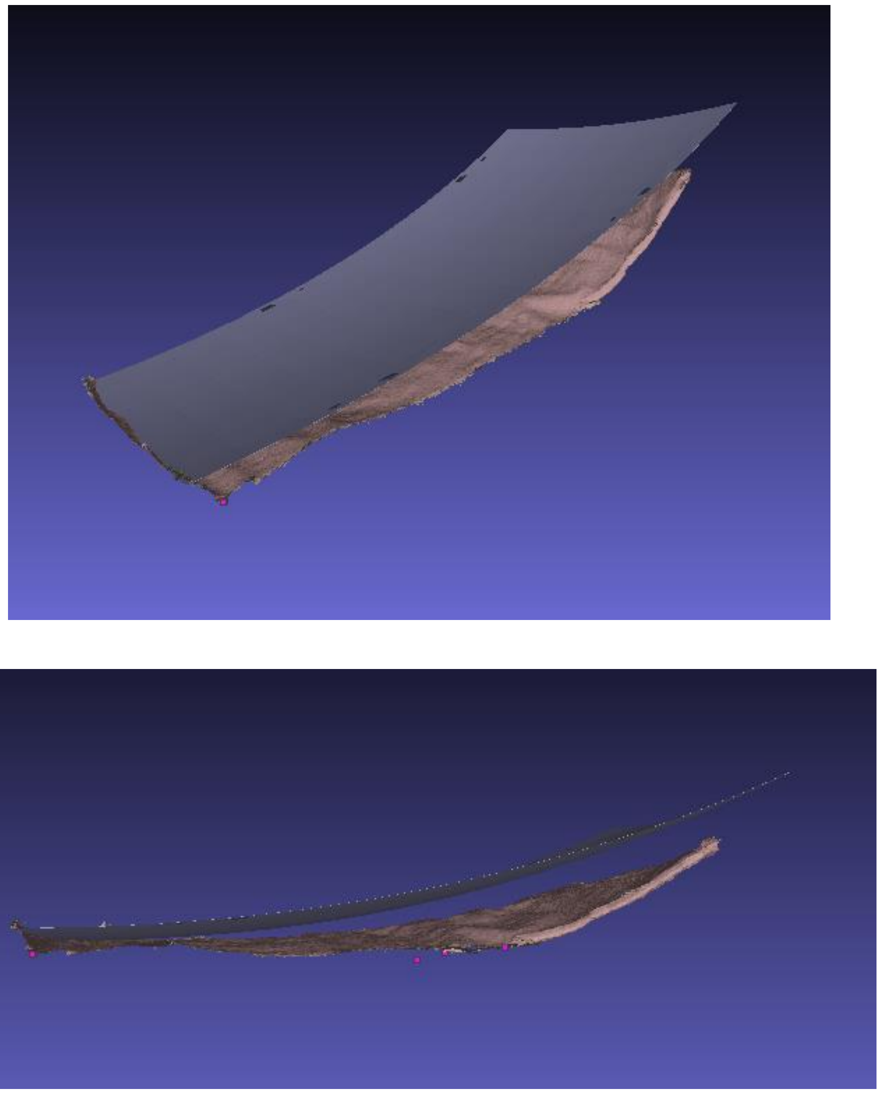

Figure 77. Ideal Parabolic Reflector overlaid with the 3D scanned reflector.

In order to assess if our prototype met the weight requirements, we weighed the prototype on a typical bathroom scale. We measured the weight of our prototype to be 19 lbs. which was successfully under our maximum weight requirement of 50 lbs.

To determine how much power our prototype used during deployment, we used a digital multimeter and measured the power supplied to the motors. We measured the power consumption of the deployment to be 10.8 W which was under our maximum power requirement of 10 W.

Each test is described in more detail in the Design Verification Plan (DVP) in Appendix D and summarized in the table below.

Table 6. Summary of original requirements and testing results.

Parameter	Requirement	Result
Reflector Size	2 m x 1 m (L x W)	Pass: Size very close to goal
Shape Tolerance	λ/20 (0.5 cm for 3 GHz signal)	Fail: Crinkled reflector, non-ideal curvature, approximations made
Storage Volume	20 cm x 20 cm x 40 cm	Pass: neglected feed
Weight	50 lbs	Pass: 19 lbs
Power Requirement	10 W	Fail: 10.8 W
Budget	$3000	Pass: $1627.85

Chapter 7: Conclusions and Recommendations

The design and manufacture of a small unit which can deploy a large parabolic reflector is no simple task, and our team has an increased appreciation for why this has never been done before. Among the more challenging aspects of the problem are achieving the complicated curvature (and doing so accurately), deploying in two directions (both with their own curvatures), packaging the reflector into the small housing, and (in our case) enabling the prototype to work in a standard Earth gravity environment. To summarize the main points of our prototype's results, the small storage volume requirement was met with the exception of a couple small items and the small amount of reflector that sticks out, the fully-deployed half-antenna size is slightly under the stated goal of 2m x 1m but still within reach of the target, and the reflector curvature is well out of the specified tolerance goal and has many wrinkles, yet still follows a general parabolic shape. Most unfortunately, the prototype cannot actually deploy the antenna as intended. The feed can be successfully deployed only when oriented upside-down, and because the reflector is so bunched in the housing and the ribs press so firmly against the walls, there is too much resistance for the selected motor to be able to push out the booms and deploy the reflector in the length direction.

A number of manufacturing errors contributed to the issues experienced with the final prototype. One of the major issues during testing was that the two reflector booms would not deploy evenly and were never quite in the same position. We realized that this discrepancy occurred because of the way the spools were machined. One spool had the boom attachment point on the same side as the keyway, while on the other spool the attachment point was placed on the opposite side from its keyway. The result was that the booms were always 180° out of phase, since their keyways had to be aligned due to their sharing the same shaft. One boom was always slightly behind the other, leading to a somewhat uneven deployment. When the tensioners were applied, one boom would pull back into the deployer a little bit instead of tensioning the boom upward as intended, making the reflector slightly lopsided. Correctly machining the two spools to match each other would mitigate this issue.

During a discussion late into the detailed design phase, it was suggested that the side plates of the housing be made of plexiglass instead of aluminum so that one could see the internal components of the prototype. This idea was adopted without thinking to change any of the other housing plates, namely the top plate, to plexiglass. The plexiglass side plates developed some cracks under the weight of the 10cm thick top plate. In hindsight, we realized that aluminum was definitely not needed for the top plate for our purposes, so if a similar prototype were to be developed, that plate could also be made of plexiglass. However, for prototypes and eventual products intended to endure launch loads and space conditions, aluminum is definitely recommended over plexiglass for the sake of strength and structural integrity of the housing.

Another problem which perplexed our team for several days involved the tape measure being used for the booms. After performing some initial deployer testing, it was observed that the tape measure had been cut to a length of 2m, while it actually needed to be around 2.15m, since the boom must reach a length of 2m after being curved. New tape measure strips were cut to this length from the same tape measure as the first ones. After installing the new booms into the deployers and attempting more deployment tests, the observed behavior was significantly worse in that the tape measure would get bunched up in the reflector and struggled to actually extend, and when they did it was with very jerky, discontinuous motions. Eventually we discovered that the axial curvature of the tape measure steel actually changes slightly along its length, and that this difference in curvature led to the different boom behaviors observed. The longer booms, which were cut from segments that were further in to the coil of tape measure, were found to be less curved and more flattened out, thus being wider and more easily jammed at the deployer exits. To avoid this problem (assuming actual tape measures are still to be used in further prototype iterations), the booms should be cut close to the free end of different tape measures of the same type. Unfortunately, our team did not have time to get a fresh tape measure and cut new booms, so the original booms were used and thus the prototype’s reflector is a little bit smaller than the stated goal of 2m when curved.

Although Fort Wayne Metals was found to be the vendor who could supply us with the parabolic Nitinol ribs within the time and monetary constraints of our project, the longest Nitinol wires they could produce were 2ft, and the design calls for ribs that stretch the entire width of the reflector (1m). Because Fort Wayne Metals required a minimum purchase of 25 ribs and we only used 5, extra ribs were used to place two ribs side by side at each fold in the reflector so that the combined ribs reached across the entire width. While this gave the reflector better structural integrity and was certainly better than letting the unsupported edges of the Mylar sag, placing the two ribs side by side inevitably changes the curvature they provide. While the difference was not noticeable visually, this factor should be considered for future iterations. Our team recommends that another vendor or process be selected that can produce full-sized 1m ribs.

During the completion and testing of our final prototype, several design problems detrimental to the prototype's performance became apparent. Perhaps the most critical design flaw was in underestimating the amount of resistance the motor experiences from the bunched-up reflector and the friction resulting from the ribs pressing strongly against the interior of the housing. This effect was very difficult to predict before actually constructing the prototype and observing its behavior. The structure that the ribs provide to the reflector prevented it from folding in clean accordion-style folds as we had hoped, developing many wrinkles in the Mylar. One way to look at this problem is to say that the friction from the reflector is too great and needs to be minimized; another way is to say that the motor underperforms and needs to be replaced with a larger motor with higher torque capabilities to overcome the friction and bunching, since at 18V and under stall conditions, the gears in the gear box of the motors use grind up and break.

The other significant design problem was the deployer design. Although the booms were successfully deployed without the ribbed reflector, throughout all deployment testing it was clear that the deployers were not ideal as the booms would jam and come out in jumps rather than one continuous, smooth motion. One factor of the poor deployer design was that it was originally designed for housing a heat-treated 17-7 steel boom, which we anticipated would require a larger coil diameter. Because heat-treatment was abandoned and actual tape measure was used for the prototype's booms, the outer coil diameter was much smaller than expected, and the boom had room to uncoil partially inside the deployer housing. The casing being too big led to jamming and irregular boom deployment. In general, there was a lot of friction between the tape measure and the deployer casing, especially at the exits, which had to be widened significantly. In hindsight, our team has decided that the main issue with the deployers is the driving method. Using the motor to directly drive the spool such that it pushes the boom out almost unavoidably results in some uncoiling in the casing as well as jamming as the edges of the tape measure get pressed against the exit geometry. Direct spool-drive seems more suited to pulling the booms in than pushing them out.

Another problem is that although the tape measure reflector booms were oriented upside-down to prevent them from snapping under the influence of the reflector's weight and the tension from the fishing line, one of the booms repeatedly snapped when placed under the tension required to lift the ends of the reflector to the necessary height. A likely reason for this is because this boom developed a slight kink in it, making it more susceptible to snapping, something which is possible to occur with these tape measure booms in this design.

With the current design, there is no place for the fishing line tensioners to coil or rest when the reflector is stowed inside the housing. The fishing line is simply tucked in with the bunches of the Mylar reflector and dangle around the top plate, which could lead to tangling.

A final design issue involves the feed deployment. As discussed earlier, the single tape measure boom and constant-tension cable were not sufficient to lift the feed mass to the full 2m height. It was suggested instead that since the feed's weight would not cause the observed buckling in space, that the test be performed upside-down. However, if it were desired to perform a straight up test in a standard gravity environment, more tensioning cables would be needed to balance the feed boom.

While the prototype certainly has a number of issues, our team believes that the overall design of our project is viable for achieving the stated goals, and with further development could be used to create a real, working CubeSat parabolic antenna deployer.

Several positive findings were made based on our final prototype. The Mylar used for the reflector is much tougher than expected and never showed signs of tearing, suggesting it as a good candidate for further iterations. Nitinol was also found to be a good material selection, as it allowed the ribs to undergo extreme bending yet still behave elastically and return to its original curvature when no longer constrained. Although the ribs pressing against the housing walls when in the stowed position prevented the motor from being able to deploy the reflector, the ribs did perform their role in deploying the reflector in the width direction when the reflector was pulled manually to unravel in the length direction. String tensioners were shown to be effective at achieving a curvature that mimics a parabola. The folding and unfolding techniques employed are plausible. Finally, all the booms were successfully deployed.

Given all of the problems and successes observed, our team decided upon several recommendations for Stellar Exploration, Inc, and any future teams attempting to improve this design and develop further iterations on the prototype. The first recommendation would be to continue to pursue the option to heat treat steel booms such that they can coil up and then uncoil into the desired parabolic curvature. Our team was unable to fully investigate this possibility due to lack of time, miscommunication with the heat treatment specialist we were in contact with, and little pre-existing knowledge of heat treatment processes. Although we struggled to find specialists who were willing and able to take on the job, it still seems like a possible solution which would avoid the complications of tensioning techniques and likely yield a more accurate curvature. If heat treatment is eventually decided to be impossible or otherwise impractical, then more research and testing should be conducted with string tensioning. Our design limited us to only tensioning the booms at the ends, but it's possible that alterations on the design could allow for several tensioning points which may provide more control and adjustability over the curvature. We suspect a large amount of testing would need to be conducted to fine tune the tensioners to yield the best shape, as the problem is very difficult to solve analytically. Another suggestion regarding the tensioners would be to include stepper motors and a microcontroller, which could be used to adjust the tensioners and booms to achieve the desired shape and even produce several different shapes for different antenna needs. A highly necessary change would be to improve the deployer design to reduce friction and jamming of the boom inside the casing. We recommend using a tighter-fitting casing so that the coil is not free to expand and bunch up, and also to change the driving method from being spool-driven to driving a roller or pair of rollers at the deployer exit to pull the boom off the spool, as this pulling action will likely be much more successful than the pushing action of the motorized spool. Also, future teams working on this project should search for a vendor who can supply Nitinol ribs of the full 1m long length to avoid having to double them up. A smaller diameter of Nitinol could also probably be used to strike a better balance between being rigid enough to support the reflector but also not press so hard against the housing module walls when stowed. More ribs could be embedded along the reflector to improve the overall shape, but this will affect the way the reflector must be folded and stowed. In the long run, the deployers, drive mechanism, and the rest of the deployment unit ought to be scaled down to fit two more reflector deployers, another motor, and another ribbed reflector into the housing for deploying the other side of the antenna. The entire project eventually would need to be scaled down further to match actual, practical CubeSat volumes. Finally, the project should undergo another level of design and zero-gravity testing to meet the challenging conditions of space and to survive the launch loads and vibrations associated with rocket travel.

Although our prototype suffered a number of issues, we believe we have demonstrated that this style of deployment could work to successfully deploy a parabolic antenna reflector from a CubeSat. We hope that we have provided Stellar Exploration, Inc with a useful prototype and plenty of key research, data, and suggestions for the future of this project. Working on this project has been a very beneficial and challenging learning experience for our team, and we are all grateful for the opportunity. We wish future teams working on this project the best of luck!

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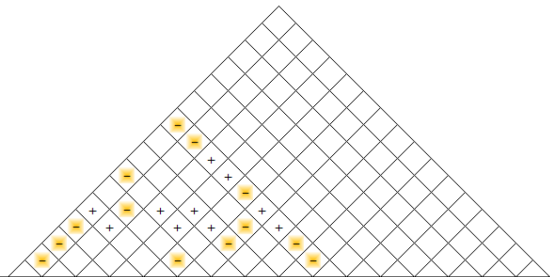
Appendix A: QFD Diagram

QFD: House of Quality
Project: Depolyable Antenna for CubeSat
Revision: 1
Date: 10-20-2016

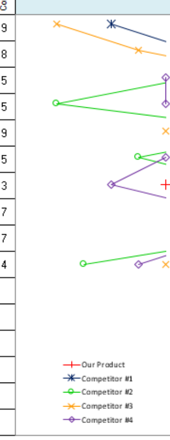
Correlations	
Positive	+
Negative	–
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

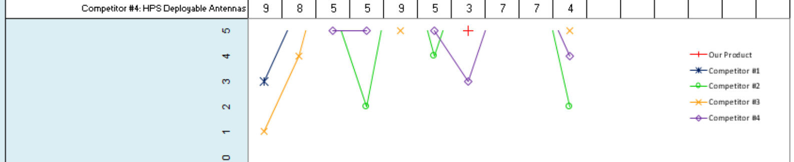


								HOW: Engineering Specifications	Size	Tolerance of Reflector Shape	Deployment Power Consumption	Stored Volume	Capable of S-Band Communication	Type of Suppliers & Materials	Weight	Resistance to Forces & Vibrations	Operating Temperature Range	Budget/Cost							NOW: Current Product Assesment - Customer Requirements					
								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
			WHO: Customers					Direction of Improvement	▲	◇	▼	▼	◇	▼	▼	▲	◇	▼												
Row #	Weight Chart	Relative Weight	Stellar Exploration	Military	Aerospace Companies	Commercial Usage	Maximum Relationship	WHAT: Customer Requirements (explicit & implicit)																	Our Current Product	Competitor #1: USC Aeneas *(Folding Umbrella)*	Competitor #2: *Northrop Grumman Astromesh*	Competitor #3: Dipole Antenna System - ISIS	Competitor #4: *HPS Deployable Antennas*	Row #
1		15%	9	7	9	7	9	Impressively Large Antenna (>= 2m x 1m)	●	○	▽	●	○	○	○	▽	▽	●							9	3	9	1	9	1
2		16%	8	9	8	9	9	Accuracy of Parabolic Shape (Effective Antenna)	●	●	▽	▽	●	○	▽	▽	▽	○							8	6	7	4	8	2
3		4%	2	2	2	2	9	Reasonable Power Consumption During Depolyment	○	▽	●	▽	▽	○	▽	▽	▽	○							6	8	6	9	5	3
4		15%	9	8	9	7	9	Reasonable Deployment Package Volume	●	▽	▽	●	▽	○	●	▽	▽	▽							8	9	1	9	5	4
5		12%	6	7	7	7	9	Useful Range of Signal Relay Capability	○	●	▽	▽	●	○	▽	▽	▽	▽							7	9	9	5	9	5
6		7%	6	3	3	4	9	Use mostly COTS Components	○	○	○	○	○	●	▽	○	○	●							8	8	4	9	5	6
7		2%	1	1	1	1	9	Lightweight Product	○	▽	▽	●	▽	▽	●	○	▽	▽							5	8	8	9	3	7
8		13%	7	7	7	7	9	Able to Endure Launch Loads	▽	▽	▽	▽	▽	○	○	●	▽	○							8	8	8	7	7	8
9		11%	6	6	6	6	9	Design for Range of Temperatures in Space	▽	▽	▽	▽	▽	○	▽	▽	●	○							8	8	8	6	7	9
10		5%	3	1	3	5	9	Fairly Low Cost	●	○	○	▽	▽	●	▽	○	○	●							7	6	2	5	4	10
11		0%																												11
12		0%																												12
13		0%																												13
14		0%																												14
15		0%																												15
16		0%																												16



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target	>= 2m x 1m	<= λ/20	< 100 W	<= 20 cm x 20 cm x 40 cm	S-Band (2-4 GHz)	0 Customization	< 50 lbs.	Withstand 50g Acceleration	0 °C to 30 °C	<= $3000						
Max Relationship	9	9	9	9	9	9	9	9	9	9						
Technical Importance Rating	557.51	379.35	154.86	367.62	368.47	372.68	290.87	232.05	213.67	405.45						
Relative Weight	17%	11%	5%	11%	11%	11%	9%	7%	6%	12%						
Weight Chart																
Our Product	9	8	6	8	7	8	5	8	8	7						
Competitor #1: USC Aeneas (Folding Umbrella)	3	6	8	9	9	8	8	9	9	6						
Competitor #2: Northrop Grumman Astromesh	9	7	6	2	9	4	8	8	8	2						
Competitor #3: Dipole Antenna System - ISIS	1	4	9	9	5	9	9	7	6	5						
Competitor #4: HPS Deployable Antennas	9	8	5	5	9	5	3	7	7	4						
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Current Product Assesment - Engineering Specifications

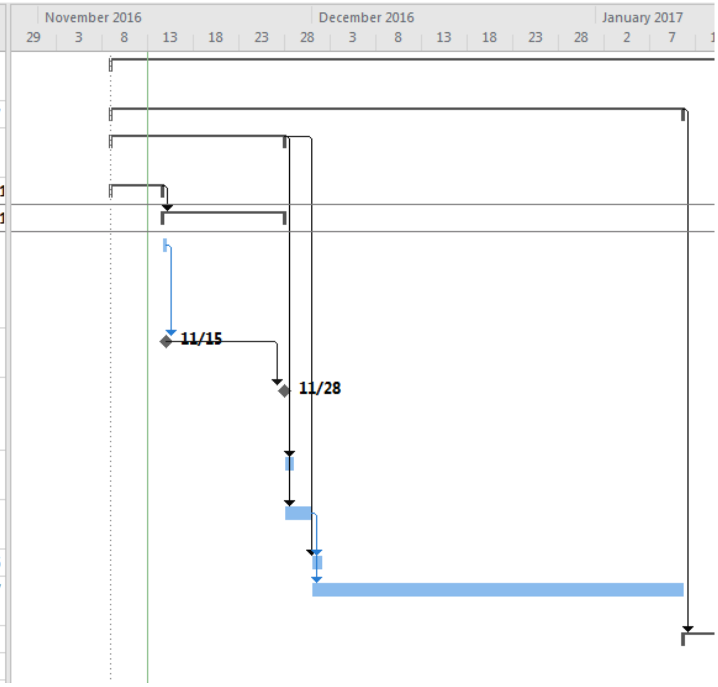


Template Revision: 0.9 Date: 4/23/2010
Christopher Battles

Appendix B.1: Planned Gantt Chart

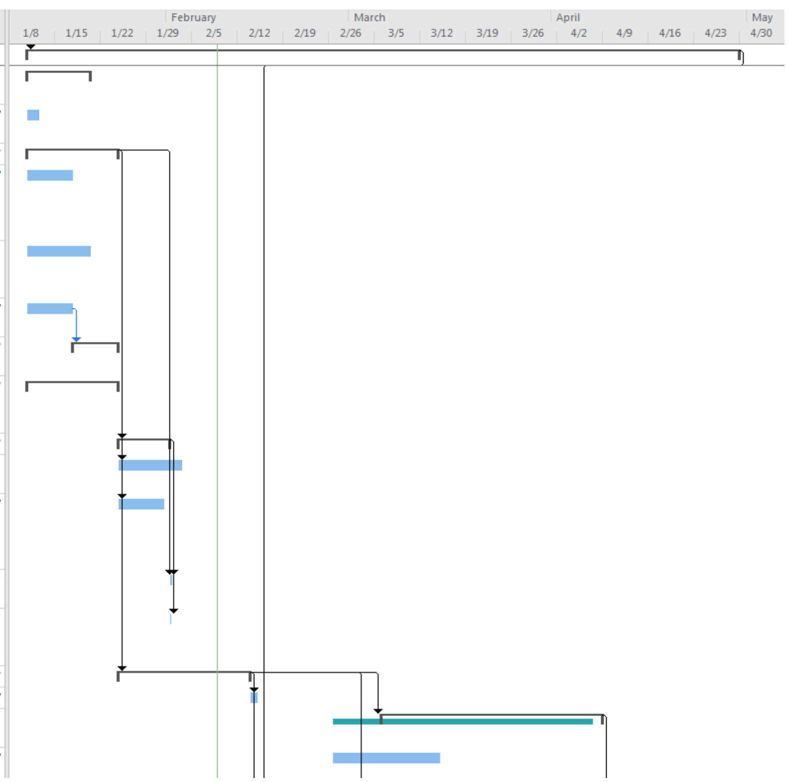
Fall Quarter

Task Name	Duration	Start	Finish
Senior Project - Deployable Antenna	**126 days**	**Wed 11/9/16**	**Thu 6/8/17**
ME 428 Requirements	**13.17 days**	**Wed 11/9/1**	**Tue 1/10/17**
Preliminary Design Review	**8.17 days**	**Wed 11/9/16**	**Mon 11/28/16**
Report	**3.75 days**	**Wed 11/9/1**	**Mon 11/14/1**
Presentation	**4.42 days**	**Mon 11/14/1**	**Mon 11/28/1**
Make PDR Presentation PowerPoint & rehearse	3 hrs	Mon 11/14/16	Mon 11/14/16
PDR Presentation to Advisor and	0 mins	Tue 11/15/16	Tue 11/15/16
PDR Presentation/Revi with Sponsor	0 mins	Mon 11/28/16	Mon 11/28/16
2nd Team Evaluation & Reflection	1 day	Mon 11/28/16	Mon 11/28/16
FMEA, DVP, & Analysis Plan	3 days	Mon 11/28/16	Wed 11/30/16
Update Gantt Chart	1 day	Wed 11/30/1	Thu 12/1/16
Make a list of long-lead parts	2 days	Wed 11/30/16	Tue 1/10/17
ME 429 Requirements	**55.83 days**	**Tue 1/10/17**	**Mon 4/3/17**
ME 430 Requirements	**57 days**	**Mon 4/3/17**	**Thu 6/8/17**



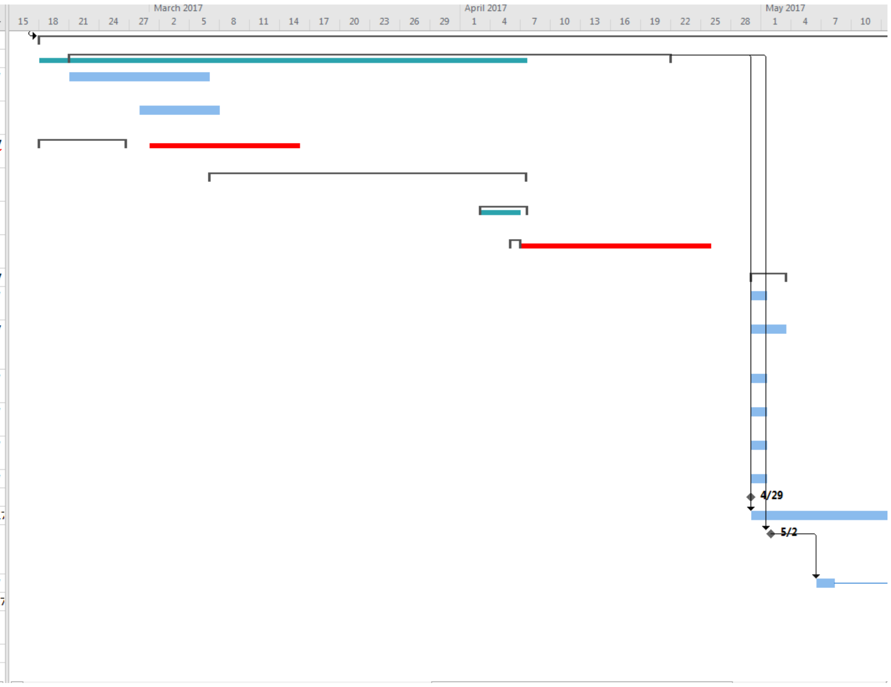
Winter Quarter

Task Name	Duration	Start	Finish
ME 429 Requirements	**79 days**	**Tue 1/10/17**	**Sat 4/29/17**
Material Selection and Initial Design	**9 days**	**Tue 1/10/17**	**Fri 1/20/17**
Order all long-lead parts	2 days	Tue 1/10/17	Thu 1/12/17
Design Analysis	**12 days**	**Tue 1/10/17**	**Tue 1/24/17**
Detailed Design of Module Housing and Reflector Containment	1 wk	Tue 1/10/17	Tue 1/17/17
Detailed Design of Deployer spool and housing	1.5 wks	Tue 1/10/17	Fri 1/20/17
Determine and size appropriate motor	1 wk	Tue 1/10/17	Tue 1/17/17
Detailed Design of Power Transmission	**6 days**	**Tue 1/17/17**	**Tue 1/24/17**
Design Motor Control System and Develop Initial Code	**12 days**	**Tue 1/10/17**	**Tue 1/24/17**
CAD Modeling	**7 days**	**Tue 1/24/17**	**Wed 2/1/17**
Initial Prototype and Non-Parabolic Testing	1.5 wks	Tue 1/24/17	Fri 2/3/17
(If heat treatment fails,) Design Back-up plan of String Tensioners	1 wk	Tue 1/24/17	Tue 1/31/17
Develop Bill of Materials	3 hrs	Wed 2/1/17	Wed 2/1/17
Schedule CDR Presentation with Sponsor	1 hr	Wed 2/1/17	Wed 2/1/17
Critical Design Review	**17.33 days**	**Tue 1/24/17**	**Tue 2/14/17**
3rd Team Evaluation	1 day	Tue 2/14/17	Tue 2/14/17
Complete Parts Ordering	**14.75 days**	**Mon 3/6/17**	**Sat 4/8/17**
Order and Heat Treat Rooms	14 days	Sun 2/26/17	Tue 3/14/17



Spring Quarter

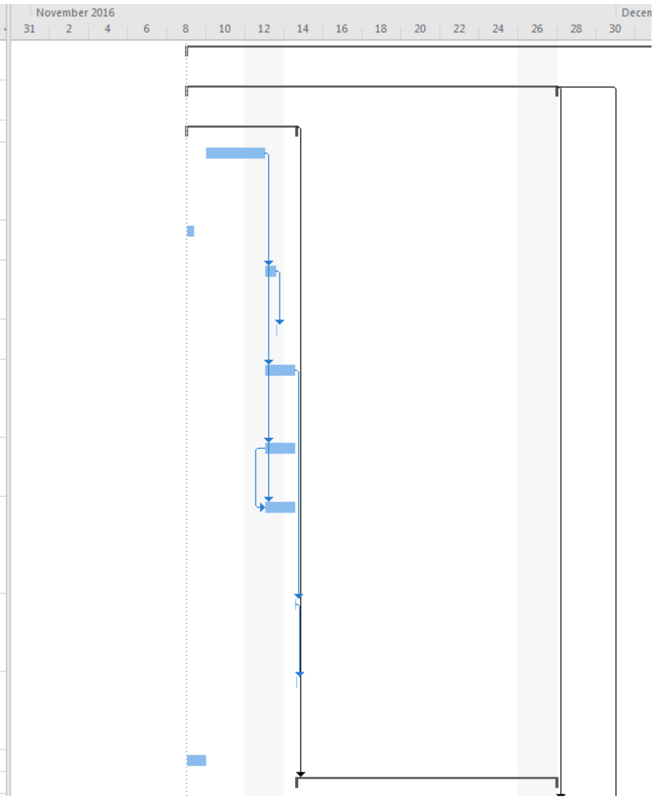
Task Name	Duration	Start	Finish
ME 430 Requirements	**79.5 days**	**Sat 2/18/17**	**Thu 6/8/17**
Prototype Construction	**37.25 days**	**Tue 2/21/17**	**Fri 4/21/17**
Housing Construction	2 wks	Tue 2/21/17	Mon 3/6/17
3D Print Stoppers and Deployers	6.75 days?	Tue 2/28/17	Tue 3/7/17
Reflector Deployer Manufacturing	**7.17 days**	**Sat 2/18/17**	**Sun 2/26/17**
Power Transmission Manufacturing	**13 days**	**Tue 3/7/17**	**Fri 4/7/17**
Feed Deployer Manufacturing	**5 days**	**Mon 4/3/17**	**Fri 4/7/17**
Reflector Manufacturing	**1 day**	**Thu 4/6/17**	**Thu 4/6/17**
Testing Phase	**3 days**	**Sat 4/29/17**	**Wed 5/3/17**
Meaure Size of Reflector	1 day	Sat 4/29/17	Mon 5/1/17
Measure Tolerance of Parabolic Reflector	3 days	Sat 4/29/17	Wed 5/3/17
Operating Temp Range	1 day	Sat 4/29/17	Mon 5/1/17
Deployment Power Consumption	1 day	Sat 4/29/17	Mon 5/1/17
Measure Stored Volume	1 day	Sat 4/29/17	Mon 5/1/17
Weight	1 day	Sat 4/29/17	Mon 5/1/17
Senior Survey	0 days	Sat 4/29/17	Sat 4/29/17
Project Testing	2.5 wks	Sat 4/29/17	Wed 5/17/17
Project Hardware/Safety Demo	0 days	Tue 5/2/17	Tue 5/2/17
5th Team Evaluation	1 day	Sat 5/6/17	Mon 5/8/17
Senior Survey	1 day	Mon 5/15/17	Mon 5/15/17
Final Design Report and Expo	**13.83 days**	**Wed 5/17/17**	**Fri 6/2/17**
6th Team Evaluation	1 day	Wed 6/7/17	Thu 6/8/17
Final Checklist	3 days	Mon 6/5/17	Thu 6/8/17



Appendix B.2: Actual Gantt Chart

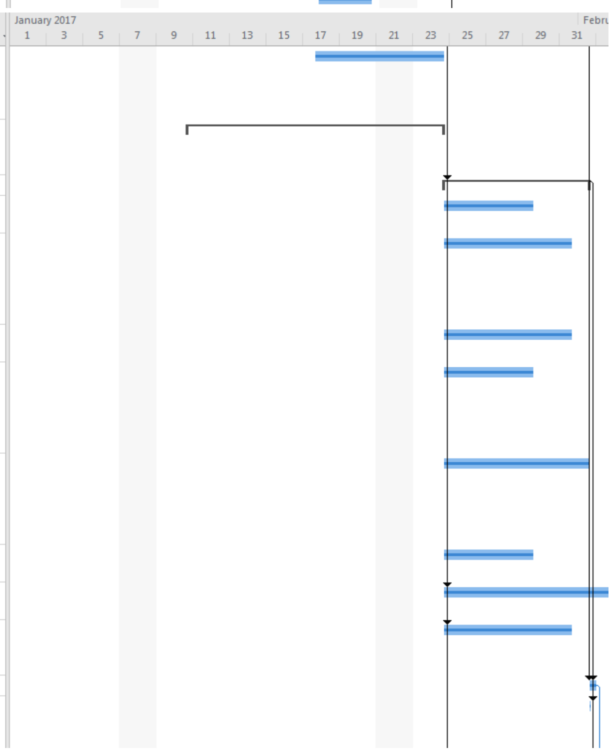
Fall Quarter

	Task Name	Duration	Start	Finish	Predecessors
2	**ME 428 Requirements**	**13.17 days**	**Wed 11/9/16**	**Tue 1/10/17**	
3	**Preliminary Design Review**	**8.17 days**	**Wed 11/9/16**	**Mon 11/28/16**	
4	**Report**	**3.75 days**	**Wed 11/9/1**	**Mon 11/14/16**	
5	Decide on Top Concept and Runners Up via Decision Matrices	1.5 days	Thu 11/10/16	Sat 11/12/16	
6	Update & Edit Project Proposal	1 hr	Wed 11/9/16	Wed 11/9/16	
7	Include descriptions and sketches of 5-10	3 hrs	Sat 11/12/16	Sun 11/13/16	5
8	Explain ideation and selection	1 hr	Sun 11/13/16	Sun 11/13/16	7
9	Develop detailed description and drawing/model of top concept	1 day	Sat 11/12/16	Mon 11/14/16	5
10	Assess how top concept meets specifications	1 day	Sat 11/12/16	Mon 11/14/16	5
11	Include supporting calculations, idea lists, decision matrices	1 day	Sat 11/12/16	Mon 11/14/16	5,10SS
12	Describe preliminary plans for building and testing	1 hr	Mon 11/14/16	Mon 11/14/16	9
13	Preliminary design safety hazard identification checklist	1 hr	Mon 11/14/16	Mon 11/14/16	12
14	Project Gantt Chart	1 day	Wed 11/9/1	Wed 11/9/16	
15	**Presentation**	**4.42 days**	**Mon 11/14/1**	**Mon 11/28/16**	**4**

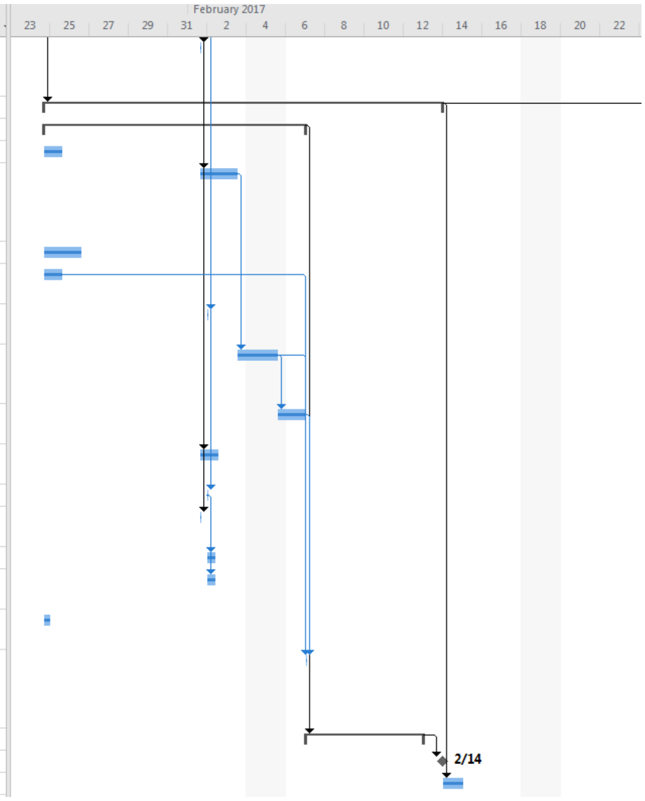


Winter Quarter

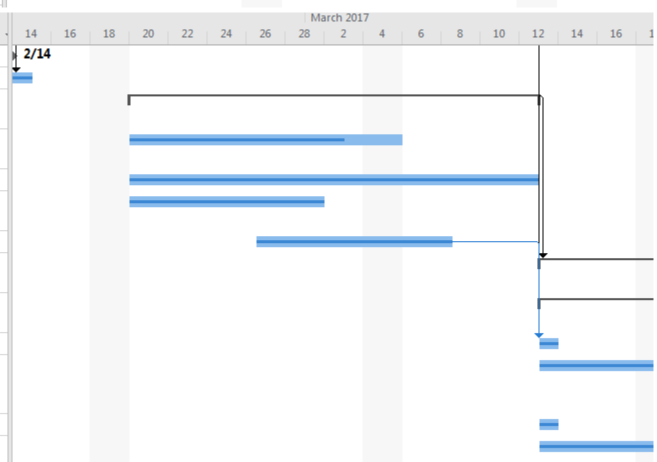
	Task Name	Duration	Start	Finish	Predecessors
23	**ME 429 Requirements**	**58.25 days**	**Tue 1/10/17**	**Wed 4/5/17**	**2**
24	**Material Selection and Initial Design**	**9 days**	**Tue 1/10/17**	**Fri 1/20/17**	
25	Perform research and calculations to pick materials for booms and ribs	1 wk	Tue 1/10/17	Tue 1/17/17	
26	Research and decide on details of heat treatment process	1.5 wks	Tue 1/10/17	Fri 1/20/17	
27	Select proper reflector mesh material, considering thickness, conductivity, etc.	5 days	Tue 1/10/17	Mon 1/16/17	
28	Design Storage Volume Frame, choose adequate material for housing	1 wk	Tue 1/10/17	Tue 1/17/17	
29	Find suppliers and order parts for early prototyping and testing	1 wk	Tue 1/10/17	Tue 1/17/17	
30	Order all long-lead parts	2 days	Tue 1/10/17	Thu 1/12/17	
31	**Design Analysis**	**12 days**	**Tue 1/10/17**	**Tue 1/24/17**	
32	Detailed Design of Module Housing and Reflector Containment	1 wk	Tue 1/10/17	Tue 1/17/17	
33	Detailed Design of Deployer spool and housing	1.5 wks	Tue 1/10/17	Fri 1/20/17	
34	Determine and size appropriate motor	1 wk	Tue 1/10/17	Tue 1/17/17	
35	**Detailed Design of Power Transmission**	**6 days**	**Tue 1/17/17**	**Tue 1/24/17**	**34**
36	Shaft Sizing	3 days	Tue 1/17/17	Fri 1/20/17	
37	Component Design and Selection (gears, bearings, etc.)	1 wk	Tue 1/17/17	Tue 1/24/17	
38	**Design Motor Control System and Develop Initial Code**	**12 days**	**Tue 1/10/17**	**Tue 1/24/17**	
42	**CAD Modeling**	**7 days**	**Tue 1/24/17**	**Wed 2/1/17**	**31**
43	CAD Model of Deployer	4 days	Tue 1/24/17	Sun 1/29/17	
44	CAD Model of Module Frame/Housing and Reflector Containment	1 wk	Tue 1/24/17	Tue 1/31/17	
45	CAD Model of Power Transmission	1 wk	Tue 1/24/17	Tue 1/31/17	
46	CAD Models of Other Parts (microcontroller, motor, other housings, etc.)	4 days	Tue 1/24/17	Sun 1/29/17	
47	Improved CAD Model of Reflector, Stowed and Deployed (Animation?)	7 days	Tue 1/24/17	Wed 2/1/17	
48	CAD Model of Feed Deployment	4 days	Tue 1/24/17	Sun 1/29/17	
49	Initial Prototype and Non-Parabolic Testing	1.5 wks	Tue 1/24/17	Fri 2/3/17	31
50	(If heat treatment fails,) Design Back-up plan of String Tensioners	1 wk	Tue 1/24/17	Tue 1/31/17	31
51	Develop Bill of Materials	3 hrs	Wed 2/1/17	Wed 2/1/17	31,42
52	Schedule CDR Presentation with Sponsor	1 hr	Wed 2/1/17	Wed 2/1/17	42



	Task Name	Duration	Start	Finish	Predecessors
52	Schedule CDR Presentation with Sponsor	1 hr	Wed 2/1/17	Wed 2/1/17	42
53	**Critical Design Review**	**17.33 days**	**Tue 1/24/17**	**Tue 2/14/17**	**31**
54	**Report**	**11.08 days**	**Tue 1/24/17**	**Mon 2/6/17**	
55	Update/Edit PDR	1 day	Tue 1/24/17	Wed 1/25/17	
56	Functional Description of Design (include layout drawing)	2 days	Wed 2/1/17	Fri 2/3/17	42
57	Supporting Analysis	2 days	Tue 1/24/17	Thu 1/26/17	
58	Safety Considerations	1 day	Tue 1/24/17	Wed 1/25/17	
59	Explanation/Justific of Material	2 hrs	Wed 2/1/17	Wed 2/1/17	51
60	Fabrication & Assembly Instructions	1 day	Fri 2/3/17	Sun 2/5/17	56
61	Maintenance & Repair Instructions	1 day	Sun 2/5/17	Mon 2/6/17	60
62	Top-Level Assembly Drawing	1 day	Wed 2/1/17	Thu 2/2/17	42
63	Bill of Materials	2 hrs	Wed 2/1/17	Wed 2/1/17	51
64	Detailed Part Drawings	1 hr	Wed 2/1/17	Wed 2/1/17	42
65	Cost Analysis	3 hrs	Wed 2/1/17	Thu 2/2/17	63
66	Literature for Purchased Items	3 hrs	Wed 2/1/17	Thu 2/2/17	63
67	Management Plan (Gantt Chart)	2 hrs	Tue 1/24/17	Tue 1/24/17	
68	Critical Design Safety Hazard Identification Checklist	1 hr	Mon 2/6/17	Mon 2/6/17	58,60,61
69	**Presentation**	**5.17 days**	**Mon 2/6/17**	**Mon 2/13/17**	**54**
73	CDR Safety Review	0 days	Tue 2/14/17	Tue 2/14/17	69
74	3rd Team Evaluation	1 day	Tue 2/14/17	Tue 2/14/17	53



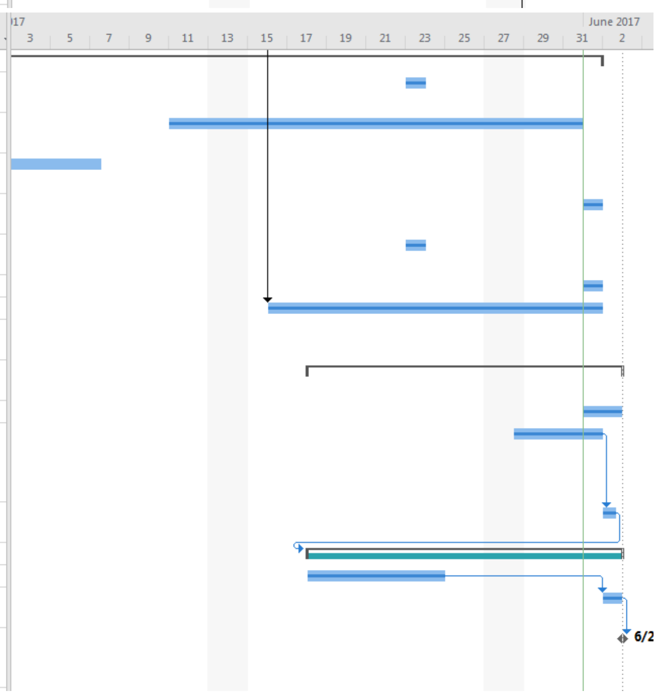
	Task Name	Duration	Start	Finish	Predecessors
73	CDR Safety Review	0 days	Tue 2/14/17	Tue 2/14/17	69
74	3rd Team Evaluation	1 day	Tue 2/14/17	Tue 2/14/17	53
75	**Complete Parts Ordering**	**18 days**	**Mon 2/20/17**	**Sun 3/12/17**	
76	Order and Heat Treat Booms	2 wks	Mon 2/20/17	Sun 3/5/17	
77	Order Ribs	3 wks	Mon 2/20/17	Sun 3/12/17	
78	All Other Components	1.5 wks	Mon 2/20/17	Wed 3/1/17	
79	Operator's Manual	1.5 wks	Sun 2/26/17	Wed 3/8/17	
80	**Initial Manufacturing Phase**	**6 days**	**Mon 3/13/17**	**Wed 4/5/17**	**75**
81	**Feed Deployer Manufacturing**	**6 days**	**Mon 3/13/17**	**Wed 4/5/17**	
82	Machine Feed Shaft	1 day	Mon 3/13/17	Mon 3/13/17	53,79
83	Machine spool, print casing, assemble	1 wk	Mon 3/13/17	Wed 4/5/17	
84	Main Shaft	1 day	Mon 3/13/17	Mon 3/13/17	
85	3D Print Stopper and Deployers	1 wk	Mon 3/13/17	Wed 4/5/17	



Spring Quarter

	Task Name	Duration	Start	Finish	Predecessors
86	ME 430 Requirements	50.33 days	Wed 4/5/17	Fri 6/2/17	23
87	Prototype Construction	21 days	Wed 4/5/17	Sun 4/30/17	
88	Housing Construction	2 wks	Wed 4/5/17	Wed 4/19/17	
89	Reflector Deployer Manufacturing	6 days	Wed 4/5/17	Wed 4/12/17	85
90	Spool Machining	1 day	Wed 4/5/17	Thu 4/6/17	
91	Assemble Deployers with Booms	1 wk	Wed 4/5/17	Wed 4/12/17	
92	Power Transmission Manufacturing	7 days	Wed 4/5/17	Thu 4/13/17	
93	Machining of gear stock	3 days	Wed 4/5/17	Sun 4/9/17	
94	Transmission Housing Machining	5 days	Wed 4/5/17	Tue 4/11/17	
95	Motor Mount Machining	3 days	Wed 4/5/17	Sun 4/9/17	
96	Power Transmission Assembly	7 days	Wed 4/5/17	Thu 4/13/17	
97	Feed Deployer Manufacturing	4 days	Wed 4/5/17	Mon 4/10/17	
98	Machine Feed Shaft	1 day	Wed 4/5/17	Thu 4/6/17	
99	Feed Deployer Assembly	4 days	Wed 4/5/17	Mon 4/10/17	
100	Reflector Manufacturing	14 days	Thu 4/13/17	Sun 4/30/17	92
101	Embed Ribs into Mylar	1 day	Thu 4/13/17	Fri 4/14/17	
102	Attach Collars to reflector	1 day	Thu 4/13/17	Fri 4/14/17	
103	Full Antenna Deployment Assembly	14 days	Thu 4/13/17	Sun 4/30/17	
104	Testing Phase	28.25 days	Sun 4/30/17	Thu 6/1/17	87
105	Meaure Size of Reflector	1 day	Mon 5/22/17	Tue 5/23/17	

	Task Name	Duration	Start	Finish	Predecessors
104	Testing Phase	28.25 days	Sun 4/30/17	Thu 6/1/17	87
105	Meaure Size of Reflector	1 day	Mon 5/22/17	Tue 5/23/17	
106	Measure Tolerance of Parabolic Reflector	3 wks	Wed 5/10/17	Wed 5/31/17	
107	Operating Temp Range	1 wk	Sun 4/30/17	Sun 5/7/17	
108	Deployment Power Consumption	0.75 days	Thu 6/1/17	Thu 6/1/17	
109	Measure Stored Volume	1 day	Mon 5/22/17	Tue 5/23/17	
110	Weight	1 day	Wed 5/31/1	Thu 6/1/17	
111	Project Testing	2.5 wks	Mon 5/15/1	Thu 6/1/17	87
112	Project Hardware/Safety Demo	0 days	Sun 4/30/17	Sun 4/30/17	87
113	Final Design Report and Expo	13.83 days	Thu 5/18/17	Fri 6/2/17	
114	Update/Edit CDR	2 days	Wed 5/31/1	Fri 6/2/17	
115	Add Details/Results about Design, Manufacturing, Prototype	4.42 days	Sun 5/28/17	Thu 6/1/17	
116	FDR Formatting	1 day	Thu 6/1/17	Fri 6/2/17	115
117	Project Expo	13.83 days	Thu 5/18/17	Fri 6/2/17	116
118	Poster	1 wk	Thu 5/18/17	Wed 5/24/17	
119	Expo Safety Review Checklist	1 day	Thu 6/1/17	Fri 6/2/17	118
120	Project Expo, Hardware Handoff, Report Submission	0 days	Fri 6/2/17	Fri 6/2/17	119



Appendix C: Design Safety Hazard Identification Checklist

DESIGN HAZARD CHECKLIST

Team: Stellar Dudes Advisor: ROSSMAN

Y	N	
☑	☐	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	☑	2. Can any part of the design undergo high accelerations/decelerations?
☐	☑	3. Will the system have any large moving masses or large forces?
☐	☑	4. Will the system produce a projectile?
☑	☐	5. Would it be possible for the system to fall under gravity creating injury?
☐	☑	6. Will a user be exposed to overhanging weights as part of the design?
☐	☑	7. Will the system have any sharp edges?
☐	☑	8. Will any part of the electrical systems not be grounded?
☐	☑	9. Will there be any large batteries or electrical voltage in the system above 40 V?
☐	☑	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☑	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐	☑	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	☑	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☑	14. Can the system generate high levels of noise?
☑	☐	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☑	☐	16. Is it possible for the system to be used in an unsafe manner?
☐	☑	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Operation of this design includes the rolling of tape measure booms and rolling and unrolling of reflector material	Tape measure boom deployer will be enclosed in housing to make sure nothing gets tangled inside the roller. During operation the operator must not interfere with the unfurling of the reflector to make sure nothing gets caught or jammed in the rollers.	3/3/2017	5/2/17
Because the project is relatively small in size, it may be subject to falling off table or other high places.	In order to prevent the project from falling, causing damage, or injuring someone, we will refrain from placing the project in high places as well as make sure it is properly mounted during use.	3/3/2017	4/30/17
The reflector is quite large and cumbersome. When deployed it could take up a lot of space.	When the project is in use, we make sure we have adequate space so the deployment will not bump, run into, or knock over anything in its path.	3/3/2017	5/23/17

Appendix D: Design Verification Plan

ME428 DVP&R Format

Report Date	2/11/17	Sponsor	Stellar Exploration Inc.	Component/Assembly	REPORTING ENGINEER:

Item No	Specification or Clause Reference	Test Description (TEST PLAN)	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED: Quantity	SAMPLES TESTED: Type	TIMING: Start date	TIMING: Finish date	TEST RESULTS: Test Result	TEST RESULTS: Quantity Pass	TEST RESULTS: Quantity Fail	NOTES (TEST REPORT)
1	Parabolic Reflector Size	The parabolic reflector will be deployed and measured using a measuring tape	Minimum 2m x 1m	All	DV/PV	1	B/C	5/25/2017	5/30/2017	1.77m x 1m	0	1	Length slightly under spec, width ok
2	Tolerance of Parabolic Reflector	The parabolic reflector shape tolerance will be scanned using a 3D scanner or XBOX Kinect. The 3D scan will be virtually compared to a CAD model of the ideal parabolic shape. Using software such as MATLAB, the error will be quantified and compared to the accepted tolerance.	Maximum Deviation from ideal parabolic shape is $\lambda_{20} = 0.5$ cm	David	PV	1	C	5/30/2017	6/1/2017	15cm	0	1	
3	Deployment Power Consumption	Only a 10 W power supply will be provided to power the motor(s). The motor(s) and gearing will be selected to abide by the power limits.	Maximum 10 W	All	CV/DV	1	A/B	6/1/2017	6/1/2017	10.8W	0	1	Slightly over expected due to high torque. Measured values varied
4	Stored Volume	Once the components (motor, tape measure reels, shafts, and reflector material) are accurately sized, we will test if these components fit in the maximum volume by placing the components in their designed locations. A successful test will have all components fit in the enclosed space.	Maximum 20 cm x 20 cm x 40 cm	All	DV			5/25/2017	5/30/2017	20cm x 20cm x 40cm	1	0	Excluding noted exceptions
5	Weight	The final product will be placed on a household scale to ensure that it does not exceed the maximum limit.	Maximum 50 lbs	All	PV	1	C	6/1/2017	6/1/2017	19lbs	1	0	Well under weight

Appendix E: Materials Consulting Group Report

Stellar Exploration Deployable Antenna – Booms and Ribs Selection

Materials Engineering Student Society

January 4th, 2017

David Otsu
Vincent Pang

Statement of Scope and Intent

The purpose of this initial report is to provide technical data sheets and vendor information for low cost, prototyping-friendly boom and rib materials for the Stellar Exploration Deployable Antenna. Although the final assembly is intended to launch into low earth orbit (LEO), the following space-related design criteria were not accounted for in this materials selection process, as the scope of this senior project is to demonstrate the feasibility of their deployable design.

- Minimized mass (cost-per-pound savings)
- Typical service temperature of LEO (-170C - 120C)
- Atomic oxygen bombardment
- Ultraviolet ray exposure

Design Objective

With the current design, the booms and ribs are required to deploy from a dimensionally constrained stowed position. This necessitates a material rated for high elasticity. Consider a beam of thickness t, bent elastically to a radius R. The surface strain of this beam is

$$\varepsilon = \frac{t}{2R}$$

and the maximum stress is

$$\sigma \geq E\frac{t}{2R}$$

This stress must not exceed the yield strength, modulus of rupture, endurance limit, or fracture strength (whichever is least), represented as σ_f. The minimum radius to which the beam can bend without damage is

$$R \leq \frac{t}{2}\left[\frac{E}{\sigma_f}\right]$$

Thus, assuming no other significant load constraints, the design objective is to maximize the material property index

$$M_1 = \frac{\sigma_f}{E}$$

Design Constraints

In addition to design objective, the following constraints were identified:

Minimum 50 GPa Young's Modulus - A minimum amount of stiffness is required to feasibly test the prototype under Earth's gravity. 50 GPa was selected arbitrarily to facilitate the selection process.

Minimum 8% Elongation at Break – A minimum Elongation at break is specified to remove materials that, despite maximizing the material property index, are unable to deflect considerably without brittle fracture.

Availability – Proprietary and highly specialized alloys were not included in this selection effort.

Using CES EduPack 2016, five alloys and their associated vendors were identified for the booms and ribs. Technical data sheets for each of these alloys are found at the end of this report.

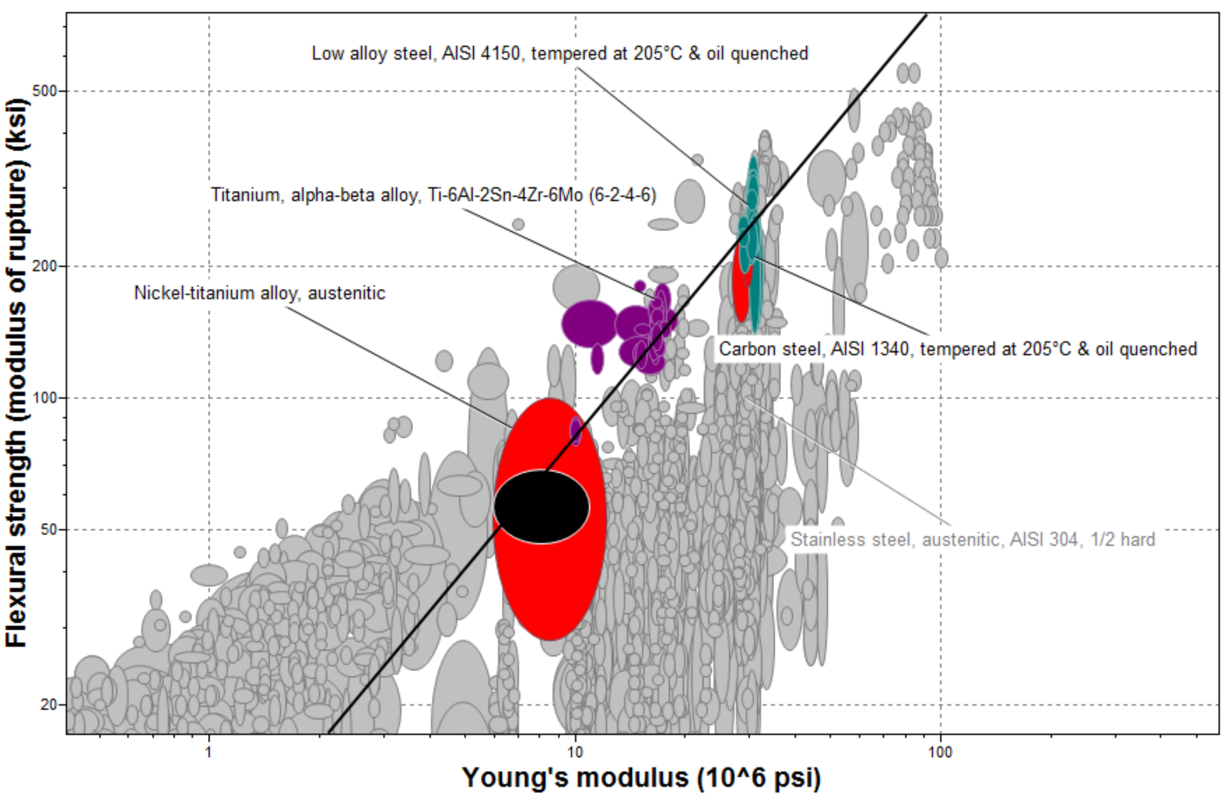


Figure 1. Ashby Chart visualizing the Material Property Index being maximized.

Vendor Information

When ordering material, it is necessary to ask for the supplier's recommended heat treatment and post-processing for **maximum elasticity**, as the heat treatments identified (if any) in this report are general guidelines only.

304L Stainless

http://smt.sandvik.com/en/products/strip-steel/strip-products/spring-steel/#tab-materials

AISI 1340

http://www.specialsteel-jy.com/1340H.html

AISI 4150

http://www.bluebladesteel.com/content.cfm/Materials/Alloy-Steel/category_id/102/page_id/149

Nitinol

http://www.memry.com/products-services/material
http://www.samaterials.com/37-nitinol

Ti 6-2-4-6

https://www.ulbrich.com/ti-6-2-4-2-s/

Addendum - Dimensional Considerations

Note that with the current design, up to 2 meters in length of material is required for the boons. It may be difficult to find vendors that will supply material in the correct condition and dimensions. Please consider this manufacturing feasibility consideration when working towards the final design.

Addendum – Initial Prototyping

It is expected that the specialty materials listed in this report will have a considerable lead time and cost. For this reason, it is suggested that common products available in bulk forms be used for initial prototyping efforts. McMaster-Carr has torsional springs and constant-force springs which can be used for this purpose:

https://www.mcmaster.com/#torsion-springs/=15rvxg2
https://www.mcmaster.com/#constant-force-springs/=15rvxmv

Stainless steel, austenitic, AISI 304, 1/2 hard

General information

Designation

AISI 304, wrought

Condition	Solution annealed; 1/2 hard
UNS number	S30400
US name	ASTM WP304, ASTM TP304, ASTM S30403, ASTM S30400, ASTM MT304, ASTM F304, AMS 5697, AMS 5567, AMS 5566, AMS 5565, AMS 5564, AMS 5563, ~ASTM S30453
EN name	X5CrNi18-10, LW20
EN number	~1.4948, ~1.4301
ISO name	X5CrNi18-9E, X5CrNi18-9, ~X5CrNiN19-9, ~X5CrNiN18-8
GB (Chinese) name	ML0Cr18Ni9, 0Cr18Ni9(-R), 0Cr18Ni9(-Q), 0Cr18Ni9(-L), 0Cr18Ni9, ~0Cr19Ni9N(-R), ~0Cr19Ni9N(-Q), ~0Cr19Ni9N(-L), ~0Cr19Ni9N
JIS (Japanese) name	SUS304, SUSF304, SUS304-WSB, SUS304-WSA, SUS304TPY, SUS304TPD, SUS304TP, SUS304TKC, SUS304TKA, SUS304TBS, SUS304TB, SUS304FB, SUS304-CSP, SUS304N1-WPB, SUS304N1-WPA, SUS304 TF, SDP4, ~SUS304L, ~SCS13AA-CF

Tradenames

STAINLESS STEEL GRADE 304, Aalco (UK); 304 STAINLESS STEEL, AK Steel (USA); STAINLESS STEEL 304, Vegas Fastener (USA); 304 STAINLESS STEEL, Electronic Alloys (UK); 304L STAINLESS STEEL, Electronic Alloys (UK); STAINLESS STEEL GRADE 304L, Aalco (UK); 304L STAINLESS STEEL, AK Steel (USA);

Typical uses

Architectural applications; beer barrels; brewing; cafeteria equipment; cookware; cryogenic plant; food and dairy-processing equipment; heat-exchanger tubes and supports; pressure vessels; process plant parts.

Composition overview

Compositional summary

Fe66-74 / Cr18-20 / Ni8-11 (impurities: Mn<2, Si<1, C<0.08, P<0.045, S<0.03)

Material family	Metal (ferrous)
Base material	Fe (Iron)

Composition detail (metals, ceramics and glasses)

C (carbon)		0	-	0.08	%
Cr (chromium)		18	-	20	%
Fe (iron)	*	65.8	-	74	%
Mn (manganese)		0	-	2	%
Ni (nickel)		8	-	11	%
P (phosphorus)		0	-	0.045	%
S (sulfur)		0	-	0.03	%
Si (silicon)		0	-	1	%

Price

Price	*	1.63	-	1.78	USD/lb

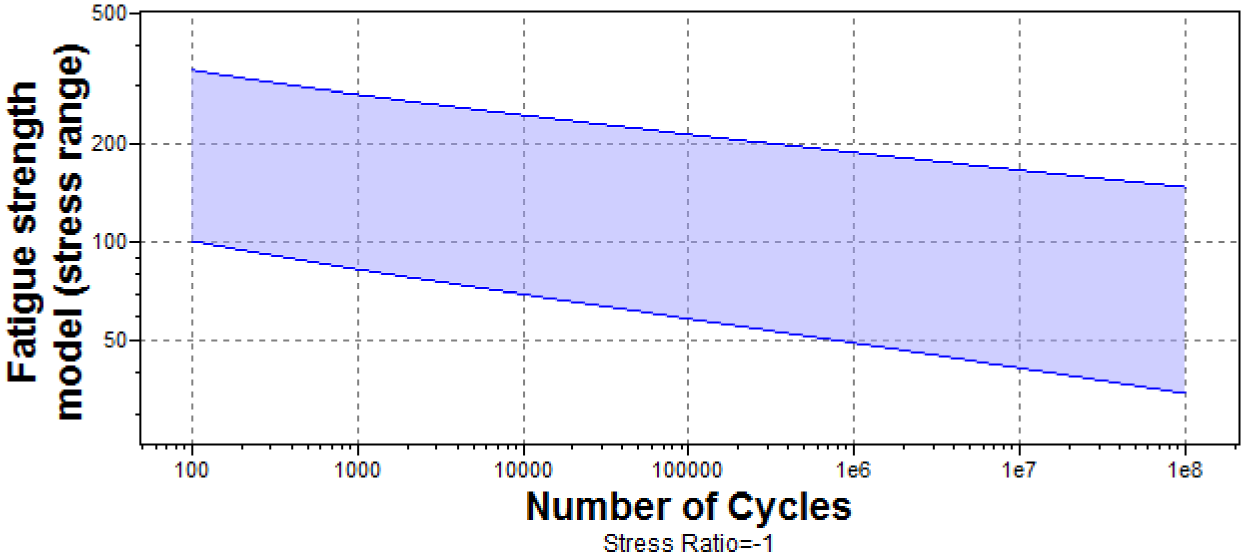
Physical properties

Density		0.284	-	0.291	lb/in^3

Mechanical properties

Young's modulus		27.6	-	29.4	10^6 psi
Yield strength (elastic limit)		100	-	116	ksi
Tensile strength		149	-	325	ksi
Elongation	*	5	-	20	% strain
Compressive strength	*	100	-	116	ksi
Flexural modulus	*	27.6	-	29.4	10^6 psi
Flexural strength (modulus of rupture)		100	-	116	ksi
Shear modulus		10.7	-	11.7	10^6 psi
Bulk modulus		19.4	-	21.9	10^6 psi
Poisson's ratio		0.265	-	0.275	
Shape factor		31			
Hardness - Vickers	*	350	-	570	HV
Hardness - Rockwell B	*	109	-	120	
Hardness - Rockwell C	*	36	-	54	
Hardness - Brinell	*	48.7	-	78.8	ksi
Fatigue strength at 10^7 cycles	*	63.2	-	109	ksi
Fatigue strength model (stress range)	*	41.5	-	167	ksi

Parameters: Stress Ratio = -1, Number of Cycles = 1e7cycles



Mechanical loss coefficient (tan delta)	*	3.1e-4	-	5e-4	

Impact & fracture properties

Fracture toughness	*	71.9	-	190	ksi.in^0.5

Thermal properties

Melting point		2.55e3	-	2.64e3	°F
Maximum service temperature		1.38e3	-	1.7e3	°F
Minimum service temperature		-328			°F
Thermal conductivity		8.09	-	9.82	BTU.ft/hr.ft^2.°F
Specific heat capacity		0.117	-	0.127	BTU/lb.°F
Thermal expansion coefficient		8.89	-	10	µstrain/°F
Latent heat of fusion	*	112	-	123	BTU/lb

Electrical properties

Electrical resistivity		65	-	77	µohm.cm
Galvanic potential	*	-0.15	-	-0.07	V

Magnetic properties

Magnetic type	Non-magnetic			

Optical properties

Transparency	Opaque			

Bio-data

Food contact	Yes			

Restricted substances risk indicators

RoHS (EU) compliant grades?	False			

Processing properties

Metal casting	Unsuitable			
Metal cold forming	Excellent			
Metal hot forming	Acceptable			
Metal press forming	Excellent			
Metal deep drawing	Excellent			
Machinability - speed	85	-	100	sfm
Weldability - MIG	Excellent			
Weldability - plasma	Excellent			
Weldability - SAW	Excellent			
Weldability - TIG	Excellent			
Brazeability	Fair			
Carbon equivalency	0.733	-	1.03	

Durability

Water (fresh)	Excellent			
Water (salt)	Excellent			
Weak acids	Excellent			
Strong acids	Acceptable			
Weak alkalis	Excellent			
Strong alkalis	Excellent			
Organic solvents	Excellent			
Oxidation at 500C	Excellent			
UV radiation (sunlight)	Excellent			
Galling resistance (adhesive wear)	Limited use			

Notes

Aluminum bronze is the most suitable mating material to minimize galling.

Flammability	Non-flammable			

Corrosion resistance of metals

Pitting resistance equivalent number (PREN)	18	-	20	
Pitting and crevice corrosion	Low (<20)			
Stress corrosion cracking	Moderate			
Intergranular (weld line) corrosion	Restricted			
Inorganic acids	Moderate			
Organic acids	Moderate			
Alkalis	Moderate			
Humidity / water	Excellent			
Sea water	Moderate			
Sour oil and gas	Moderate			

Primary production energy, CO2 and water

Embodied energy, primary production	2.73e4	-	3.01e4	BTU/lb

Sources

56.7 MJ/kg (Hammond and Jones, 2008); 76.6 MJ/kg (Ecoinvent v2.2)

CO2 footprint, primary production	4.31	-	4.76	lb/lb

Sources

4.53 kg/kg (Ecoinvent v2.2)

NOx creation	* 0.0293	-	0.0324	lb/lb
SOx creation	* 0.0501	-	0.0554	lb/lb

Water usage	*	3.82e3	-	4.24e3	in^3/lb

Processing energy, CO2 footprint & water

Rough rolling, forging energy	*	2.67e3	-	2.95e3	BTU/lb
Rough rolling, forging CO2	*	0.465	-	0.514	lb/lb
Rough rolling, forging water	*	116	-	174	in^3/lb
Extrusion, foil rolling energy	*	5.21e3	-	5.76e3	BTU/lb
Extrusion, foil rolling CO2	*	0.909	-	1	lb/lb
Extrusion, foil rolling water	*	186	-	280	in^3/lb
Wire drawing energy	*	1.92e4	-	2.12e4	BTU/lb
Wire drawing CO2	*	3.35	-	3.7	lb/lb
Wire drawing water	*	466	-	699	in^3/lb
Metal powder forming energy	*	1.63e4	-	1.79e4	BTU/lb
Metal powder forming CO2	*	3.02	-	3.34	lb/lb
Metal powder forming water	*	1.14e3	-	1.71e3	in^3/lb
Vaporization energy	*	4.67e6	-	5.16e6	BTU/lb
Vaporization CO2	*	815	-	900	lb/lb
Vaporization water	*	1.25e5	-	1.88e5	in^3/lb
Coarse machining energy (per unit wt removed)	*	586	-	647	BTU/lb
Coarse machining CO2 (per unit wt removed)	*	0.102	-	0.113	lb/lb
Fine machining energy (per unit wt removed)	*	4.02e3	-	4.44e3	BTU/lb
Fine machining CO2 (per unit wt removed)	*	0.701	-	0.775	lb/lb
Grinding energy (per unit wt removed)	*	7.83e3	-	8.66e3	BTU/lb
Grinding CO2 (per unit wt removed)	*	1.37	-	1.51	lb/lb
Non-conventional machining energy (per unit wt removed)	*	4.67e4	-	5.16e4	BTU/lb
Non-conventional machining CO2 (per unit wt removed)	*	8.15	-	9	lb/lb

Recycling and end of life

Recycle		False			
Embodied energy, recycling	*	6.06e3	-	6.66e3	BTU/lb
CO2 footprint, recycling	*	1.1	-	1.22	lb/lb
Recycle fraction in current supply		35.5	-	39.3	%
Downcycle		False			
Combust for energy recovery		Combust for energy recovery			
Landfill		False			
Biodegrade		Biodegrade			

Possible substitutes for principal component

Iron is the least expensive and most widely used metal. In most applications, iron and steel compete either with less expensive nonmetallic materials or with more expensive materials having a property advantage. Iron and steel compete with lighter materials, such as aluminum and plastics, in the motor vehicle industry; aluminum,concrete, and wood in construction; and aluminum, glass, paper, and plastics in containers.

Geo-economic data for principal component

Principal component	Iron			
Typical exploited ore grade	45.1	-	49.9	%
Minimum economic ore grade	25	-	70	%
Abundance in Earth's crust	4.1e4	-	6.3e4	ppm
Abundance in seawater	0.0025	-	0.003	ppm
Annual world production, principal component	2.26e9			ton/yr
Reserves, principal component	1.57e11			l. ton

Main mining areas (metric tonnes per year)

Australia, 530e6
Brazil, 389e6
Canada, 40e6
China, 1.32e9
India, 150e3
Iran, 37e3

Kazakhstan, 25e6
Russia, 102e6
South Africa, 67e6
Sweden, 26e6
Ukraine, 80e6
United States of America, 52e6
Venezuela, 30e6
Other countries, 88e6

Eco-indicators for principal component

Eco-indicator 95	413	millipoints/lb
Eco-indicator 99	192	millipoints/lb

Notes

Keywords

RDN 260, Roldan S.A. (SPAIN); RDN 240, Roldan S.A. (SPAIN); RDN 210, Roldan S.A. (SPAIN); RDN 340, Roldan S.A. (SPAIN); YOONSTEEL S2, Yoonsteel (Malaysia) Sdn. Bhd (MALAYSIA); ARGESTE 4306 LA/LF/SB/VC, Stahlwerk Ergste Westig GmbH (GERMANY); STAINWELD 308-15, Lincoln Electric Co. (USA); STAINWELD 308-16, Lincoln Electric Co. (USA); EASTERN STAINLESS TYPE 347, Eastern Stainless Corp. (USA); PROJECT 70 STAINLESS TYPE 347, Carpenter Technology Corp. (USA); EASTERN STAINLESS TYPE 304L, Eastern Stainless Corp. (USA); PROJECT 7000 STAINLESS TYPE 304L, Carpenter Technology Corp. (USA); PROJECT 70 STAINLESS TYPE 304L, Carpenter Technology Corp. (USA); SPARTAN REDHEUGH 347S31, Spartan Redheugh Ltd (UK);

Standards with similar compositions

The following information is taken from ASM AlloyFinder 3 - see link to References table for further information.

ONORM M3120 X5CrNi18105 (Austria)
EN 10088/3(95) 1.4301 (Europe)
EN 10088/3(95) X5CrNi18-10 (Europe)
BDS 6738(72) 0Ch18N10 (Bulgaria)
GB 1220(92) 0Cr18Ni9 (China)
GB 1221(92) 0Cr18Ni9 (China)
GB 13296(91) 0Cr18Ni9 (China)
GB 4232(93) ML0Cr18Ni9 (China)
GB 4237(92) 0Cr18Ni9 (China)
GB 4238(92) 0Cr18Ni9 (China)
GB 4239(91) 0Cr18Ni9 (China)
GB 4240(93) 0Cr18Ni9(-L,-Q,-R) (China)
CSN 417240 17240 (Czech Republic)
SFS 700 X4CrNi189 (Finland)
SFS 725(86) X4CrNi189 (Finland)
AFNOR NFA35573 Z6CN18.09 (France)
AFNOR NFA35574 Z6CN18.09 (France)
AFNOR NFA35577 Z6CN18.09 (France)
AFNOR NFA36209 Z5CN18.09 (France)
AFNOR NFA36607 Z5CN18.09 (France)
DIN 17440(96) WNr 1.4301 (Germany)
DIN 17441(97) WNr 1.4301 (Germany)
DIN EN 10088(95) WNr 1.4301 (Germany)
DIN EN 10088(95) X5CrNi18-10 (Germany)
MSZ 4360(87) KO33 (Hungary)
MSZ 4360(87) X8CrNi1810 (Hungary)
MSZ 4398(86) KO33 (Hungary)
IS 1570/5(85) X04Cr19Ni9 (India)
IS 6527 04Cr18Ni10 (India)
IS 6528 04Cr18Ni10 (India)
IS 6529 04Cr18Ni10 (India)

IS 6603 04Cr18Ni10 (India)
IS 6911 04Cr18Ni10 (India)
UNI 6901(71) X5CrNi1810 (Italy)
UNI 6904(71) X5CrNi1810 (Italy)
UNI 7500(75) X5CrNi1810 (Italy)
JIS G3214(91) SUSF304 (Japan)
JIS G4303(91) SUS304 (Japan)
JIS G4303(91) SUS304J3 (Japan)
JIS G4304(91) SUS304 (Japan)
JIS G4305(91) SUS304 (Japan)
JIS G4305(91) SUS304J1 (Japan)
JIS G4305(91) SUS304J2 (Japan)
JIS G4306 SUS304 (Japan)
JIS G4307 SUS304 (Japan)
JIS G4308 SUS304J3 (Japan)
JIS G4308(98) SUS304 (Japan)
JIS G4309 SUS304 (Japan)
JIS G4309 SUS304J3 (Japan)
JIS G4313(96) SUS304-CSP (Japan)
JIS G4315 SUS304 (Japan)
JIS G4315 SUS304J3 (Japan)
DGN B-218 TP304 (Mexico)
DGN B-224 TP304 (Mexico)
DGN B-83 304 (Mexico)
NMX-B-171(91) MT304 (Mexico)
NMX-B-176(91) TP304 (Mexico)
NMX-B-186-SCFI(94) TP304 (Mexico)
NMX-B-196(68) TP304 (Mexico)
NS 14350 14350 (Norway)
AS 1449(94) 304 (NSW Australia)
AS 2837(86) 304 (NSW Australia)
CSA G110.3 304 (ON Canada)
CSA G110.6 304 (ON Canada)
CSA G110.9 304 (ON Canada)
PNH86020 0H18N9 (Poland)
STAS 3583(87) 5NiCr180 (Romania)
GOST O8Ch18N10 (Russian Federation)
GOST 5632(61) 0KH18N10 (Russian Federation)
GOST 5632(72) 08Ch18N10 (Russian Federation)
UNE 36016(75) F.3504 (Spain)
UNE 36016(75) X6CrNi19-10 (Spain)
UNE 36016/1(89) E-304 (Spain)
UNE 36016/1(89) F.3504 (Spain)
UNE 36087(78) F.3541 (Spain)
UNE 36087(78) F.3551 (Spain)
UNE 36087(78) X5CrNi18-10 (Spain)
UNE 36087(78) X5CrNi18-11 (Spain)
SS 142332 2332 (Sweden)
SS 142333 2333 (Sweden)
ISO 4954(93) X5CrNi189E (International)
ISO 683-13(74) 11 (International)
BS 1449/2(83) 304S15 (United Kingdom)
BS 1449/2(83) 304S16 (United Kingdom)
BS 1449/2(83) 304S31 (United Kingdom)
BS 1501/3(73) 304S15 (United Kingdom)
BS 1501/3(73) 304S29 (United Kingdom)

BS 1501/3(90) 304S31 (United Kingdom)
BS 1501/3(90) 304S51 (United Kingdom)
BS 1501/3(90) 304S61 (United Kingdom)
BS 1502 304S31 (United Kingdom)
BS 1503(89) 304S31 (United Kingdom)
BS 1506(90) 304S31 (United Kingdom)
BS 1554(90) 304S15 (United Kingdom)
BS 1554(90) 304S31 (United Kingdom)
BS 3059/2(90) 304S51 (United Kingdom)
BS 3605 304S18 (United Kingdom)
BS 3605 304S25 (United Kingdom)
BS 3605/1(91) 304S31 (United Kingdom)
BS 3605/1(91) 304S51 (United Kingdom)
BS 3606(78) 304S22 (United Kingdom)
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BS 970/1(96) 304S31 (United Kingdom)
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AMS 5560H(92) (USA)
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AMS 5566 (USA)
AMS 5567 (USA)
AMS 5639 (USA)
AMS 5697 (USA)
AMS 5857(90) (USA)
AMS 5868(93) (USA)
AMS 7228 (USA)
AMS 7245 (USA)
ASME SA182 304 (USA)
ASME SA213 304 (USA)
ASME SA240 304 (USA)
ASME SA249 304 (USA)
ASME SA312 304 (USA)
ASME SA358 304 (USA)
ASME SA376 304 (USA)
ASME SA403 304 (USA)
ASME SA409 304 (USA)
ASME SA430 304 (USA)
ASME SA479 304 (USA)
ASME SA688 304 (USA)
ASTM A167(96) 304 (USA)
ASTM A182 304 (USA)
ASTM A182/A182M(98) F304 (USA)
ASTM A193/A193M(98) 304 (USA)
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ASTM A193/A193M(98) B8A (USA)
ASTM A194 304 (USA)
ASTM A194/A194M(98) 8 (USA)
ASTM A194/A194M(98) 8A (USA)
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ASTM A213/A213M(95) TP304 (USA)
ASTM A240/A240M(98) S30400 (USA)

ASTM A249/249M(96) TP304 (USA)
ASTM A269 304 (USA)
ASTM A270(95) 304 (USA)
ASTM A271(96) 304 (USA)
ASTM A276(98) 304 (USA)
ASTM A312/A312M(95) 304 (USA)
ASTM A313/A313M(95) 304 (USA)
ASTM A314 304 (USA)
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ASTM A336/A336M(98) F304 (USA)
ASTM A358/A358M(95) 304 (USA)
ASTM A368(95) 304 (USA)
ASTM A376 304 (USA)
ASTM A409 304 (USA)
ASTM A430 304 (USA)
ASTM A473 304 (USA)
ASTM A479 304 (USA)
ASTM A492 304 (USA)
ASTM A493 304 (USA)
ASTM A511(96) MT304 (USA)
ASTM A554(94) MT304 (USA)
ASTM A580/A580M(98) 304 (USA)
ASTM A632(90) TP304 (USA)
ASTM A666(96) 304 (USA)
ASTM A688/A688M(96) TP304 (USA)
ASTM A793(96) 304 (USA)
ASTM A813/A813M(95) TP304 (USA)
ASTM A814/A814M(96) TP304 (USA)
ASTM A851(96) TP304 (USA)
ASTM A908(95) 304 (USA)
ASTM A943/A943M(95) TP304 (USA)
ASTM A965/965M(97) F304 (USA)
ASTM A988(98) S30400 (USA)
MIL-S-23195(A)(65) 304 (USA)
MIL-S-23196 304 (USA)
MIL-S-27419(USAF)(68) 304 (USA)
MIL-S-5059D(90) 304 (USA)
MIL-T-8504B(98) 304 (USA)
MIL-T-8506A 304 (USA)
SAE J405(98) S30400 (USA)
SAE J467(68) 304 (USA)
AISI 304 (USA)
COPANT 513 TP304 (Venezuela)
COPANT R195 TP 304 (Venezuela)

Links

ProcessUniverse
Producers
Reference
Shape
Values marked * are estimates.
No warranty is given for the accuracy of this data

Carbon steel, AISI 1340, tempered at 205°C & oil quenched

General information

Designation

AISI 1340				
Condition	Tempered at 205°C & oil quenched			
UNS number	G13400, ~H13400			
EN name	BS S 156, BS S 157, 38Mn6			
EN number	1.1127			

Typical uses

General construction; general mechanical engineering; automotive; tools; axles; gears; springs.

Composition overview

Compositional summary

Fe97-98 / Mn1.6-1.9 / C0.38-0.43 / Si0.15-0.35 (impurities: S<0.04, P<0.035)

Material family	Metal (ferrous)			
Base material	Fe (Iron)			

Composition detail (metals, ceramics and glasses)

C (carbon)		0.38	-	0.43	%
Fe (iron)	*	97.2	-	97.9	%
Mn (manganese)		1.6	-	1.9	%
P (phosphorus)		0	-	0.035	%
S (sulfur)		0	-	0.04	%
Si (silicon)		0.15	-	0.35	%

Price

Price	*	0.263	-	0.268	USD/lb

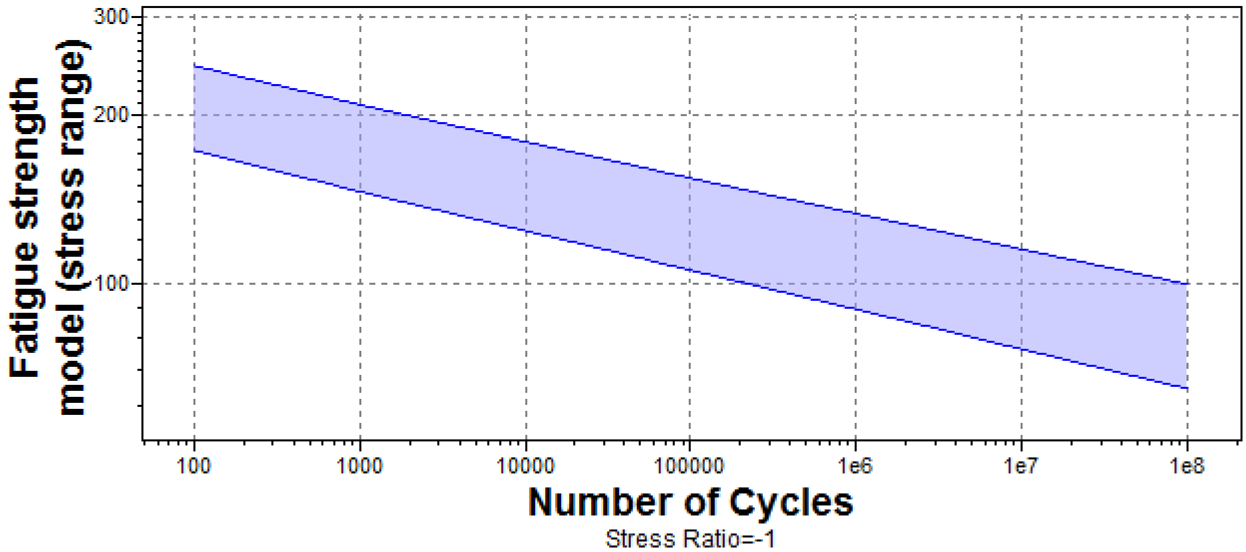
Physical properties

Density		0.282	-	0.285	lb/in^3

Mechanical properties

Young's modulus		29	-	31.2	10^6 psi
Yield strength (elastic limit)		207	-	255	ksi
Tensile strength		236	-	289	ksi
Elongation		8	-	14	% strain
Compressive strength	*	207	-	255	ksi
Flexural modulus	*	29	-	31.2	10^6 psi
Flexural strength (modulus of rupture)		207	-	255	ksi
Shear modulus		11.2	-	12.2	10^6 psi
Bulk modulus		22.5	-	25.4	10^6 psi
Poisson's ratio		0.285	-	0.295	
Shape factor		15			
Hardness - Vickers		455	-	555	HV
Fatigue strength at 10^7 cycles	*	87.2	-	101	ksi
Fatigue strength model (stress range)	*	76.2	-	115	ksi

Parameters: Stress Ratio = -1, Number of Cycles = 1e7cycles



Mechanical loss coefficient (tan delta)	*	2.2e-4	-	2.8e-4	

Impact & fracture properties

Fracture toughness	*	10.9	-	24.6	ksi.in^0.5

Thermal properties

Melting point		2.61e3	-	2.74e3	°F
Maximum service temperature	*	329	-	383	°F
Minimum service temperature		32			°F
Thermal conductivity	*	26	-	31.8	BTU.ft/hr.ft^2.°F
Specific heat capacity	*	0.105	-	0.124	BTU/lb.°F
Thermal expansion coefficient	*	6.11	-	7.22	µstrain/°F
Latent heat of fusion	*	116	-	118	BTU/lb

Electrical properties

Electrical resistivity	*	15	-	22	µohm.cm
Galvanic potential	*	-0.52	-	-0.44	V

Magnetic properties

Magnetic type	Magnetic

Optical properties

Transparency	Opaque

Bio-data

Food contact	Yes

Restricted substances risk indicators

RoHS (EU) compliant grades?	False

Processing properties

Metal casting	Unsuitable		
Metal cold forming	Acceptable		
Metal hot forming	Acceptable		
Metal press forming	Acceptable		
Metal deep drawing	Limited use		
Carbon equivalency	0.647	-	0.747

Durability

Water (fresh)	Acceptable
Water (salt)	Limited use
Weak acids	Limited use
Strong acids	Unacceptable

Weak alkalis		Acceptable			
Strong alkalis		Limited use			
Organic solvents		Excellent			
Oxidation at 500C		Acceptable			
UV radiation (sunlight)		Excellent			
Galling resistance (adhesive wear)		Acceptable			

Notes

Aluminum bronze is the most suitable mating material to minimize galling.

Flammability		Non-flammable			

Primary production energy, CO2 and water

Embodied energy, primary production		1.32e4	-	1.46e4	BTU/lb

Sources

19.4 MJ/kg (Dhingra, Overly, Davis, 1999); 23 MJ/kg (Norgate, Jahanshahi, Rankin, 2007); 27.9 MJ/kg (Ecoinvent v2.2); 29.2 MJ/kg (Hammond and Jones, 2008); 32.8 MJ/kg (Hammond and Jones, 2008); 34.7 MJ/kg (Hammond and Jones, 2008); 35.4 MJ/kg (Hammond and Jones, 2008); 37.2 MJ/kg (Sullivan and Gaines, 2010); 38 MJ/kg (Hammond and Jones, 2008); 45.4 MJ/kg (Hammond and Jones, 2008)

CO2 footprint, primary production		2.26	-	2.49	lb/lb

Sources

0.396 kg/kg (Voet, van der and Oers, van, 2003); 1.75 kg/kg (Ecoinvent v2.2); 1.81 kg/kg (Voet, van der and Oers, van, 2003); 2.23 kg/kg (Voet, van der and Oers, van, 2003); 2.3 kg/kg (Norgate, Jahanshahi, Rankin, 2007); 2.74 kg/kg (Hammond and Jones, 2008); 2.77 kg/kg (Hammond and Jones, 2008); 2.87 kg/kg (Hammond and Jones, 2008); 2.89 kg/kg (Hammond and Jones, 2008); 3.03 kg/kg (Hammond and Jones, 2008); 3.27 kg/kg (Hammond and Jones, 2008)

NOx creation		0.0039	-	0.00431	lb/lb
SOx creation		0.00836	-	0.00924	lb/lb
Water usage	*	1.26e3	-	1.39e3	in^3/lb

Processing energy, CO2 footprint & water

Casting energy	*	4.67e3	-	5.16e3	BTU/lb
Casting CO2	*	0.814	-	0.9	lb/lb
Casting water	*	569	-	853	in^3/lb
Rough rolling, forging energy	*	5.63e3	-	6.22e3	BTU/lb
Rough rolling, forging CO2	*	0.981	-	1.08	lb/lb
Rough rolling, forging water	*	198	-	297	in^3/lb
Extrusion, foil rolling energy	*	1.11e4	-	1.23e4	BTU/lb
Extrusion, foil rolling CO2	*	1.94	-	2.15	lb/lb
Extrusion, foil rolling water	*	349	-	524	in^3/lb
Wire drawing energy	*	4.14e4	-	4.58e4	BTU/lb
Wire drawing CO2	*	7.22	-	7.98	lb/lb
Wire drawing water	*	1e3	-	1.51e3	in^3/lb
Metal powder forming energy	*	1.63e4	-	1.79e4	BTU/lb
Metal powder forming CO2	*	3.02	-	3.34	lb/lb
Metal powder forming water	*	1.14e3	-	1.71e3	in^3/lb
Vaporization energy	*	4.67e6	-	5.17e6	BTU/lb
Vaporization CO2	*	815	-	901	lb/lb
Vaporization water	*	1.25e5	-	1.88e5	in^3/lb
Coarse machining energy (per unit wt removed)	*	1.03e3	-	1.14e3	BTU/lb
Coarse machining CO2 (per unit wt removed)	*	0.18	-	0.199	lb/lb
Fine machining energy (per unit wt removed)	*	8.46e3	-	9.35e3	BTU/lb
Fine machining CO2 (per unit wt removed)	*	1.48	-	1.63	lb/lb
Grinding energy (per unit wt removed)	*	1.67e4	-	1.85e4	BTU/lb
Grinding CO2 (per unit wt removed)	*	2.92	-	3.22	lb/lb
Non-conventional machining energy (per unit wt removed)	*	4.67e4	-	5.17e4	BTU/lb
Non-conventional machining CO2 (per unit wt removed)	*	8.15	-	9.01	lb/lb

Recycling and end of life

Recycle		False			
Embodied energy, recycling	*	3.48e3	-	3.85e3	BTU/lb
CO2 footprint, recycling	*	0.636	-	0.703	lb/lb
Recycle fraction in current supply		39.9	-	44	%

Downcycle	False
Combust for energy recovery	Combust for energy recovery
Landfill	False
Biodegrade	Biodegrade

Possible substitutes for principal component

Iron is the least expensive and most widely used metal. In most applications, iron and steel compete either with less expensive nonmetallic materials or with more expensive materials having a property advantage. Iron and steel compete with lighter materials, such as aluminum and plastics, in the motor vehicle industry; aluminum,concrete, and wood in construction; and aluminum, glass, paper, and plastics in containers.

Geo-economic data for principal component

Principal component	Iron			
Typical exploited ore grade	45.1	-	49.9	%
Minimum economic ore grade	25	-	70	%
Abundance in Earth's crust	4.1e4	-	6.3e4	ppm
Abundance in seawater	0.0025	-	0.003	ppm
Annual world production, principal component	2.26e9			ton/yr
Reserves, principal component	1.57e11			l. ton

Main mining areas (metric tonnes per year)

Australia, 530e6
Brazil, 389e6
Canada, 40e6
China, 1.32e9
India, 150e3
Iran, 37e3
Kazakhstan, 25e6
Russia, 102e6
South Africa, 67e6
Sweden, 26e6
Ukraine, 80e6
United States of America, 52e6
Venezuela, 30e6
Other countries, 88e6

Eco-indicators for principal component

Eco-indicator 95	39	millipoints/lb

Notes

Keywords

ROC 250, Astralloy Wear Technology Corp. (USA); XK1345, Steelmark-Eagle & Globe (AUSTRALIA); XK1340, Steelmark-Eagle & Globe (AUSTRALIA); XK1335, Steelmark-Eagle & Globe (AUSTRALIA); A-1203, AFORA (Aceros Afora S.A.) (SPAIN);

Standards with similar compositions

The following information is taken from ASM AlloyFinder 3 - see link to References table for further information.

BDS 6354 40G2F (Bulgaria)
GB 3077(88) 40Mn2 (China)
GB 8162(87) 40Mn2 (China)
GB/T 3078(94) 40Mn2 (China)
YB/T 5052(93) 40Mn2 (China)
DIN 42MnV7 (Germany)
DIN WNr 1.5223 (Germany)
DGN B-203 1340 (Mexico)
DGN B-297 1340 (Mexico)
NMX-B-300(91) 1340 (Mexico)
AS 1442 K1340 (NSW Australia)
AS 1442(92) X1340 (NSW Australia)

AS 1443(94) X1340 (NSW Australia)
ASTM A29/A29M(93) 1340 (USA)
ASTM A322(96) 1340 (USA)
ASTM A331(95) 1340 (USA)
ASTM A519(96) 1340 (USA)
ASTM A547 1340 (USA)
ASTM A752(93) 1340 (USA)
ASTM A829/A829M(95) 1340 (USA)
DoD-F-24669/1(86)(86) 1340 (USA)
MIL-S-16974E(86) 1340 (USA)
SAE 770(84) 1340 (USA)
SAE J404(94) 1340 (USA)
AISI 1340 (USA)
COPANT 334 1340 (Venezuela)
COPANT 514 1340 (Venezuela)

Links

ProcessUniverse
Producers
Reference
Shape
Values marked * are estimates.
No warranty is given for the accuracy of this data

Low alloy steel, AISI 4150, tempered at 205°C & oil quenched

General information

Designation

AISI 4150	
Condition	Tempered at 205°C & oil quenched
UNS number	G41500
US name	SAE 4150, ASTM 4150, ASTM G41500, ASTM 1A 1, ASTM 4150H, ~SAE PS 40, ~SAE 4150H
GB (Chinese) name	50CrMo

Typical uses

General construction; general mechanical engineering; automotive; tools; axles; gears; springs.

Composition overview

Compositional summary

Fe97-98 / Cr0.8-1.1 / Mn0.75-1 / C0.48-0.53 / Si0.15-0.35 / Mo0.15-0.25 (impurities: S<0.04, P<0.035)

Material family	Metal (ferrous)
Base material	Fe (Iron)

Composition detail (metals, ceramics and glasses)

C (carbon)		0.48	-	0.53	%
Cr (chromium)		0.8	-	1.1	%
Fe (iron)	*	96.7	-	97.7	%
Mn (manganese)		0.75	-	1	%
Mo (molybdenum)		0.15	-	0.25	%
P (phosphorus)		0	-	0.035	%
S (sulfur)		0	-	0.04	%
Si (silicon)		0.15	-	0.35	%

Price

Price	*	0.286	-	0.299	USD/lb

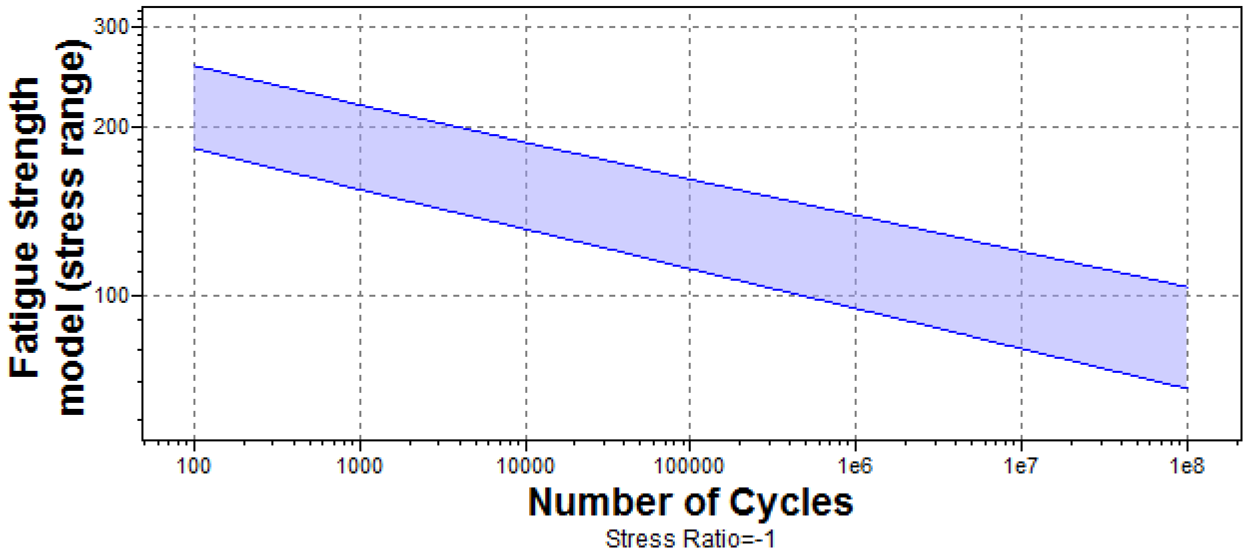
Physical properties

Density		0.282	-	0.285	lb/in^3

Mechanical properties

Young's modulus		29.2	-	30.7	10^6 psi
Yield strength (elastic limit)		225	-	276	ksi
Tensile strength		252	-	307	ksi
Elongation		8	-	12	% strain
Compressive strength	*	225	-	276	ksi
Flexural modulus	*	29.2	-	30.7	10^6 psi
Flexural strength (modulus of rupture)		225	-	276	ksi
Shear modulus		11.2	-	12	10^6 psi
Bulk modulus		22.5	-	25.1	10^6 psi
Poisson's ratio		0.285	-	0.295	
Shape factor		13			
Hardness - Vickers		475	-	585	HV
Fatigue strength at 10^7 cycles	*	91.4	-	105	ksi
Fatigue strength model (stress range)	*	80.2	-	120	ksi

Parameters: Stress Ratio = -1, Number of Cycles = 1e7cycles



Mechanical loss coefficient (tan delta)	*	2e-4	-	2.6e-4	

Impact & fracture properties

Fracture toughness	*	20.9	-	42.8	ksi.in^0.5

Thermal properties

Melting point		2.57e3	-	2.73e3	°F
Maximum service temperature	*	329	-	383	°F
Minimum service temperature	*	-54.4	-	-0.4	°F
Thermal conductivity	*	23.1	-	26.6	BTU.ft/hr.ft^2.°F
Specific heat capacity	*	0.107	-	0.117	BTU/lb.°F
Thermal expansion coefficient	*	6.11	-	7.22	µstrain/°F
Latent heat of fusion	*	114	-	120	BTU/lb

Electrical properties

Electrical resistivity		20	-	25	µohm.cm
Galvanic potential	*	-0.5	-	-0.42	V

Magnetic properties

Magnetic type	Magnetic

Optical properties

Transparency	Opaque

Bio-data

Food contact	Yes

Restricted substances risk indicators

RoHS (EU) compliant grades?	False

Processing properties

Metal casting	Unsuitable		
Metal cold forming	Excellent		
Metal hot forming	Excellent		
Metal press forming	Excellent		
Metal deep drawing	Limited use		
Carbon equivalency	0.795	-	0.967

Durability

Water (fresh)	Acceptable
Water (salt)	Limited use
Weak acids	Limited use
Strong acids	Unacceptable

Weak alkalis		Acceptable		
Strong alkalis		Limited use		
Organic solvents		Excellent		
Oxidation at 500C		Acceptable		
UV radiation (sunlight)		Excellent		
Galling resistance (adhesive wear)		Acceptable		
Flammability		Non-flammable		

Primary production energy, CO2 and water

Embodied energy, primary production — 1.32e4 - 1.46e4 BTU/lb

Sources

19.4 MJ/kg (Dhingra, Overly, Davis, 1999); 23 MJ/kg (Norgate, Jahanshahi, Rankin, 2007); 27.9 MJ/kg (Ecoinvent v2.2); 29.2 MJ/kg (Hammond and Jones, 2008); 32.8 MJ/kg (Hammond and Jones, 2008); 34.7 MJ/kg (Hammond and Jones, 2008); 35.4 MJ/kg (Hammond and Jones, 2008); 37.2 MJ/kg (Sullivan and Gaines, 2010); 38 MJ/kg (Hammond and Jones, 2008); 45.4 MJ/kg (Hammond and Jones, 2008)

CO2 footprint, primary production — 2.26 - 2.49 lb/lb

Sources

0.396 kg/kg (Voet, van der and Oers, van, 2003); 1.75 kg/kg (Ecoinvent v2.2); 1.81 kg/kg (Voet, van der and Oers, van, 2003); 2.23 kg/kg (Voet, van der and Oers, van, 2003); 2.3 kg/kg (Norgate, Jahanshahi, Rankin, 2007); 2.74 kg/kg (Hammond and Jones, 2008); 2.77 kg/kg (Hammond and Jones, 2008); 2.87 kg/kg (Hammond and Jones, 2008); 2.89 kg/kg (Hammond and Jones, 2008); 3.03 kg/kg (Hammond and Jones, 2008); 3.27 kg/kg (Hammond and Jones, 2008)

NOx creation	*	0.0126	-	0.0139	lb/lb
SOx creation	*	0.0215	-	0.0238	lb/lb
Water usage	*	1.34e3	-	1.48e3	in^3/lb

Processing energy, CO2 footprint & water

Casting energy	*	4.62e3	-	5.1e3	BTU/lb
Casting CO2	*	0.806	-	0.89	lb/lb
Casting water	*	563	-	844	in^3/lb
Rough rolling, forging energy	*	6.08e3	-	6.71e3	BTU/lb
Rough rolling, forging CO2	*	1.06	-	1.17	lb/lb
Rough rolling, forging water	*	210	-	315	in^3/lb
Extrusion, foil rolling energy	*	1.2e4	-	1.33e4	BTU/lb
Extrusion, foil rolling CO2	*	2.1	-	2.32	lb/lb
Extrusion, foil rolling water	*	374	-	561	in^3/lb
Wire drawing energy	*	4.48e4	-	4.95e4	BTU/lb
Wire drawing CO2	*	7.81	-	8.63	lb/lb
Wire drawing water	*	1.09e3	-	1.63e3	in^3/lb
Metal powder forming energy	*	1.59e4	-	1.76e4	BTU/lb
Metal powder forming CO2	*	2.96	-	3.27	lb/lb
Metal powder forming water	*	1.12e3	-	1.67e3	in^3/lb
Vaporization energy	*	4.67e6	-	5.16e6	BTU/lb
Vaporization CO2	*	815	-	901	lb/lb
Vaporization water	*	1.25e5	-	1.88e5	in^3/lb
Coarse machining energy (per unit wt removed)	*	1.1e3	-	1.21e3	BTU/lb
Coarse machining CO2 (per unit wt removed)	*	0.191	-	0.212	lb/lb
Fine machining energy (per unit wt removed)	*	9.13e3	-	1.01e4	BTU/lb
Fine machining CO2 (per unit wt removed)	*	1.59	-	1.76	lb/lb
Grinding energy (per unit wt removed)	*	1.81e4	-	2e4	BTU/lb
Grinding CO2 (per unit wt removed)	*	3.15	-	3.48	lb/lb
Non-conventional machining energy (per unit wt removed)	*	4.67e4	-	5.16e4	BTU/lb
Non-conventional machining CO2 (per unit wt removed)	*	8.15	-	9.01	lb/lb

Recycling and end of life

Recycle		False			
Embodied energy, recycling	*	3.48e3	-	3.85e3	BTU/lb
CO2 footprint, recycling	*	0.636	-	0.703	lb/lb
Recycle fraction in current supply		39.9	-	44	%
Downcycle		False			

Combust for energy recovery	Combust for energy recovery
Landfill	False
Biodegrade	Biodegrade

Possible substitutes for principal component

Iron is the least expensive and most widely used metal. In most applications, iron and steel compete either with less expensive nonmetallic materials or with more expensive materials having a property advantage. Iron and steel compete with lighter materials, such as aluminum and plastics, in the motor vehicle industry; aluminum,concrete, and wood in construction; and aluminum, glass, paper, and plastics in containers.

Geo-economic data for principal component

Principal component	Iron			
Typical exploited ore grade	45.1	-	49.9	%
Minimum economic ore grade	25	-	70	%
Abundance in Earth's crust	4.1e4	-	6.3e4	ppm
Abundance in seawater	0.0025	-	0.003	ppm
Annual world production, principal component	2.26e9			ton/yr
Reserves, principal component	1.57e11			l. ton

Main mining areas (metric tonnes per year)

Australia, 530e6
Brazil, 389e6
Canada, 40e6
China, 1.32e9
India, 150e3
Iran, 37e3
Kazakhstan, 25e6
Russia, 102e6
South Africa, 67e6
Sweden, 26e6
Ukraine, 80e6
United States of America, 52e6
Venezuela, 30e6
Other countries, 88e6

Eco-indicators for principal component

Eco-indicator 95	49.9	millipoints/lb
Eco-indicator 99	89.9	millipoints/lb

Notes

Keywords

MTD 4, Bethlehem Lukens Plate (USA); TKS 50CRMO4, ThyssenKrupp Stahl AG (GERMANY);

Standards with similar compositions

The following information is taken from ASM AlloyFinder 3 - see link to References table for further information.

IAS IRAM 4150 (Argentina)
EN 10083/1(91)A1(96) 1.7228 (Europe)
EN 10083/1(91)A1(96) 50CrMo4 (Europe)
AFNOR NFA35565(94) 48CD4 (France)
AFNOR NFA35565(94) 48CrMo4 (France)
AFNOR NFA35571 50SCD5 (France)
DIN 1652(90) 50CrMo4 (Germany)
DIN 1652(90) WNr 1.7228 (Germany)
DIN 17201(89) WNr 1.7228 (Germany)
DIN 17212(72) 49CrMo4 (Germany)
DIN 17212(72) WNr 1.7238 (Germany)
DIN 17230(80) 48CrMo4 (Germany)
DIN 17230(80) WNr 1.3565 (Germany)
DIN EN 10083(91) 50CrMo4 (Germany)

UNI 3545(80) 51CrMoV4 (Italy)
DGN B-203 4150 (Mexico)
DGN B-297 4150 (Mexico)
NMX-B-300(91) 4150 (Mexico)
AS 1444 X4150 (NSW Australia)
AS 1444(96) 4150 (NSW Australia)
TS 2288(97) 51CrMoV4-17701 (Turkey)
ASTM A29/A29M(93) 4150 (USA)
ASTM A322(96) 4150 (USA)
ASTM A331(95) 4150 (USA)
ASTM A519(96) 4150 (USA)
ASTM A752(93) 4150 (USA)
ASTM A829/A829M(95) 4150 (USA)
ASTM A866(94) 4150 (USA)
MIL-B-11595E(88) ORD 4150 (USA)
MIL-B-11595E(88) ORD 4150 ReS (USA)
MIL-S-11595 ORD4150 (USA)
SAE 770(84) 4150 (USA)
SAE J404(94) 4150 (USA)
AISI 4150 (USA)
COPANT 334 4150 (Venezuela)
COPANT 514 4150 (Venezuela)
C.4733 (Yugoslavia)
C.4736 (Yugoslavia)

Links

ProcessUniverse
Producers
Reference
Shape
Values marked * are estimates.
No warranty is given for the accuracy of this data

Nickel-titanium alloy, austenitic

General information

Overview

Nitinol exhibits the ability to undergo reversible phase changes (austenitic - martensitic) in the solid state. This leads to shape memory and superelastic characteristics, which has resulted in wide spread use in applications such as frames for glasses and vascular stents that utilise this shape memory functionality. This record represents the performance in the austenitic state.

Designation

Ni-45Ti Nitinol

UNS number	N01555

Typical uses

Medical device applications including stents, heart valves, guidewires, bone fixation devices and dental restorations; Frames for glasses; Mobile phone components; Underwires for bras; Switches or variable resistors;

Composition overview

Compositional summary

Ni54-57 / Ti43-46 (impurities: C<0.07, Co<0.05, Fe<0.05, O<0.05, Nb<0.025, Cr<0.01, Cu<0.01, H<0.005)

Material family	Metal (non-ferrous)
Base material	Ni (Nickel)

Composition detail (metals, ceramics and glasses)

C (carbon)		0	-	0.07	%
Co (cobalt)		0	-	0.05	%
Cr (chromium)		0	-	0.01	%
Cu (copper)		0	-	0.01	%
Fe (iron)		0	-	0.05	%
H (hydrogen)		0	-	0.005	%
Nb (niobium)		0	-	0.025	%
Ni (nickel)		54.5	-	57	%
O (oxygen)		0	-	0.05	%
Ti (titanium)		42.7	-	45.5	%

Price

Price	*	9.34	-	10.4	USD/lb

Physical properties

Density		0.232	-	0.236	lb/in^3

Mechanical properties

Young's modulus		5.95	-	12	10^6 psi
Yield strength (elastic limit)		28.3	-	100	ksi
Tensile strength		130	-	276	ksi
Elongation		5	-	50	% strain
Compressive strength	*	59.5	-	69.3	ksi
Flexural modulus	*	8.56	-	9.44	10^6 psi
Flexural strength (modulus of rupture)		28.3	-	100	ksi
Shear modulus	*	3.42	-	3.77	10^6 psi
Bulk modulus	*	8.56	-	9.44	10^6 psi
Poisson's ratio		0.32	-	0.34	
Shape factor		14			
Hardness - Vickers	*	1.23e3	-	1.43e3	HV
Fatigue strength at 10^7 cycles	*	19.4	-	23.5	ksi

Impact & fracture properties

Fracture toughness	*	247	-	298	ksi.in^0.5

Thermal properties

Melting point		2.34e3	-	2.43e3	°F
Maximum service temperature	*	-58	-	212	°F

Minimum service temperature		-459			°F
Thermal conductivity		9.88	-	10.9	BTU.ft/hr.ft^2.°F
Specific heat capacity		0.196	-	0.204	BTU/lb.°F
Thermal expansion coefficient		6	-	6.22	µstrain/°F
Latent heat of fusion		10.2	-	10.6	BTU/lb

Electrical properties

Electrical resistivity		82	-	100	µohm.cm
Galvanic potential	*	-0.23	-	-0.15	V

Magnetic properties

Magnetic type — Magnetic

Optical properties

Transparency — Opaque

Bio-data

Food contact — Yes

Restricted substances risk indicators

RoHS (EU) compliant grades? — False

Processing properties

Metal casting	Acceptable
Metal cold forming	Excellent
Metal hot forming	Excellent
Metal press forming	Acceptable
Metal deep drawing	Limited use

Durability

Water (fresh)	Excellent
Water (salt)	Excellent
Weak acids	Excellent
Strong acids	Acceptable
Weak alkalis	Excellent
Strong alkalis	Excellent
Organic solvents	Excellent
Oxidation at 500C	Excellent
UV radiation (sunlight)	Excellent
Galling resistance (adhesive wear)	Limited use

Notes

Tendency to gall when formed but excellent self-mating resistance with minimal lubrication.

Flammability — Non-flammable

Primary production energy, CO2 and water

Embodied energy, primary production	*	1.44e5	-	1.59e5	BTU/lb
CO2 footprint, primary production	*	20.2	-	22.3	lb/lb
NOx creation	*	0.133	-	0.147	lb/lb
SOx creation	*	0.228	-	0.252	lb/lb
Water usage	*	3.88e4	-	4.29e4	in^3/lb

Processing energy, CO2 footprint & water

Casting energy	*	5.04e3	-	5.57e3	BTU/lb
Casting CO2	*	0.879	-	0.971	lb/lb
Casting water	*	614	-	921	in^3/lb
Rough rolling, forging energy	*	4.59e3	-	5.07e3	BTU/lb
Rough rolling, forging CO2	*	0.8	-	0.884	lb/lb
Rough rolling, forging water	*	169	-	254	in^3/lb
Extrusion, foil rolling energy	*	9.05e3	-	1e4	BTU/lb
Extrusion, foil rolling CO2	*	1.58	-	1.75	lb/lb
Extrusion, foil rolling water	*	292	-	438	in^3/lb
Wire drawing energy	*	3.36e4	-	3.71e4	BTU/lb
Wire drawing CO2	*	5.86	-	6.48	lb/lb

Wire drawing water	*	815	-	1.22e3	in^3/lb
Metal powder forming energy	*	7.03e3	-	7.77e3	BTU/lb
Metal powder forming CO2	*	1.23	-	1.36	lb/lb
Metal powder forming water	*	494	-	741	in^3/lb
Vaporization energy	*	4.15e5	-	4.59e5	BTU/lb
Vaporization CO2	*	72.5	-	80.1	lb/lb
Vaporization water	*	1.11e4	-	1.67e4	in^3/lb
Coarse machining energy (per unit wt removed)	*	873	-	967	BTU/lb
Coarse machining CO2 (per unit wt removed)	*	0.152	-	0.169	lb/lb
Fine machining energy (per unit wt removed)	*	6.9e3	-	7.63e3	BTU/lb
Fine machining CO2 (per unit wt removed)	*	1.2	-	1.33	lb/lb
Grinding energy (per unit wt removed)	*	1.34e4	-	1.48e4	BTU/lb
Grinding CO2 (per unit wt removed)	*	2.34	-	2.58	lb/lb
Non-conventional machining energy (per unit wt removed)	*	4.15e3	-	4.59e3	BTU/lb
Non-conventional machining CO2 (per unit wt removed)	*	0.725	-	0.801	lb/lb

Recycling and end of life

Recycle		False			
Embodied energy, recycling	*	2.14e4	-	2.36e4	BTU/lb
CO2 footprint, recycling	*	3.91	-	4.32	lb/lb
Recycle fraction in current supply		0.1			%
Downcycle		False			
Combust for energy recovery		Combust for energy recovery			
Landfill		False			
Biodegrade		Biodegrade			

Geo-economic data for principal component

Principal component		Nickel			
Typical exploited ore grade	*	0.997	-	1.1	%
Minimum economic ore grade	*	0.1	-	2	%
Abundance in Earth's crust	*	80	-	90	ppm
Abundance in seawater	*	5e-4	-	0.002	ppm
Annual world production, principal component		1.41e6			ton/yr
Reserves, principal component		6.99e7			l. ton

Main mining areas (metric tonnes per year)

Australia, 240e3
Brazil, 149e3
Canada, 225e3
China, 95e3
Colombia, 75e3
Cuba, 66e3
Dominican Republic, 12.5e3
Indonesia, 440e3
Madagascar, 26e3
New Caledonia, 145e3
the Philippines, 440e3
Russia, 250e3
South Africa, 48e3
Other countries, 274e3

Notes

Other notes

Nitinol demonstrates both superelasticity and shape memory functionality due to it being able to undergo phase changes in the solid state. Martensitic and austenitic crystal structures are possible and it is the reversible transition between these two phases that results in these unique material properties.

At low temperatures below the transition temperature nitinol exists in the martensitic phase, whereas above this temperature it exists in the austenitic phase. This transition temperature varies depending on the composition of the nitinol and can be from -50°C to 150°C. The shape of the nitinol structure, known as the parent shape is defined in the high temperature austenitic phase and is remembered by the material, even when it is deformed at lower temperatures. So when the structure is returned to the austenitic phase the parent shape is returned and demonstrates thermal shape memory.

The closely related effect of superelasticity in nitinol also results from this transition between phases, but instead of temperature the application of stress causes the phase change. Within a certain temperature range it is possible to apply a stress to a nitinol structure that changes the material from the austenitic phase to the martensitic phase, whilst causing a shape change. When the stress is removed the austenitic phase is restored and the nitinol structure returns to is parent shape. So applying and then removing a stress to nitinol materials can result in the same effect as cooling and heating it through its transition temperature.

Keywords

Fort Wayne FWM NiTi, Johnson Matthey NITI, Memry, NASA SP-5110, NDC SE508 Tubing, NDC SE508 Wire, NDC SM495 Wire,Special Metals Body-Temperature Ni-Ti, Special Metals Chrome-Doped Superelastic Ni-Ti,Special Metals High-Strength,Superelastic Ni-Ti, Special Metals High-Temperature Shape Memory Ni-Ti, Special Metals Ribbon High-Temperature Shape Memory Ni-Ti, Special Metals Superelastic Ni-Ti

Links

ProcessUniverse
Producers
Reference
Values marked * are estimates.
No warranty is given for the accuracy of this data

Titanium, alpha-beta alloy, Ti-6Al-2Sn-4Zr-6Mo (6-2-4-6)

General information

Designation

Ti-6Al-2Sn-4Zr-6Mo (6-2-4-6)

Typical uses

Gas turbine applications, deep sour wells.

Composition overview

Compositional summary

Ti80-84 / Al5.5-6.5 / Mo5.5-6.5 / Zr3.5-4.5 / Sn1.8-2.2 (impurities: Fe<0.15, C<0.04, N<0.04)

Material family		Metal (non-ferrous)			
Base material		Ti (Titanium)			

Composition detail (metals, ceramics and glasses)

Al (aluminum)		5.5	-	6.5	%
C (carbon)		0	-	0.04	%
Fe (iron)		0	-	0.15	%
Mo (molybdenum)		5.5	-	6.5	%
N (nitrogen)		0	-	0.04	%
Sn (tin)		1.75	-	2.25	%
Ti (titanium)	*	80	-	83.8	%
Zr (zirconium)		3.5	-	4.5	%

Price

Price	*	10.4	-	11.1	USD/lb

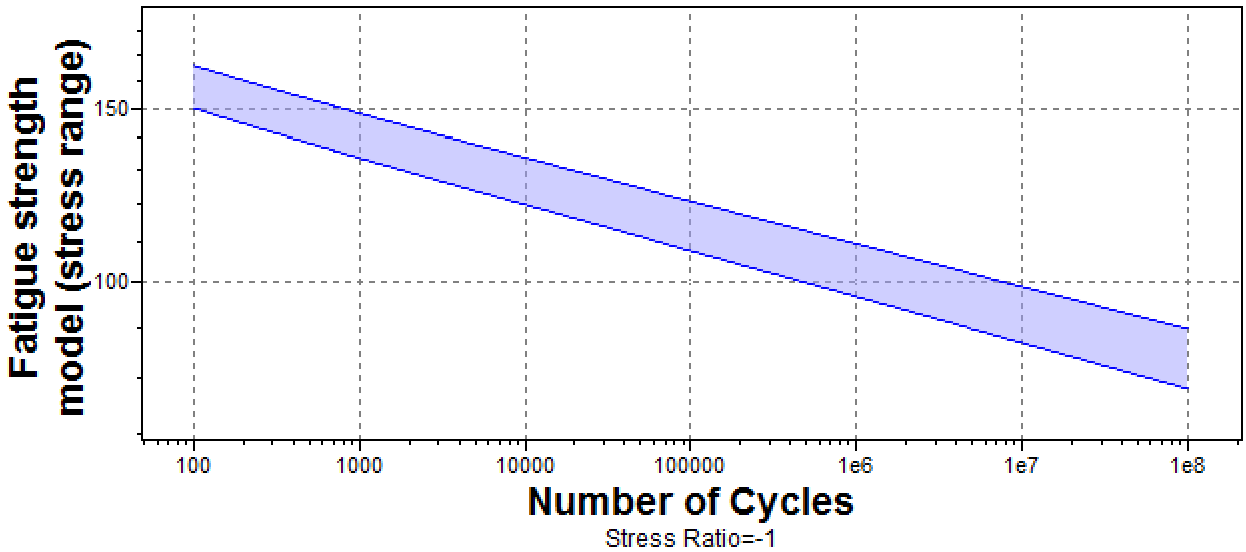
Physical properties

Density		0.168			lb/in^3

Mechanical properties

Young's modulus		16.4	-	16.7	10^6 psi
Yield strength (elastic limit)		155	-	160	ksi
Tensile strength		170	-	174	ksi
Elongation		10	-	20	% strain
Compressive strength	*	162	-	170	ksi
Flexural modulus	*	16.4	-	16.7	10^6 psi
Flexural strength (modulus of rupture)		162	-	170	ksi
Shear modulus		5.95	-	6.24	10^6 psi
Bulk modulus		18.1	-	21.5	10^6 psi
Poisson's ratio		0.35	-	0.37	
Shape factor		11			
Hardness - Vickers		336	-	351	HV
Fatigue strength at 10^7 cycles	*	91.8	-	93.7	ksi
Fatigue strength model (stress range)	*	86.8	-	99.1	ksi

Parameters: Stress Ratio = -1, Number of Cycles = 1e7cycles



Mechanical loss coefficient (tan delta)	*	0.001	-	0.002	
Impact & fracture properties					
Fracture toughness	*	63.7	-	72.8	ksi.in^0.5
Thermal properties					
Melting point		2.96e3	-	2.99e3	°F
Maximum service temperature		824	-	860	°F
Minimum service temperature		-459			°F
Thermal conductivity		4.04	-	4.1BTU.ft/hr.ft^2.°F	
Specific heat capacity	*	0.129	-	0.155	BTU/lb.°F
Thermal expansion coefficient		5.22	-	5.44	µstrain/°F
Latent heat of fusion		155	-	159	BTU/lb
Electrical properties					
Electrical resistivity	*	158	-	200	µohm.cm
Galvanic potential	*	-0.12	-	-0.04	V
Magnetic properties					
Magnetic type		Non-magnetic			
Optical properties					
Transparency		Opaque			
Bio-data					
Food contact		No			
Restricted substances risk indicators					
RoHS (EU) compliant grades?		False			
Processing properties					
Metal casting		Acceptable			
Metal cold forming		Limited use			
Metal hot forming		Acceptable			
Metal press forming		Acceptable			
Metal deep drawing		Limited use			
Durability					
Water (fresh)		Excellent			
Water (salt)		Excellent			
Weak acids		Excellent			
Strong acids		Acceptable			
Weak alkalis		Excellent			

Strong alkalis	Acceptable			
Organic solvents	Excellent			
Oxidation at 500C	Acceptable			
UV radiation (sunlight)	Excellent			
Galling resistance (adhesive wear)	Limited use			

Notes

High tendency to gall can be overcome by anodizing.

Flammability	Non-flammable			

Primary production energy, CO2 and water

Embodied energy, primary production	* 2.33e5	-	2.57e5	BTU/lb
CO2 footprint, primary production	* 31.3	-	34.5	lb/lb
NOx creation	* 0.215	-	0.237	lb/lb
SOx creation	* 0.367	-	0.406	lb/lb
Water usage	* 1.09e4	-	1.2e4	in^3/lb

Processing energy, CO2 footprint & water

Casting energy	* 5.64e3	-	6.23e3	BTU/lb
Casting CO2	* 0.984	-	1.09	lb/lb
Casting water	* 687	-	1.03e3	in^3/lb
Rough rolling, forging energy	* 6.83e3	-	7.54e3	BTU/lb
Rough rolling, forging CO2	* 1.19	-	1.32	lb/lb
Rough rolling, forging water	* 231	-	346	in^3/lb
Extrusion, foil rolling energy	* 1.35e4	-	1.5e4	BTU/lb
Extrusion, foil rolling CO2	* 2.36	-	2.61	lb/lb
Extrusion, foil rolling water	* 415	-	623	in^3/lb
Wire drawing energy	* 5.04e4	-	5.57e4	BTU/lb
Wire drawing CO2	* 8.79	-	9.72	lb/lb
Wire drawing water	* 1.22e3	-	1.83e3	in^3/lb
Metal powder forming energy	* 2.02e4	-	2.24e4	BTU/lb
Metal powder forming CO2	* 3.76	-	4.17	lb/lb
Metal powder forming water	* 1.42e3	-	2.13e3	in^3/lb
Vaporization energy	* 6.26e6	-	6.92e6	BTU/lb
Vaporization CO2	* 1.09e3	-	1.21e3	lb/lb
Vaporization water	* 1.68e5	-	2.52e5	in^3/lb
Coarse machining energy (per unit wt removed)	* 1.21e3	-	1.34e3	BTU/lb
Coarse machining CO2 (per unit wt removed)	* 0.211	-	0.233	lb/lb
Fine machining energy (per unit wt removed)	* 1.03e4	-	1.13e4	BTU/lb
Fine machining CO2 (per unit wt removed)	* 1.79	-	1.98	lb/lb
Grinding energy (per unit wt removed)	* 2.03e4	-	2.25e4	BTU/lb
Grinding CO2 (per unit wt removed)	* 3.54	-	3.92	lb/lb
Non-conventional machining energy (per unit wt removed)	* 6.26e4	-	6.92e4	BTU/lb
Non-conventional machining CO2 (per unit wt removed)	* 10.9	-	12.1	lb/lb

Recycling and end of life

Recycle	False			
Embodied energy, recycling	* 3.08e4	-	3.4e4	BTU/lb
CO2 footprint, recycling	* 5.63	-	6.22	lb/lb
Recycle fraction in current supply	21.8	-	24.1	%
Downcycle	False			
Combust for energy recovery	Combust for energy recovery			
Landfill	False			
Biodegrade	Biodegrade			

Possible substitutes for principal component

There are few substitutes for titanium in aircraft and space use without some sacrifice of performance. For industrial uses, high-nickel steel, zirconium, and, to a limited extent, the superalloy metals may be substituted. In certain applications, ground calcium carbonate, precipitated calcium carbonate, kaolin, and talc compete with titanium dioxide as a white pigment.

Geo-economic data for principal component

Principal component	Titanium			
Typical exploited ore grade	15.2	-	16.8	%
Minimum economic ore grade	2	-	30	%
Abundance in Earth's crust	4.4e3	-	6.6e3	ppm
Abundance in seawater	0.001			ppm
Annual world production, principal component	1.87e5	-	2.07e5	ton/yr
Reserves, principal component	7.14e8			l. ton

Main mining areas (metric tonnes per year)

Australia, 1.39e6
Brazil, 47e3
Canada, 770e3
China, 950e3
India, 366e3
Madagascar, 430e3
Mozambique, 489e3
Norway, 400e3
Sierra Leone, 90e3
South Africa, 1.22e6
Ukraine, 470e3
United States of America, 300e3
Vietnam, 500e3
Other countries, 107e3

Notes

Other notes

Elevated temperature characteristics of Ti-6242 with higher strength levels. Competitive over Ti-6242 up to approximately 727K.

Keywords

OMC 6AL-2SN-4ZR-6MO, Manufacturer unknown ();

Standards with similar compositions

IMI ; Grade ; DIN ; BSTA ; AMS 4981

Links

ProcessUniverse
Producers
Reference
Shape
Values marked * are estimates.
No warranty is given for the accuracy of this data

Appendix F: BOM Including Cost Analysis, List of Vendors, and Contact Information

BOM

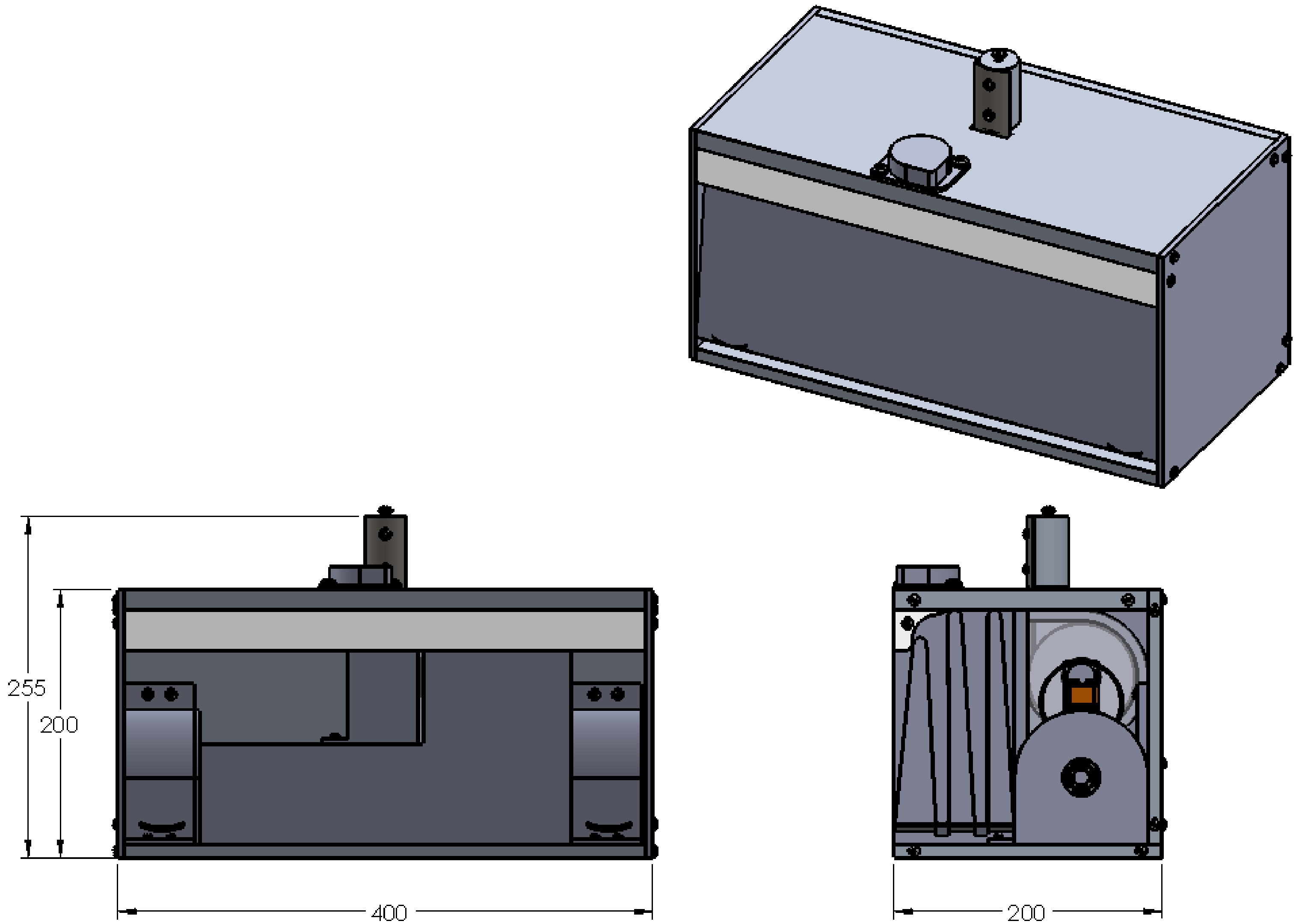
Part Description	Material	Supplier	Contact Information	upplier Part Numbe	Qty.	Unit Cost	Total Cost	Recieved?
Booms	1074/1075 Spring Steel	McMaster-Carr	https://www.mcmaster.com/#9074k12/=17gdntl	9074K12	2	$19.71	$39.42	Y
Ribs	Nitinol	Fort Wayne Metals	Angie Zachman angie_zachman@fwmetals.com 260-399-2102	172952	25	$800.00	$800.00	N
Top, Bottom, Back Plates	Aluminum 6061 (2ft x 2ft x 3/8 in)	Midwest	https://www.midweststeelsupply.com/store/6061aluminumplate	N/A	1	$59.17	$59.17	Y
Spool & Feed	6061 Aluminum Rod 4" 1 ft length	McMaster-Carr	https://www.mcmaster.com/#8974k97/=168uflh	8974K97	1	$53.00	$53.00	Y
Bearings	Steel Ball Bearing	McMaster-Carr	https://www.mcmaster.com/#5972k95/=1611ng2	5972K95	6	$7.11	$42.66	Y
Main Shaft	1045 Carbon Steel	McMaster-Carr	https://www.mcmaster.com/#1497k31/=16hdltd	8632T8	1	$29.37	$29.37	Y
Shaft Key	Steel	McMaster-Carr	https://www.mcmaster.com/#98491a100/=16agce8	98491A100	1	$1.09	$1.09	Y
Gear Stock	High Load Metal Gear Stock	McMaster-Carr	https://www.mcmaster.com/#6847k13/=16793pd	6847K13	1	$44.91	$44.91	Y
Motor Mounts	Aluminum 6061	McMaster-Carr	https://www.mcmaster.com/#9140t273/=16hdpfc	9146T84	2	$24.22	$48.44	Y
Feed Stand	Aluminum 6061 Angle	McMaster-Carr	https://www.mcmaster.com/#8982k69/=16hdr20	8982K92	1	$32.97	$32.97	Y
Tape Measure	N/A	Home Depot	Home Depot	N/A	1	$37.77	$37.77	Y
Mylar Roll	Mylar	Amazon	mazon.com/gp/product/B00725XC42/ref=oh_aui_detailpage_o01_s00?ie	N/A	1	$21.95	$21.95	Y
Clear Acrylic "	Acrylic 12"x12" x 3/16"	Amazon	mazon.com/gp/product/B006WPXZZO/ref=oh_aui_detailpage_o01_s01?i	N/A	4	$11.49	$45.96	Y
12 V Battery Supply Box	N/A	Amazon	mazon.com/gp/product/B00VE7HBMS/ref=oh_aui_detailpage_o01_s03?i	N/A	2	$8.00	$16.00	Y
Cable Ties	White 11"	Miners Ace Hardware	Miners Ace Hardware	N/A	1	$2.99	$2.99	Y
Eye Bolt	Steel 3/16" x 1.5	Miners Ace Hardware	Miners Ace Hardware	N/A	1	$0.99	$0.99	Y
Fishing Line	Microfiliment	Miners Ace Hardware	Miners Ace Hardware	N/A	1	$2.99	$2.99	Y
M4 -.7x16 Fastener 100pk	Steel	Miners Ace Hardware	Miners Ace Hardware	N/A	1	$13.99	$13.99	Y
Boom Fastener	Steel	Miners Ace Hardware	Miners Ace Hardware	N/A	12	$0.12	$1.44	Y
Set Screw for Gears	Steel	Miners Ace Hardware	Miners Ace Hardware	N/A	4	$0.30	$1.20	Y
Reel Mount Screws	Steel	Miners Ace Hardware	Miners Ace Hardware	N/A	4	$0.45	$1.80	Y
Feed Top Screw	Steel	Miners Ace Hardware	Miners Ace Hardware	N/A	2	$0.10	$0.20	Y
Shaft Key	Steel	Miners Ace Hardware	Miners Ace Hardware	N/A	3	$0.45	$1.35	Y
26 RPM Econ Motor	N/A	Servocity	Servocity	638380	8	$9.99	$79.92	Y
Shaft Coupler	Steel 12mm to 4mm	Servocity	Servocity	625238	1	$4.99	$4.99	Y
AA Batteries	N/A	Rite Aid	Rite Aid	N/A	2	$11.99	$23.98	Y
9V Batteries	N/A	Amazon	y-Alkaline-Batteries-8-Pack/dp/B00MH4QM1S/ref=sr_1_3_a_it?ie=UTF8	N/A	1	$9.99	$9.99	Y
Switches	N/A	RadioShack	RadioShack	N/A	3	$1.29	$3.87	Y
18V Variable Power Supply	N/A	RadioShack	RadioShack	N/A	1	$9.99	$9.99	Y
Extra Fasteners	Steel	Miners Ace Hardware	Miners Ace Hardware	N/A	10+	$1.78	$17.77	Y
Corner Brackets	Steel	Miners Ace Hardware	Miners Ace Hardware	N/A	2	0.59	$1.18	Y
Constant Force Reel	N/A	Almark Enterprises	p://almarkenterprises.com/product/ml4575-13-force-5-lbs-length-84-inch	ML4575	2	$17.00	$34.00	Y
						Shipping	$93.82	
						Tax	$48.68	
						Total	$1,627.85	

Appendix G: Drawing Packet Including Vendor Supplied Component Specification and Data Sheets

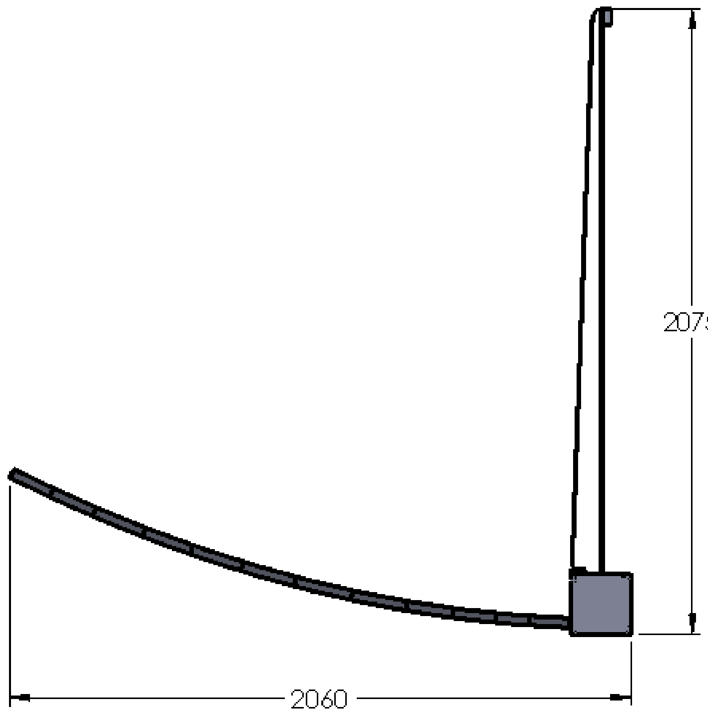
Drawing List

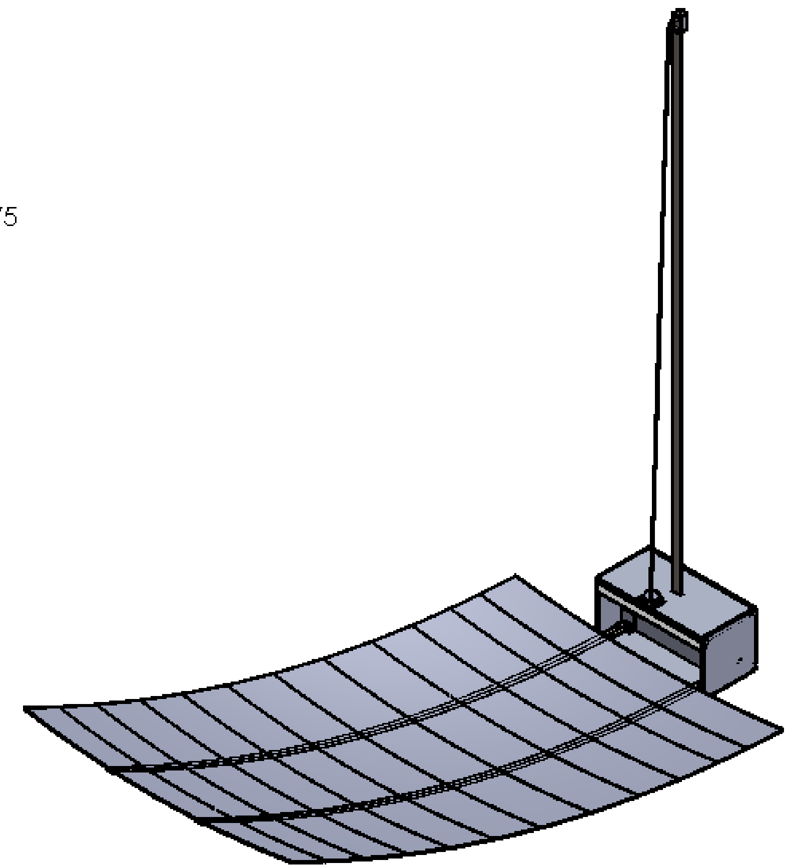
Subsystem	Part/Dwg. Number	Part Description
0. Deployable Antenna Assembly		
	100-HT-S	Heat Treatment, Stowed
	100-HT-D	Heat Treatment, Deployed
	100-ST-S	String Tensioners, Stowed
	100-ST-D	String Tensioners, Deployed
	100-E	Exploded View
I. Housing Assembly	200-HT	Housing Assembly (Heat Treatment)
	200-ST	Housing Assembly (String Tensioners)
	201-HT	Top Plate (Heat Treatment)
	201-ST	Top Plate (String Tensioners)
	202	Side Plate
	203	Bottom Plate
	204	Stopper
	205	Retractable Reel
	206	Cable Eyebolt
	207	Back Plate
	208	M6 Fastener
II. Reflector Deployer Assembly	300-HT	Reflector Deployer (Heat Treatment)
	300-ST	Reflector Deployer (String Tensioners)
	301-HT	Deployer Casing (Heat Treatment)
	301-ST	Deployer Casing (String Tensioners)
	302	Deployer Casing Cover
	303	Spool
	304-HT	Tape Measure Boom (Heat Treatment)
	304-ST	Tape Measure Boom (String Tensioners)
	305	Boom Fasteners (M2 x 0.4 mm) (100 pack)
	306	Bearings

III. Power Transmission	400	Power Transmission Assembly
	401	Main Shaft
	402	Shaft Key
	403	Motor Gear
	404	Main Shaft Gear
	405	Gear Stock
	406	Motor
	407	Set Screw for Gears
	408	Motor Mount
	409	Cable Ties
IV. Feed Deployment	500	Power Transmission Assembly
	501	Feed Deployer
	501-1	Feed Deployer Casing
	501-2	Feed Boom
	502	Feed Stand
	503	12 mm Feed Shaft
	504	Motor Shaft Coupler
	505	Feed Motor Mount
	506	Feed
	507	Feed Top Screw
V. Reflector	600	Reflector Assembly
	601	Mylar Sheet
	602	Nitinol Ribs
IV. Other Components	700	All Other Fasteners (M4x 0.7 mm) 100 pack
	701	9V Battery Supply
	702	Tensioning Cable

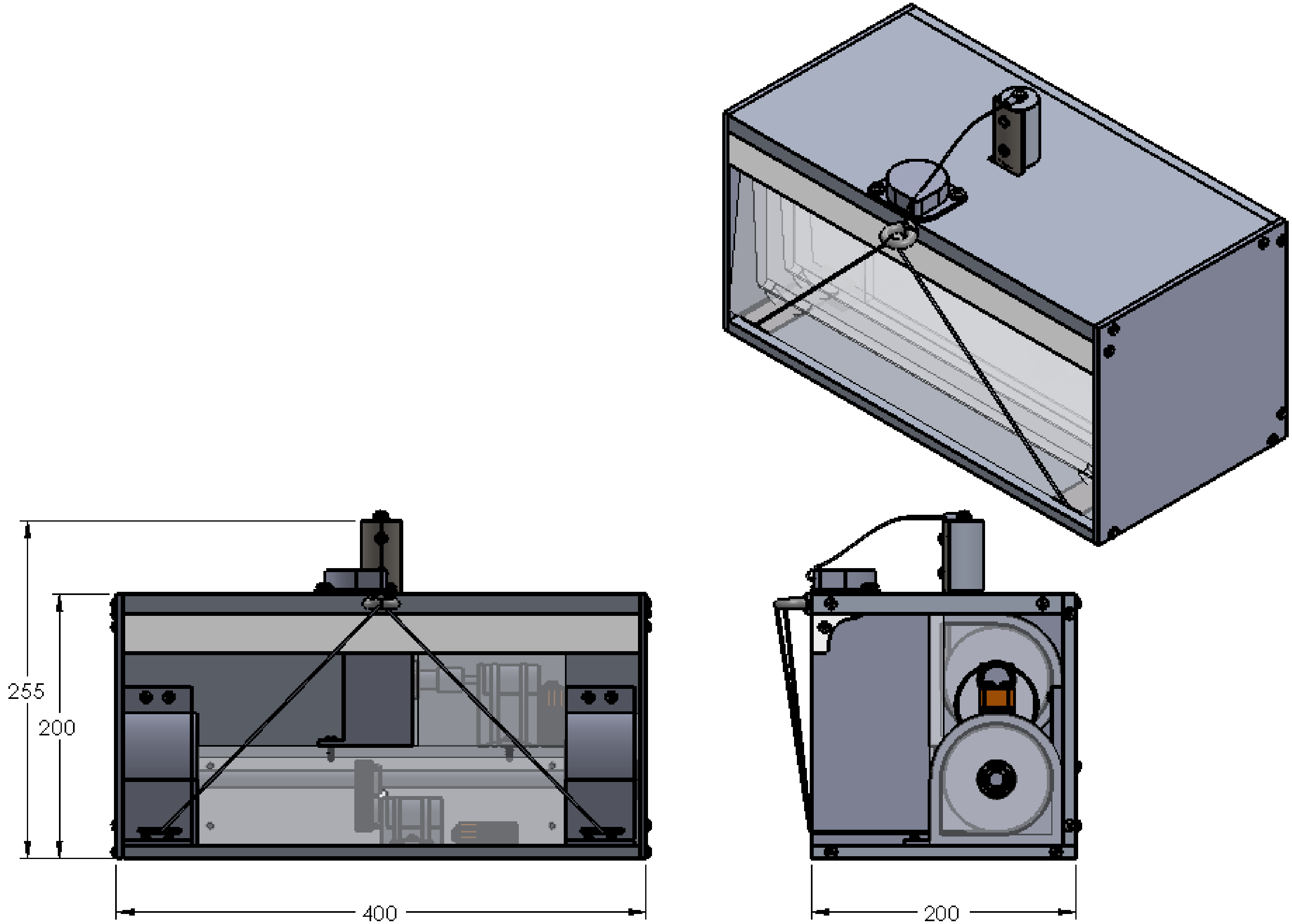


Cal Poly Mechanical Engineering	Part/Dwg. #: 100-HT-S	Title: Final Assembly (HT, Stowed)	Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR / Lab Section: 07	Date: 2/6/17 / Scale: 1:4	DEPLOYABLE ANTENNA PROJECT

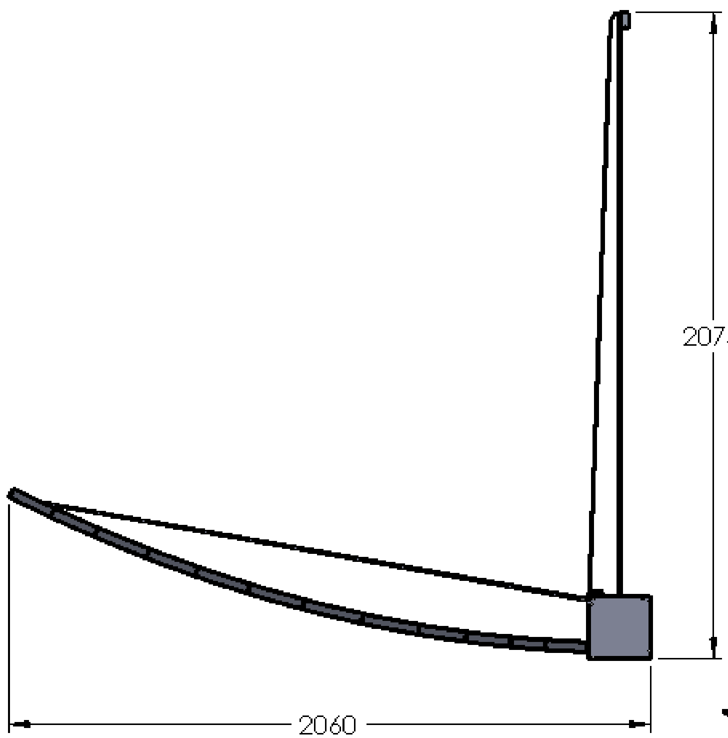


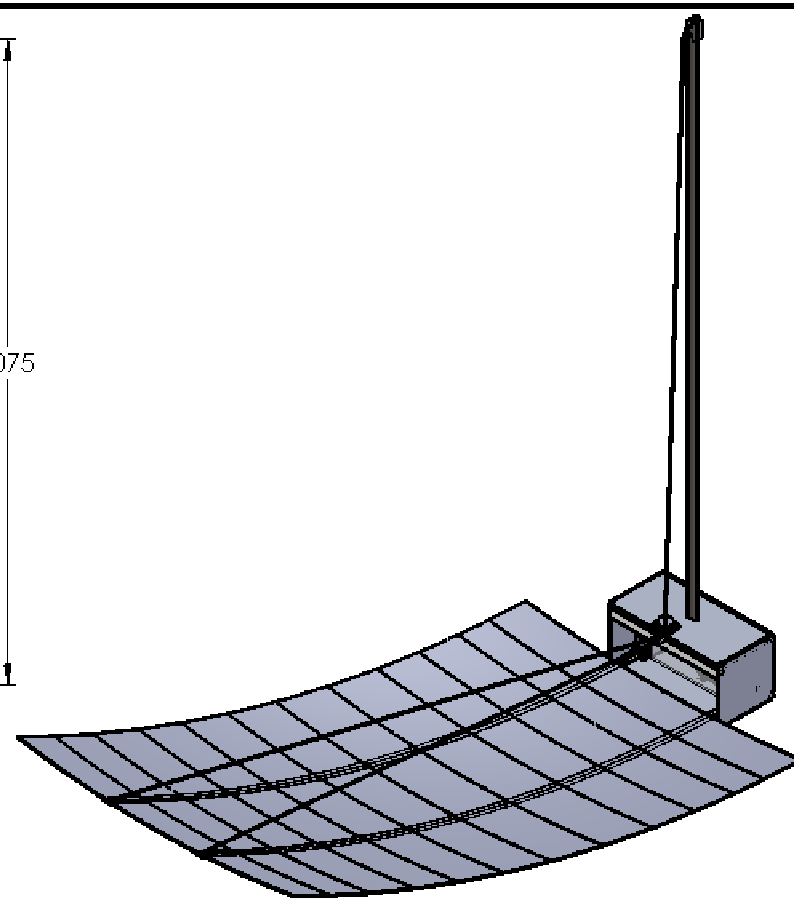


Cal Poly Mechanical Engineering	Part/Dwg. #: 100-HT-D	Title: Final Assembly (HT. Deployed)	Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR / Lab Section: 07	Date: 2/6/17 / Scale: 1:20	DEPLOYABLE ANTENNA PROJECT



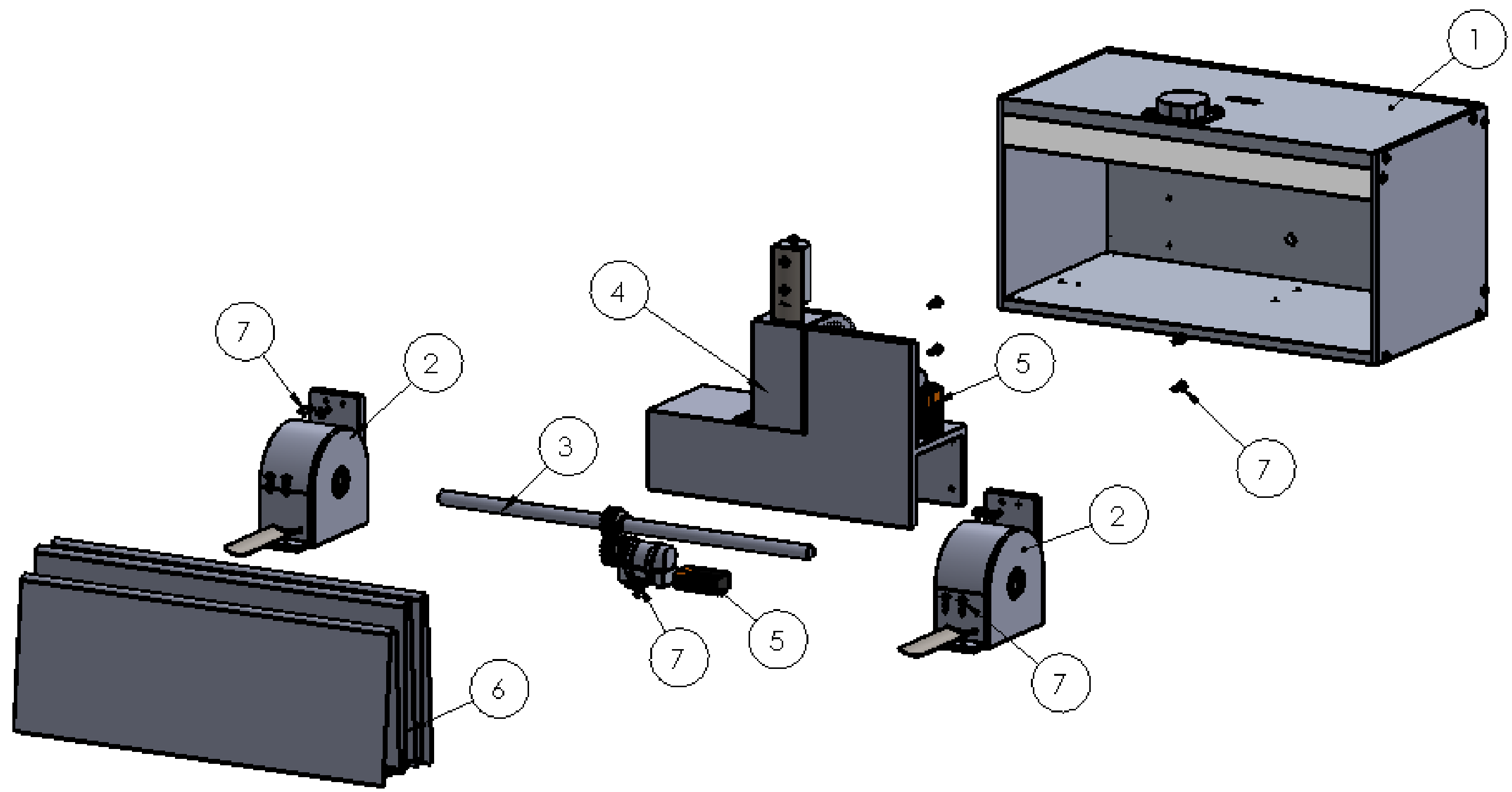
Cal Poly Mechanical Engineering ME 429 SENIOR PROJECT	Part/Dwg. #: 100-ST-S		Title: Final Assembly (Strings, Stowed)		Drwn. By: CALEB BARBER
	Team: STELLAR	Lab Section: 07	Date: 2/6/17	Scale: 1:4	DEPLOYABLE ANTENNA PROJECT





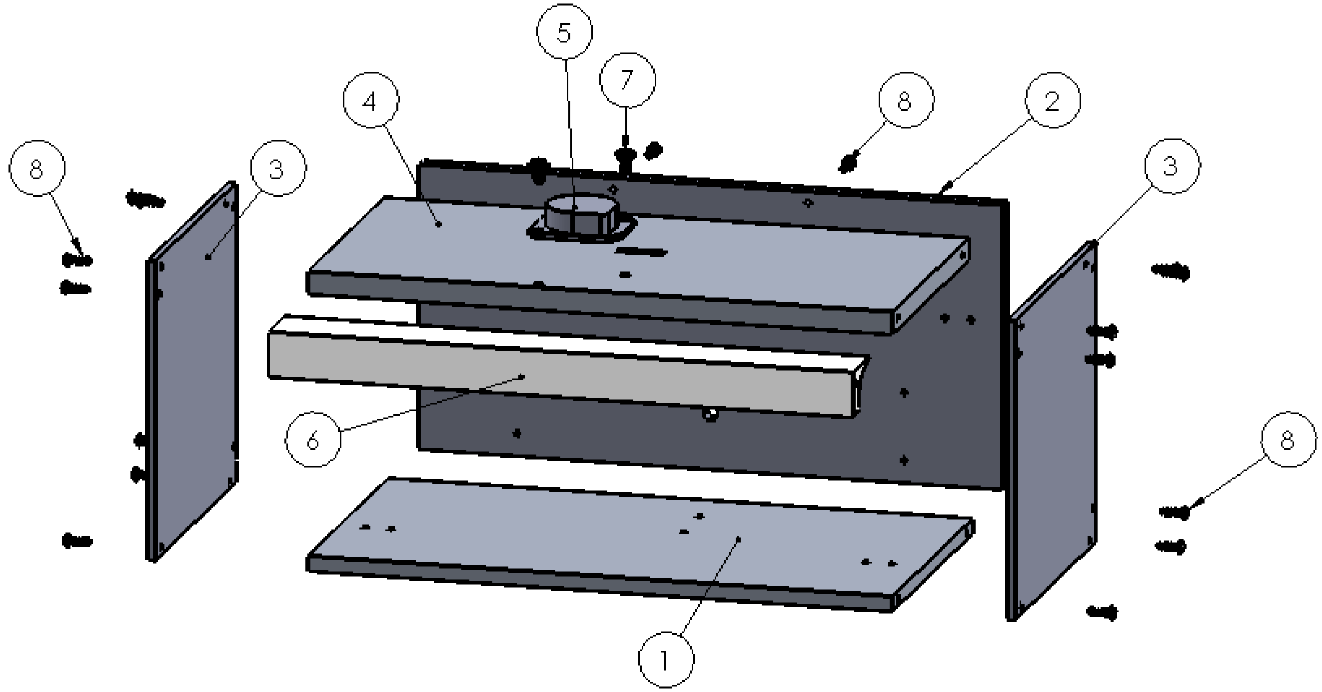
SCALE 1:16

Cal Poly Mechanical Engineering	Part/Dwg. #: 100-ST-D	Title: Final Assembly (Strings. Deployed)	Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR / Lab Section: 07	Date: 2/6/17 / Scale: 1:20	DEPLOYABLE ANTENNA PROJECT



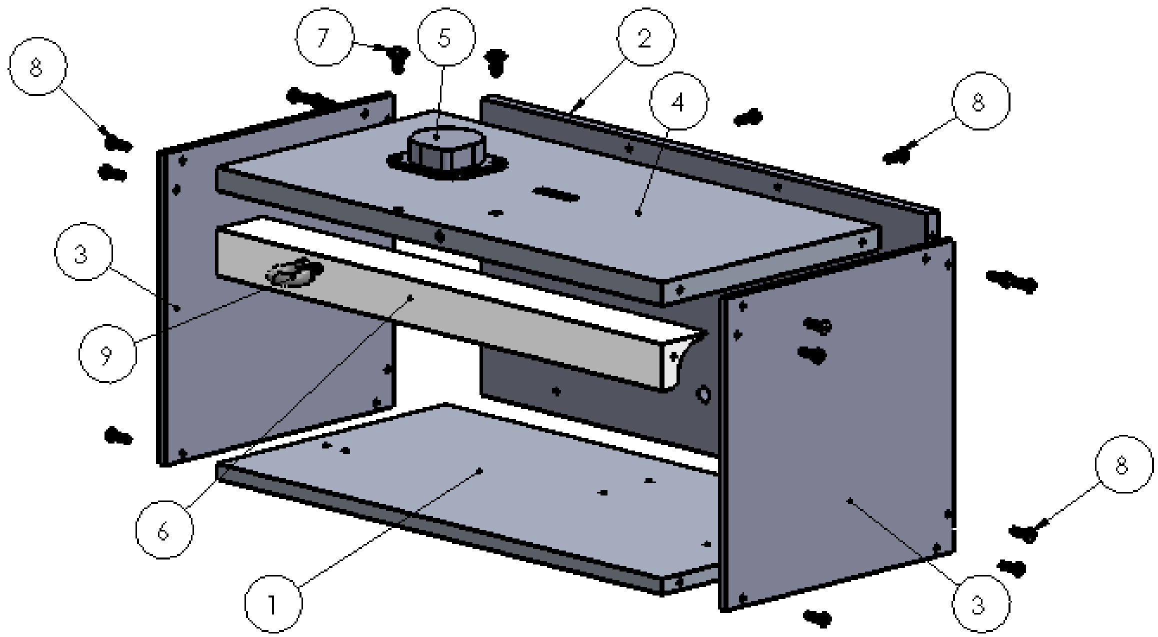
ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	200	Housing Assembly	-	1
2	300	Reflector Deployer Assmbl.	-	2
3	400	Power Transmission Assmbl.	-	1
4	500	Feed Deployment Assembly	-	1
5	701	9V Battery	-	2
6	600	Reflector Assembly	-	1
7	700	Common M4 Fastener	Steel	14

Cal Poly Mechanical Engineering ME 429 SENIOR PROJECT	Part/Dwg. #: 100-E-S Team: STELLAR / Lab Section: 07	Title: Final Assmbl. Expl. View - Stowed Date: 2/8/17 / Scale: 1:6	Drwn. By: CALEB BARBER DEPLOYABLE ANTENNA PROJECT



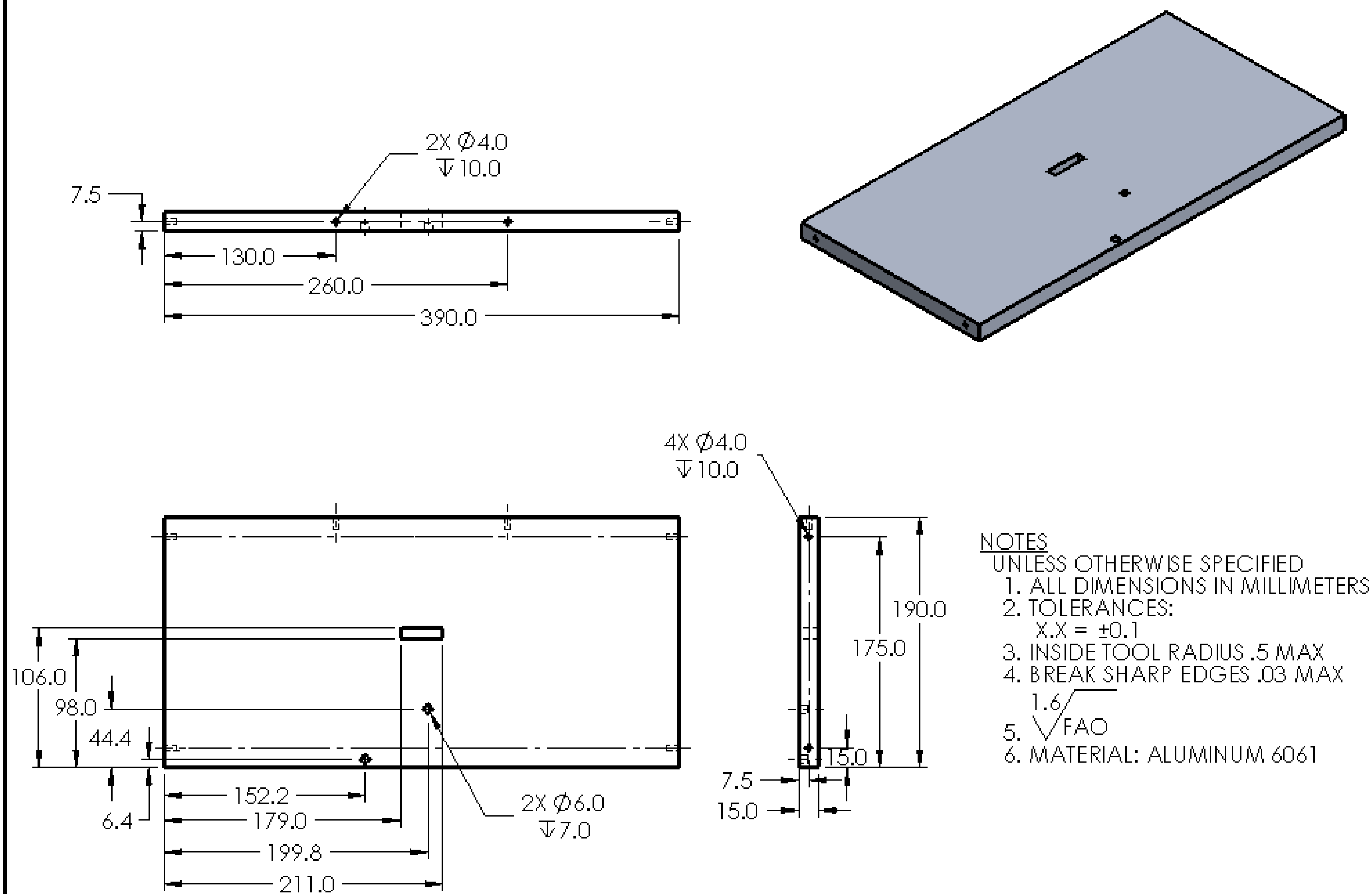
ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	203	Bottom Plate	AL 6061	1
2	207	Back Plate	AL 6061	1
3	202	Side Plate	AL 6061	2
4	201-HT	Top Plate (Heat Treatment)	AL 6061	1
5	205	Retractable Reel	-	1
6	204	Stopper	ABS	1
7	208	M6 Fastener	Steel	2
8	700	Common M4 Fastener	Steel	16

Cal Poly Mechanical Engineering ME 429 SENIOR PROJECT	Part/Dwg. #: 200-HT		Title: Housing Assembly (Heat Treament)	Drwn. By: CALEB BARBER
	Team: STELLAR	Lab Section: 07	Date: 2/8/17	Scale: 1:4	DEPLOYABLE ANTENNA PROJECT



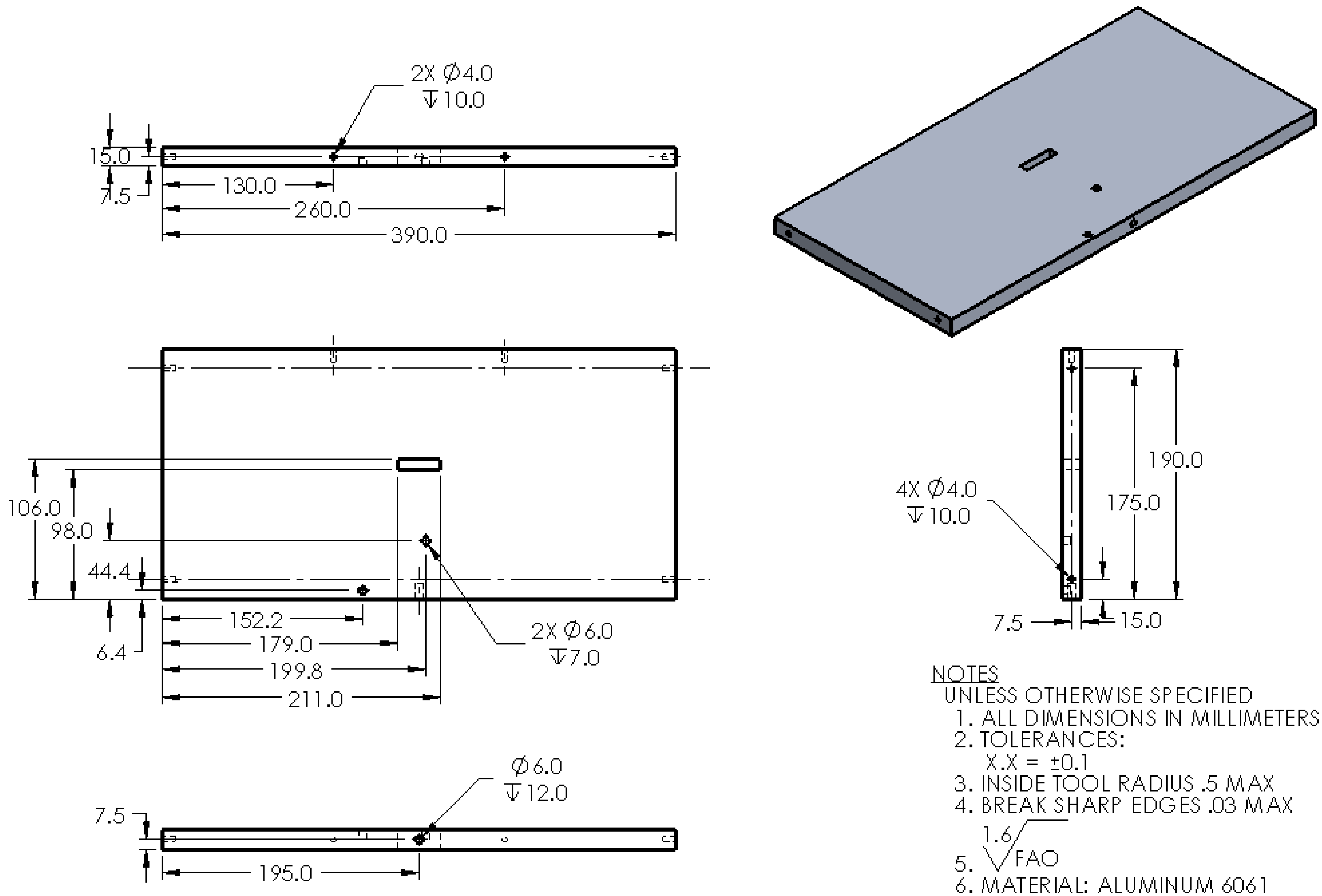
ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	203	Bottom Plate	AL 6061	1
2	207	Back Plate	AL 6061	1
3	202	Side Plate	AL 6061	2
4	201-ST	Top Plate (String Tensioners)	AL 6061	1
5	205	Retractable Reel	-	1
6	204	Stopper	ABS	1
7	208	M6 Fastener	Steel	2
8	700	Common M4 Fastener	Steel	16
9	206	Eyehook	Steel	1

Cal Poly Mechanical Engineering ME 429 SENIOR PROJECT	Part/Dwg. #: 200-ST		Title: Housing Assembly (String Tensioners)	Drwn. By: CALEB BARBER
	Team: STELLAR	Lab Section: 07	Date: 2/8/17 Scale: 1:4	DEPLOYABLE ANTENNA PROJECT



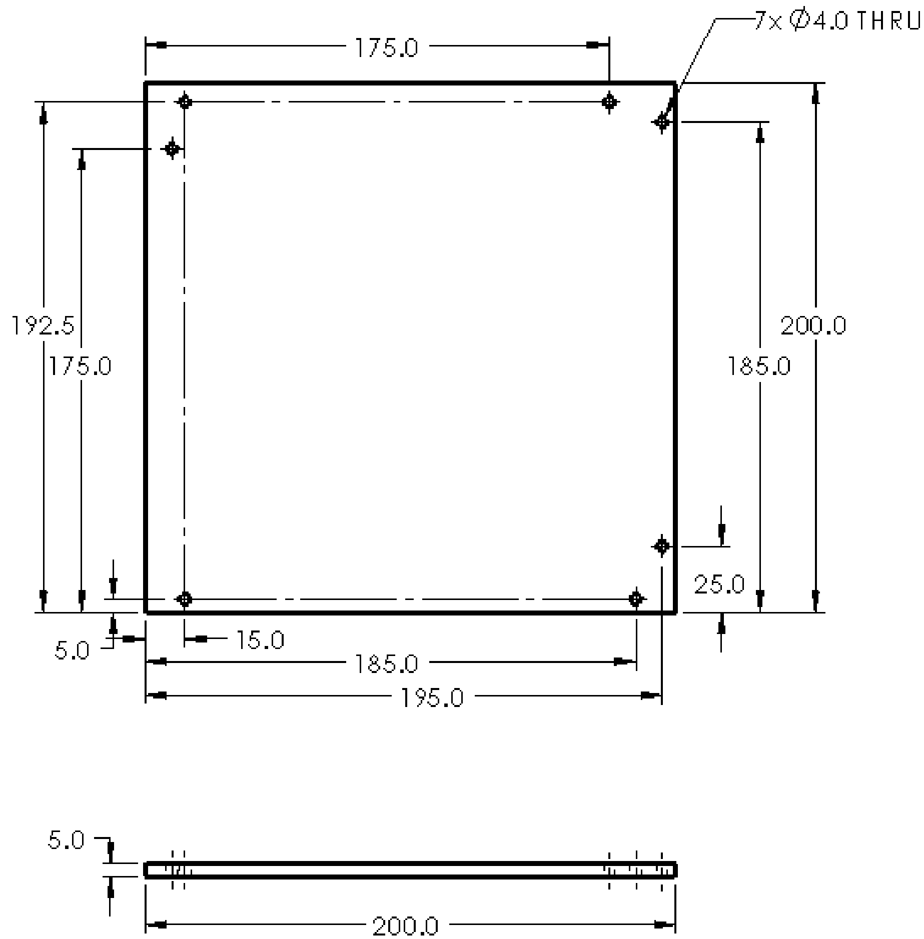
NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS .5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: ALUMINUM 6061

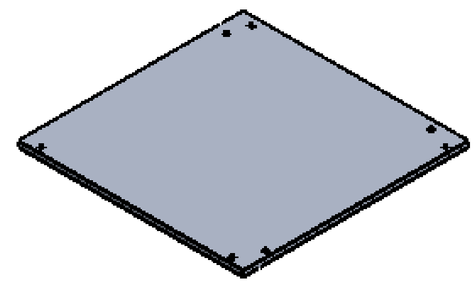
Cal Poly Mechanical Engineering	Part/Dwg. #: 201-HT		Title: Top Plate (Heat Treatment)		Drwn. By: DAVID GALVEZ
ME 429 SENIOR PROJECT	Team: STELLAR	Lab Section: 07	Date: 2/8/17	Scale: 1:4	DEPLOYABLE ANTENNA PROJECT



NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN MILLIMETERS
2. TOLERANCES:
X.X = ±0.1
3. INSIDE TOOL RADIUS .5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: ALUMINUM 6061

Cal Poly Mechanical Engineering	Part/Dwg. #: 201-ST		Title: Top Plate (String Tensioners)		Drwn. By: DAVID GALVEZ
ME 429 SENIOR PROJECT	Team: STELLAR	Lab Section: 07	Date: 2/8/17	Scale: 1:4	DEPLOYABLE ANTENNA PROJECT



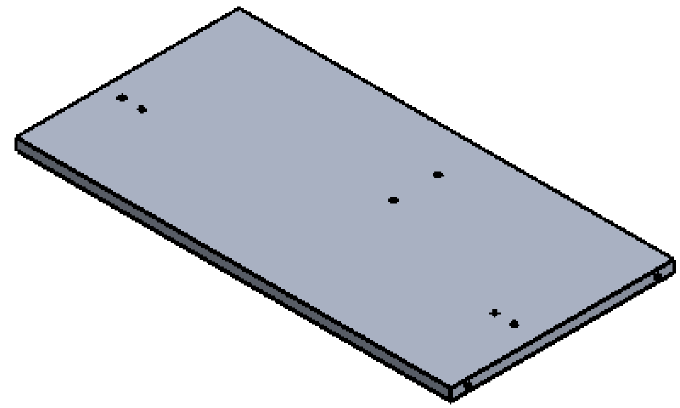


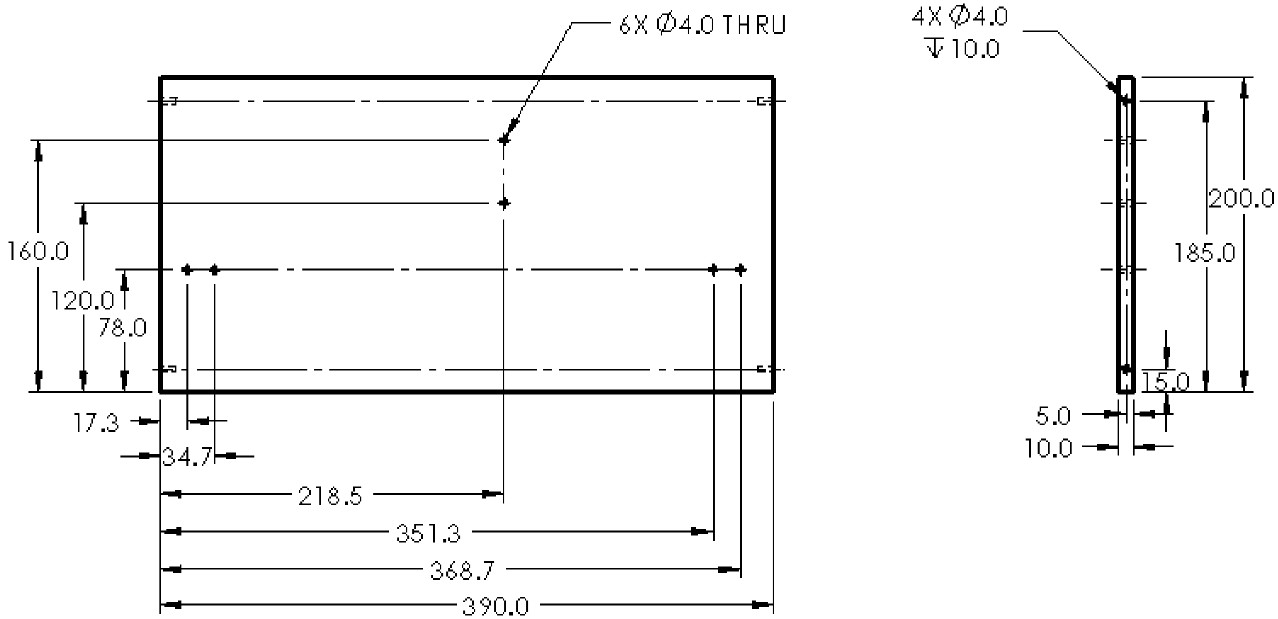
SCALE 1:4

NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN MILLIMETERS
2. TOLERANCES:
X.X = ±0.1
3. INSIDE TOOL RADIUS .5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: ALUMINUM 6061

Cal Poly Mechanical Engineering	Part/Dwg. #: 202	Title: Side Plate	Drwn. By: DAVID GALVEZ
ME 429 SENIOR PROJECT	Team: STELLAR / Lab Section: 07	Date: 2/8/17 / Scale: 5:12	DEPLOYABLE ANTENNA PROJECT

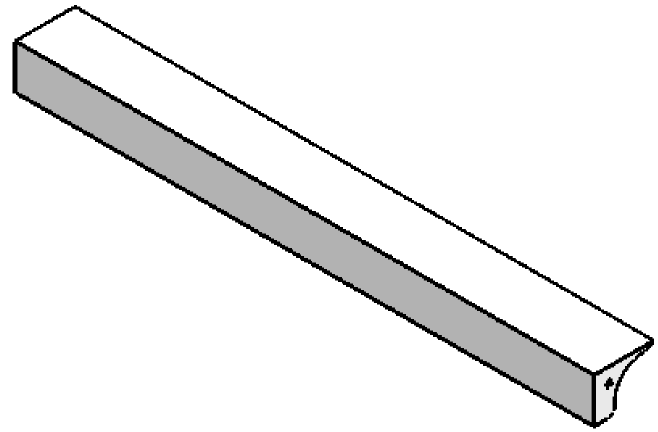
NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN MILLIMETERS
2. TOLERANCES:
X.X = ±0.1
3. INSIDE TOOL RADIUS .5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: ALUMINUM 6061

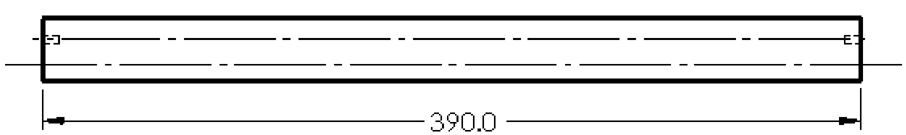


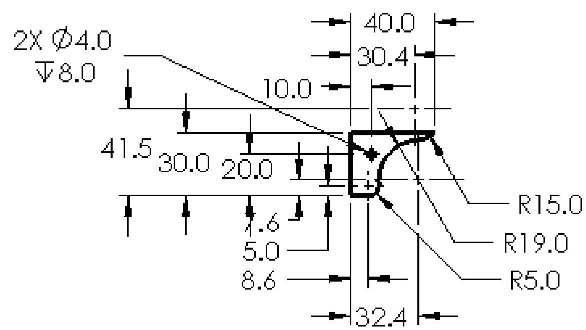


Cal Poly Mechanical Engineering	Part/Dwg. #: 203		Title: Bottom Plate		Drwn. By: DAVID GALVEZ
ME 429 SENIOR PROJECT	Team: STELLAR	Lab Section: 07	Date: 2/8/17	Scale: 1:4	DEPLOYABLE ANTENNA PROJECT

NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN MILLIMETERS
2. TOLERANCES:
X.X = ±0.1
3. INSIDE TOOL RADIUS .5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: ABS PLASTIC







Cal Poly Mechanical Engineering	Part/Dwg. #: 204	Title: Stopper	Drwn. By: DAVID GALVEZ
ME 429 SENIOR PROJECT	Team: STELLAR / Lab Section: 07	Date: 2/8/17 / Scale: 1:3	DEPLOYABLE ANTENNA PROJECT

ML4575-13 Force .5 lbs. Length 84 inches

$17.00

Part Number: 205

1

Add to cart

Description | Additional Information

Product Description

Unique little reels that have unlimited possibilities for managing cable bundles or any other small devices through a range of travel, or for security. Force 0.5 lbs.

Unique little reels that have unlimited possibilities for managing cable bundles or any other small devices through a range of travel, or for security. Stainless steel braided wire is available in 4 different lengths and spring pull weights to satisfy numerous applications. Small 2" footprint allows mounting in restricted locations, either horizontally or vertically. Swaged on ring terminal is your attachment point and prevents wire from retracting back inside the reel when released. Locking mechanisms are not available.

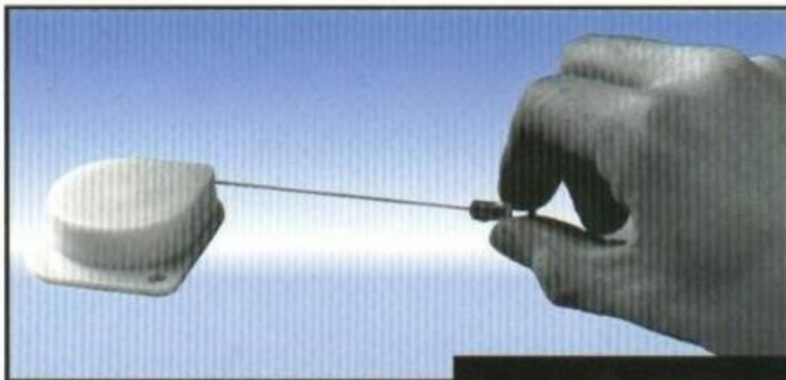
- ML4575-13 Force .5 lbs. – length 84 inches
- RoHS Compliant

Base Reel Outline

Series ML-4575 Stock Spring-Powered, Base Mounted Reel

FEATURES

- *Tamper-proof, closed case design*
- *Tough, durable Celcon construction*
- *stainless steel cable*
- *Compact design*



BASE MOUNTED REEL

DESCRIPTION

Designed for counterbalancing, retrieving, retracting and product security applications. The ML-4575 series utilizes the SPIR'ATOR® prestressed spiral spring. This base mounted reel series offers a variety of cable lengths and cable tensions. The unit is supplied with a stainless steel cable.

The base, arbor and drum, made of Celcon, provide a case designed for long term use. Tampering with the spring unit is impossible due to the closed case construction. Two .238" mounting holes are provided in the base.

SPECIFICATIONS

SPRING: Type 301 Stainless Steel SPIR'ATOR® Spring

CABLE: .018" dia 7x7 Stainless Steel,

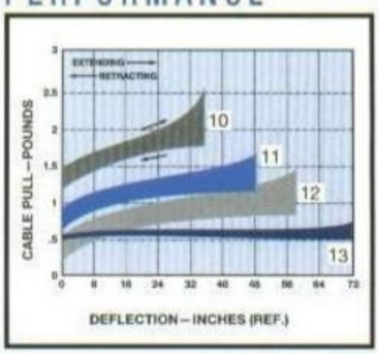
BASE: Celcon

DRUM: Celcon

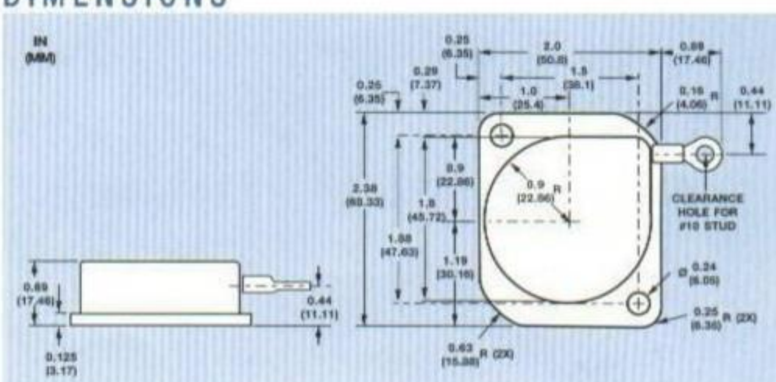
CABLE	LENGTHS
ML4575-10	42in
ML4575-11	52in
ML4575-12	64in
ML4575-13	84in

SPECIFICATIONS SUBJECT TO CHANGE WITHOUT NOTICE

PERFORMANCE



DIMENSIONS



AIMARK Enterprises Inc.

PHONE: 610-762-4390

Zinc-Plated Steel Eyebolt - for Lifting

M6 x 1 Thread Size, 12 mm Thread Length

Each

ADD TO ORDER

In stock
$3.82 Each
3107T41

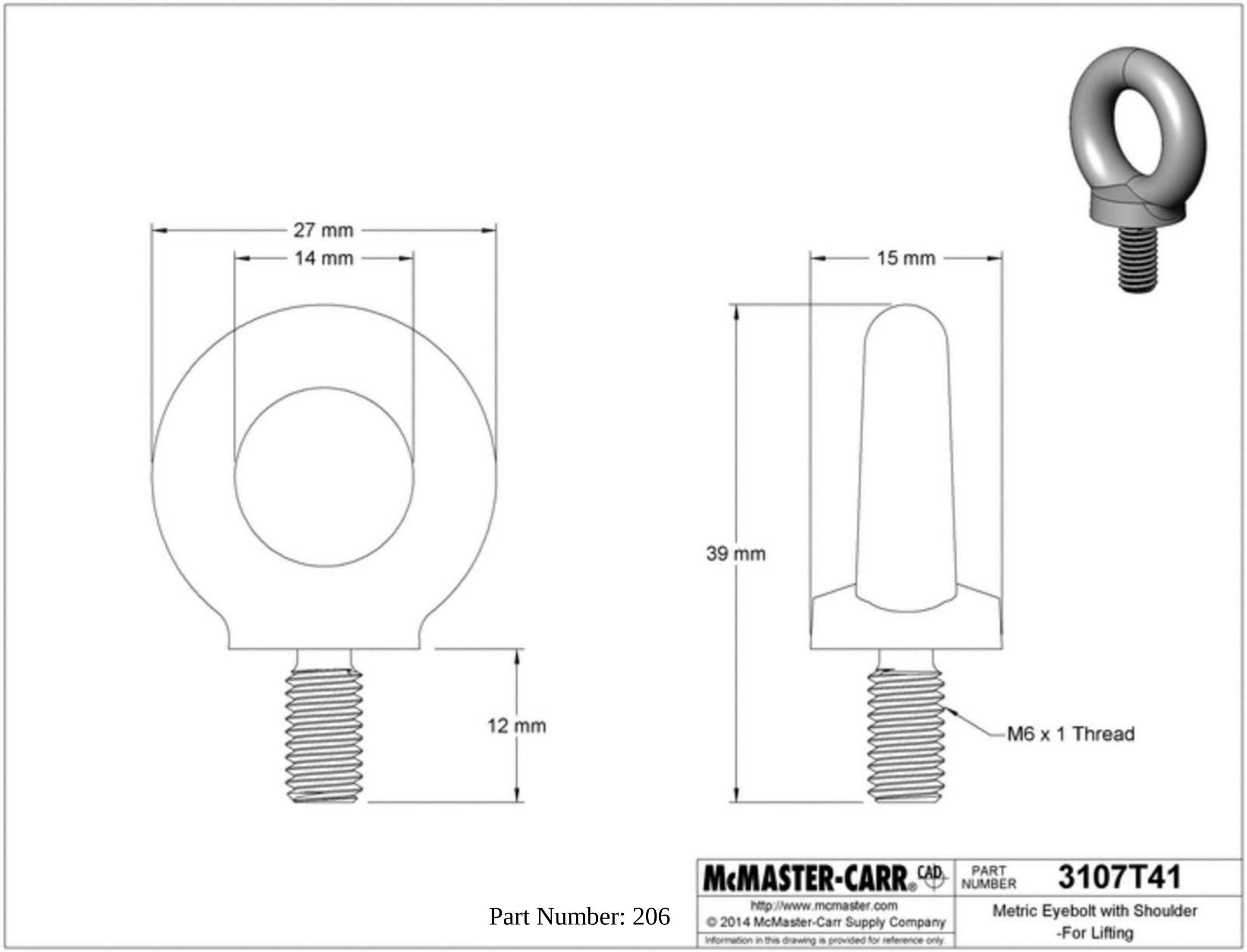
Application	For Lifting
Body Style	With Shoulder
Thread	
Size	M6
Pitch	1 mm
Length	12 mm
Shank Length	12 mm
Overall Length	39 mm
Eye Diameter	14 mm
Vertical Capacity	150 lbs.
Eye Style	Closed
Eye Shape	Round
Material	Zinc-Plated Steel
Threading	Fully Threaded
Movement	Rigid
Specifications Met	DIN 580
RoHS	Compliant

Also known as machinery eyebolts.

Zinc-plated steel eyebolts offer good corrosion resistance.

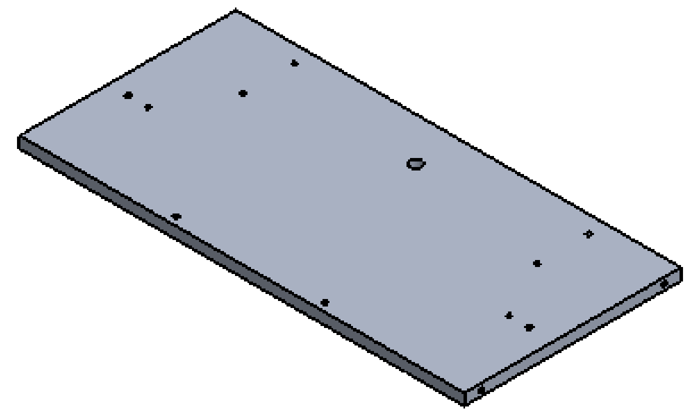
Note: Capacities listed are for vertical lifting only. Eyebolts with shoulder can be used for angular lifting up to 45°, but the capacities will be significantly reduced. For angular lifting, we recommend Hoist Rings.

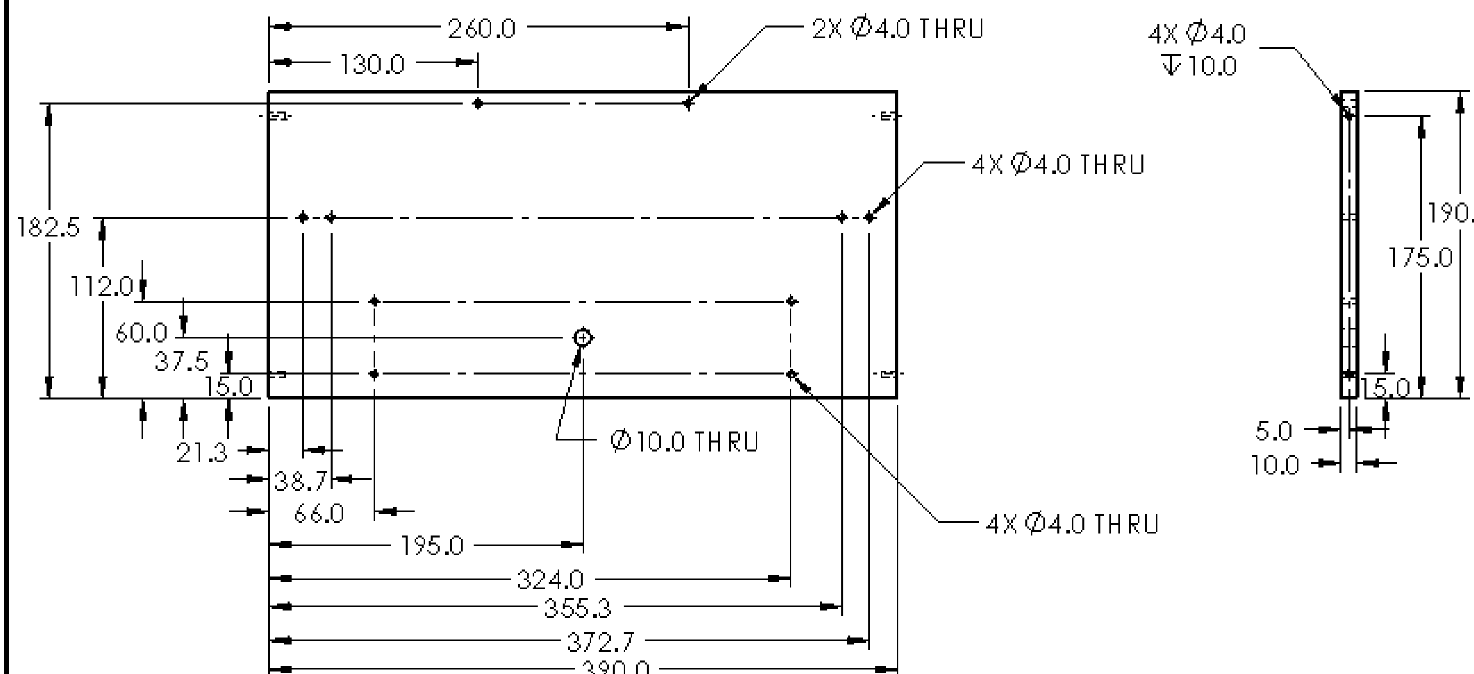
Warning: Never use to lift people or items over people.



Part Number: 206

NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN MILLIMETERS
2. TOLERANCES:
X.X = ±0.1
3. INSIDE TOOL RADIUS .5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: ALUMINUM 6061





Cal Poly Mechanical Engineering	Part/Dwg. #: 207	Title: Back Plate	Drwn. By: DAVID GALVEZ
ME 429 SENIOR PROJECT	Team: STELLAR / Lab Section: 07	Date: 2/8/17 / Scale: 1:4	DEPLOYABLE ANTENNA PROJECT

Steel Phillips Rounded Head Screws

6-32 Thread Size, 1/4" Long

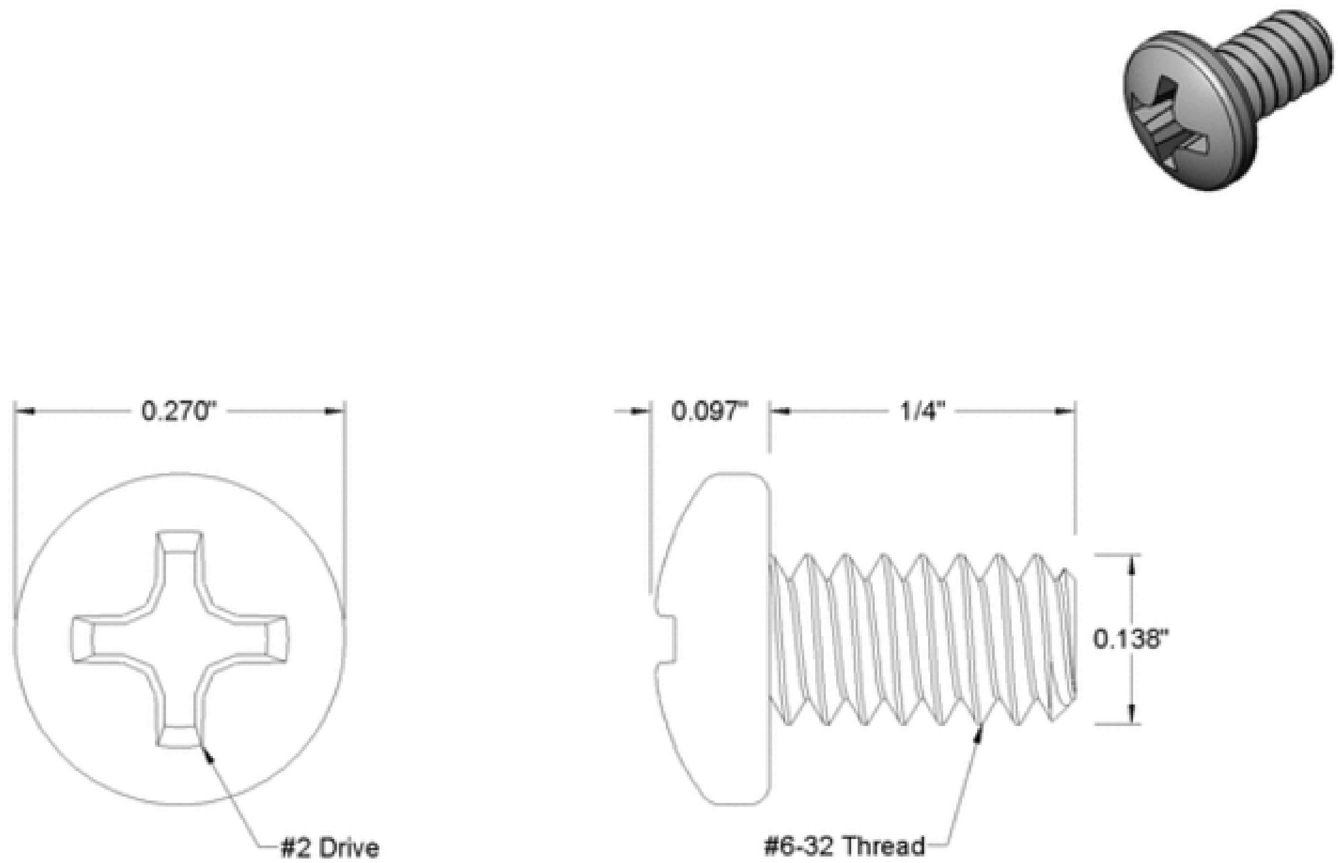
Packs of 100

ADD TO ORDER

In stock
$1.83 per pack of 100
90272A144

Thread Size	6-32
Length	1/4"
Threading	Fully Threaded
Head Diameter	0.27"
Head Height	0.097"
Drive Size	No. 2
Material	Zinc-Plated Steel
Hardness	Rockwell B70
Tensile Strength	60,000 psi
Screw Size Decimal Equivalent	0.138"
Thread Type	UNC
Thread Spacing	Coarse
Thread Fit	Class 2A
Thread Direction	Right Hand
Head Type	Rounded
Rounded Head Style	Pan
Rounded Head Profile	Standard
Drive Style	Phillips
System of Measurement	Inch
RoHS	Compliant

These pan head screws are zinc plated for corrosion resistance in wet environments. Length is measured from under the head.



Part Number: 208

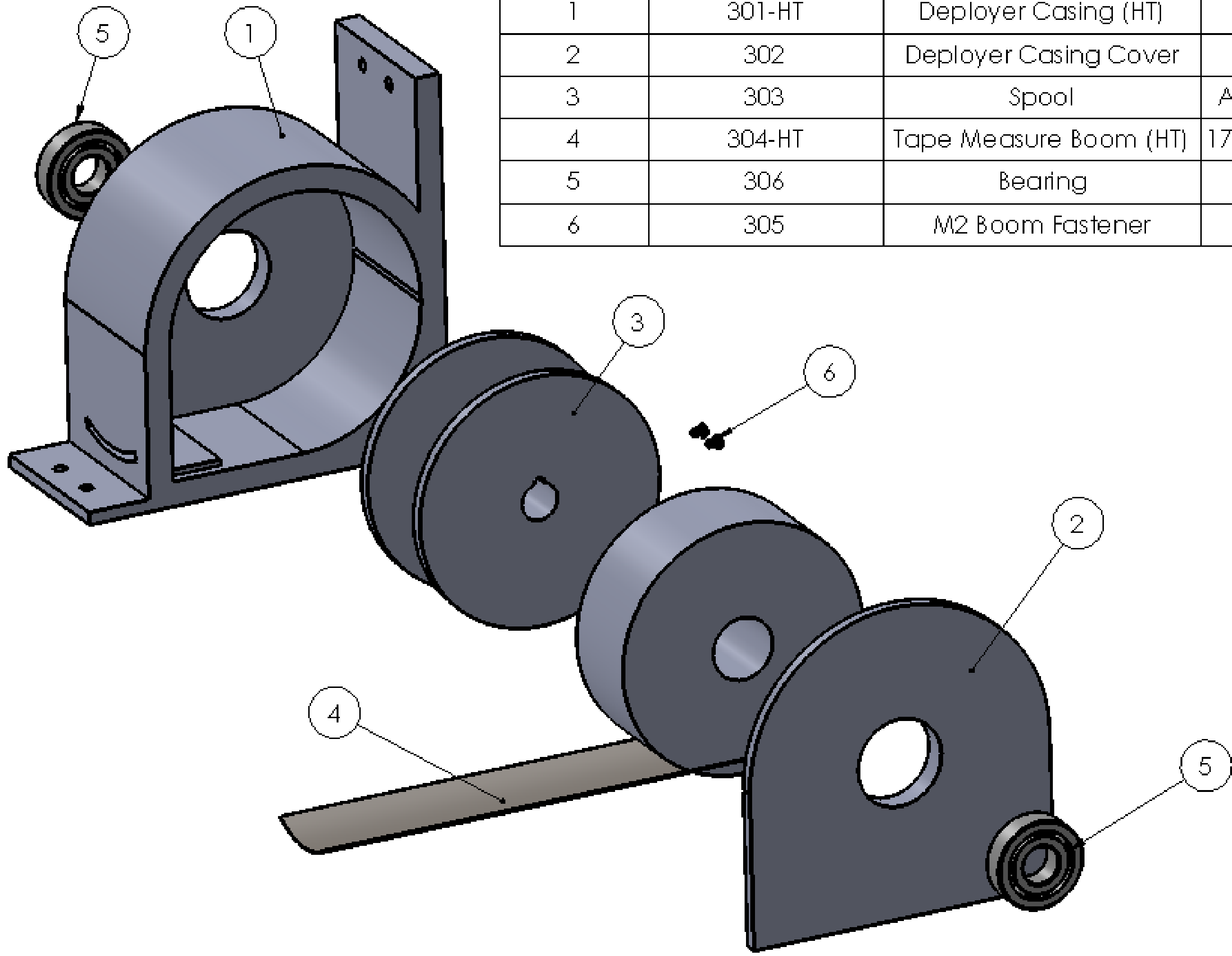
McMASTER-CARR® CAD

http://www.mcmaster.com

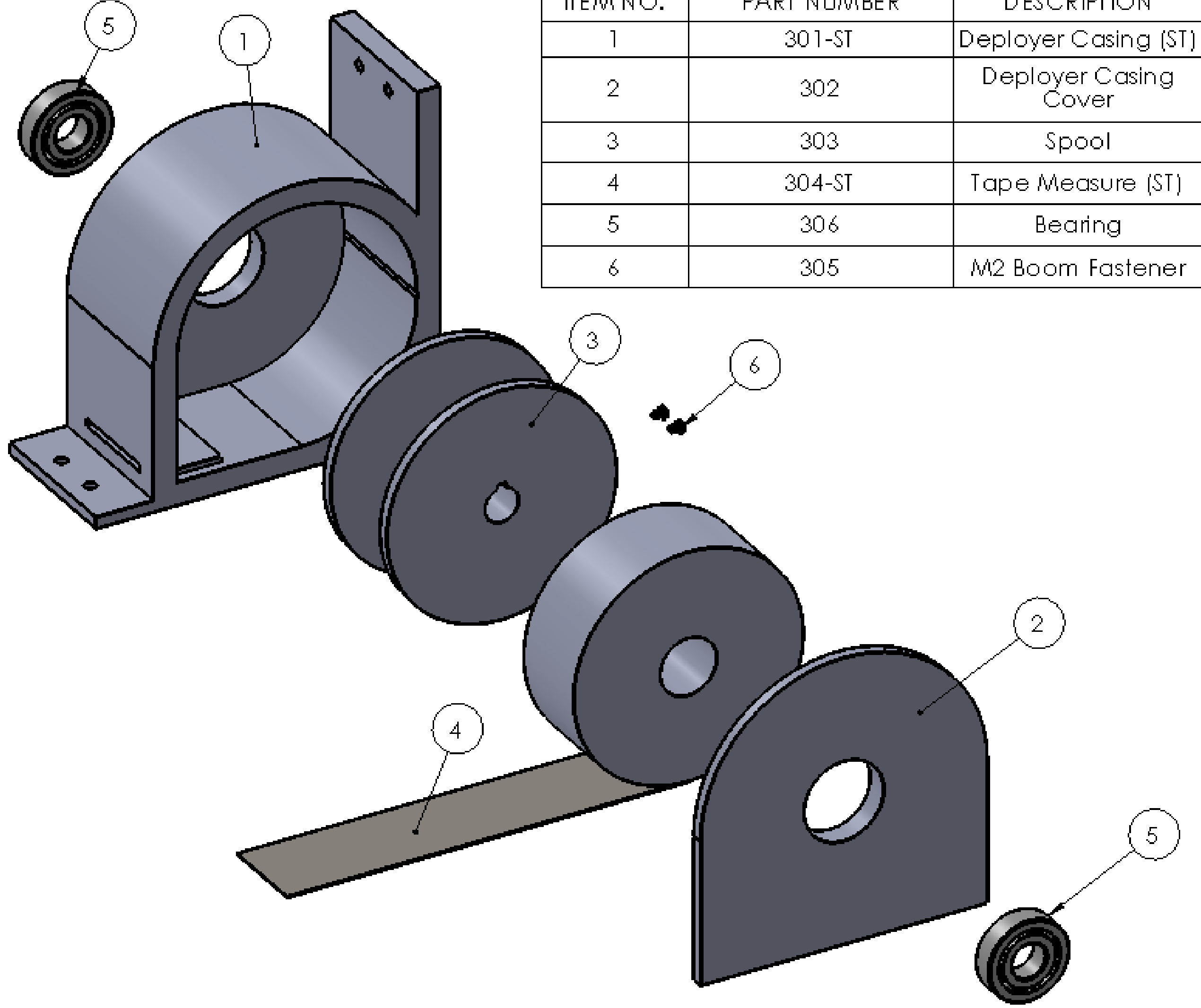
PART NUMBER 90272A144

Pan Head Phillips Machine Screw

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	301-HT	Deployer Casing (HT)	ABS	1
2	302	Deployer Casing Cover	ABS	1
3	303	Spool	AL 6061	1
4	304-HT	Tape Measure Boom (HT)	17-7 Steel	1
5	306	Bearing	Steel	2
6	305	M2 Boom Fastener	Steel	2



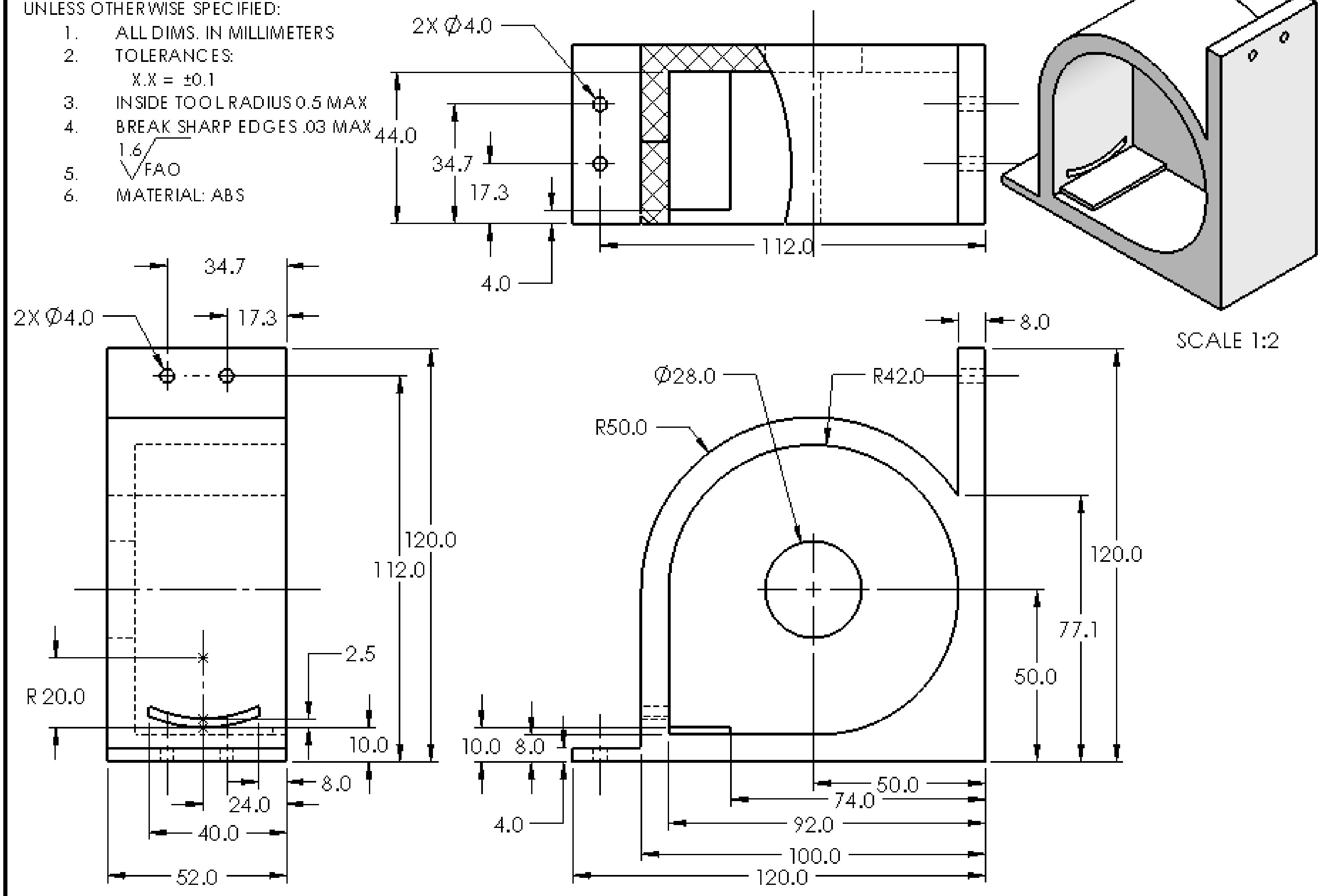
Cal Poly Mechanical Engineering	Part/Dwg. #: 300-HT	Title: Reflector Deployer (HT)	Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR / Lab Section: 07	Date: 2/8/17 / Scale: 7:12	DEPLOYABLE ANTENNA PROJECT



ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	301-ST	Deployer Casing (ST)	ABS	1
2	302	Deployer Casing Cover	ABS	1
3	303	Spool	AL 6061	1
4	304-ST	Tape Measure (ST)	17-7 Steel	1
5	306	Bearing	Steel	2
6	305	M2 Boom Fastener	Steel	2

Cal Poly Mechanical Engineering ME 429 SENIOR PROJECT	Part/Dwg. #: 300-HT		Title: Reflector Deployer (HT)		Drwn. By: CALEB BARBER
	Team: STELLAR	Lab Section: 07	Date: 2/8/17	Scale: 7:12	DEPLOYABLE ANTENNA PROJECT

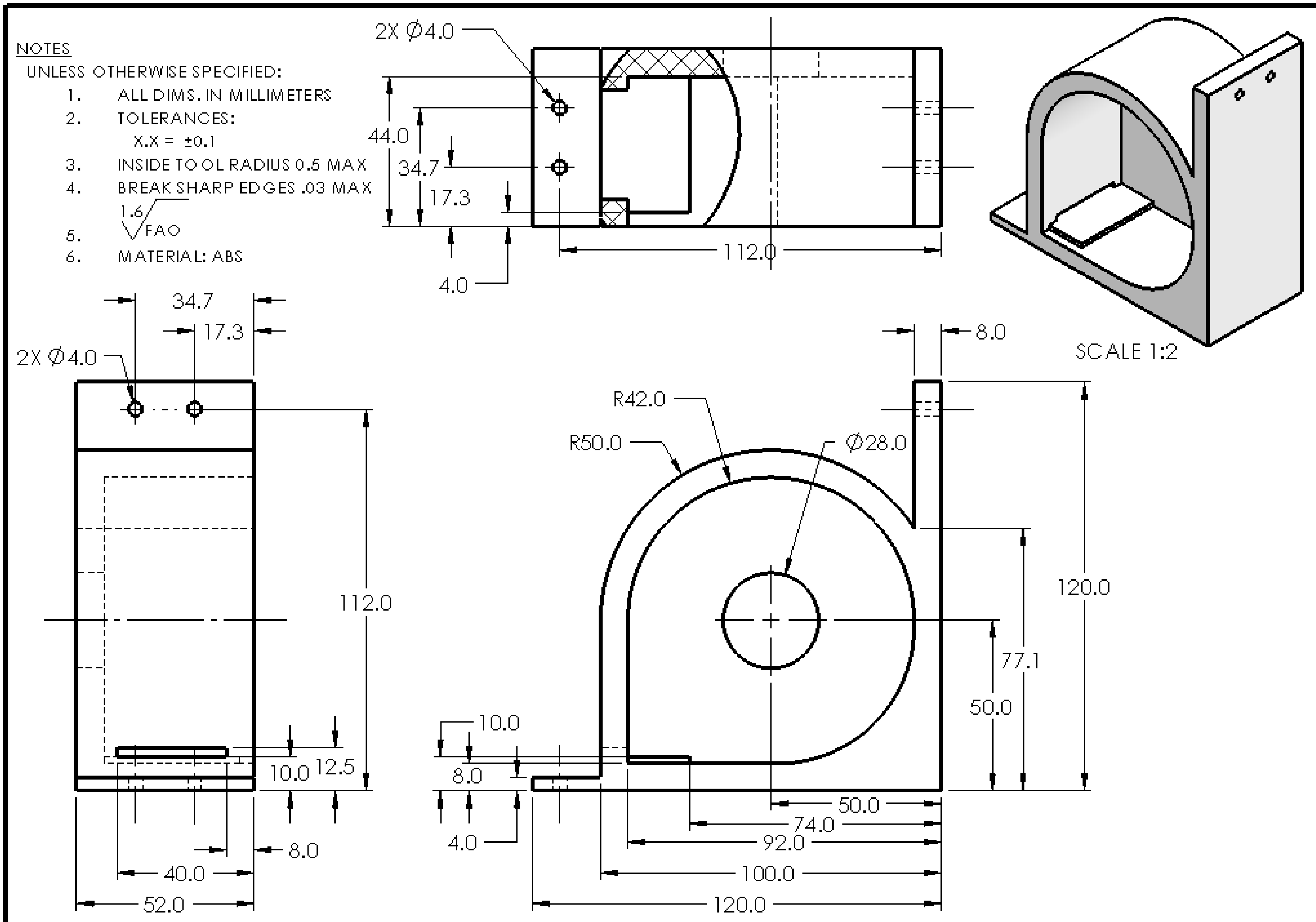
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √FAO
6. MATERIAL: ABS



Cal Poly Mechanical Engineering	Part/Dwg. #: 301-HT	Title: Deployer Casing (Heat Treatment)	Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR / Lab Section: 07	Date: 2/8/17 / Scale: 2:3	DEPLOYABLE ANTENNA PROJECT

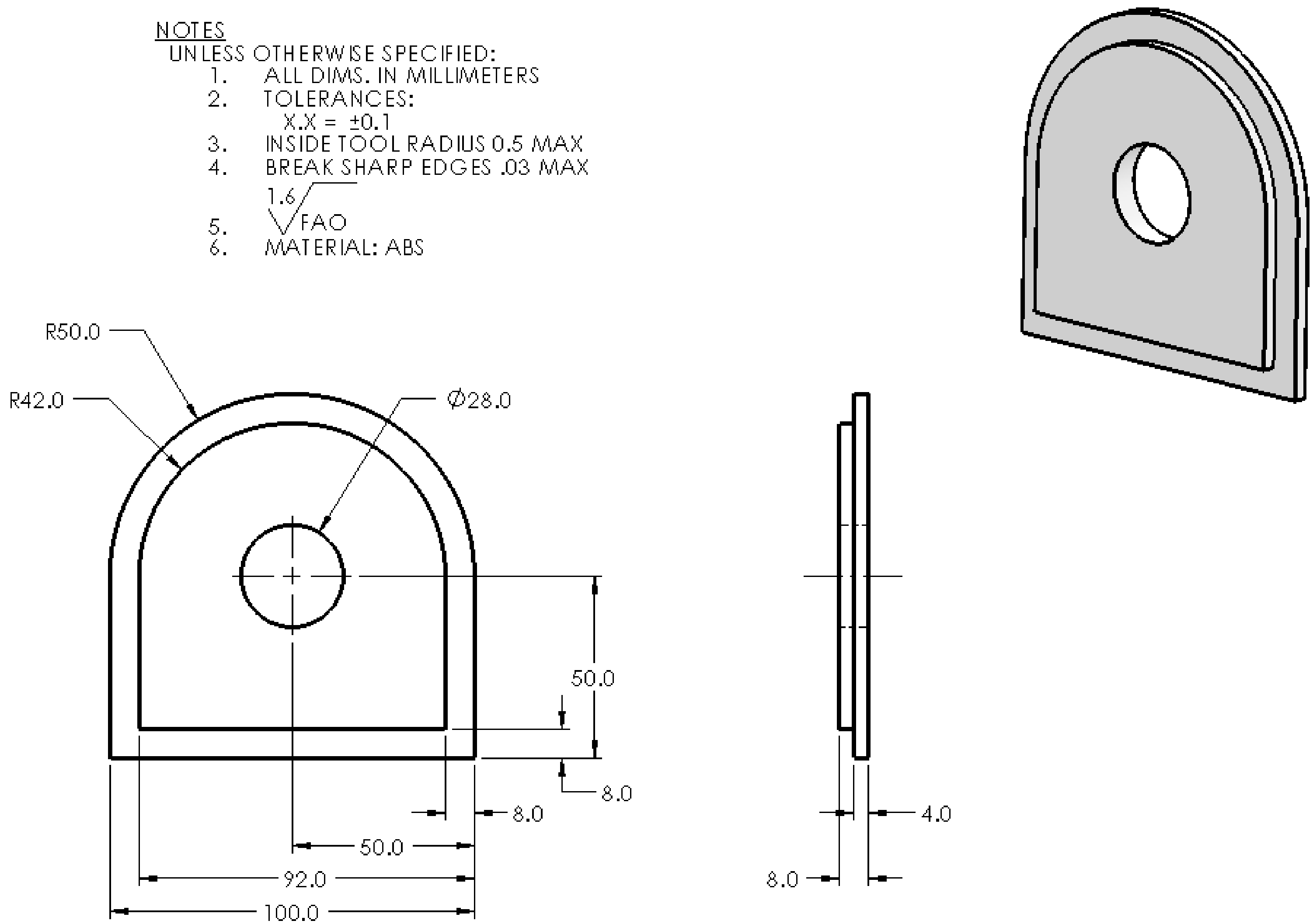
NOTES
UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: ABS



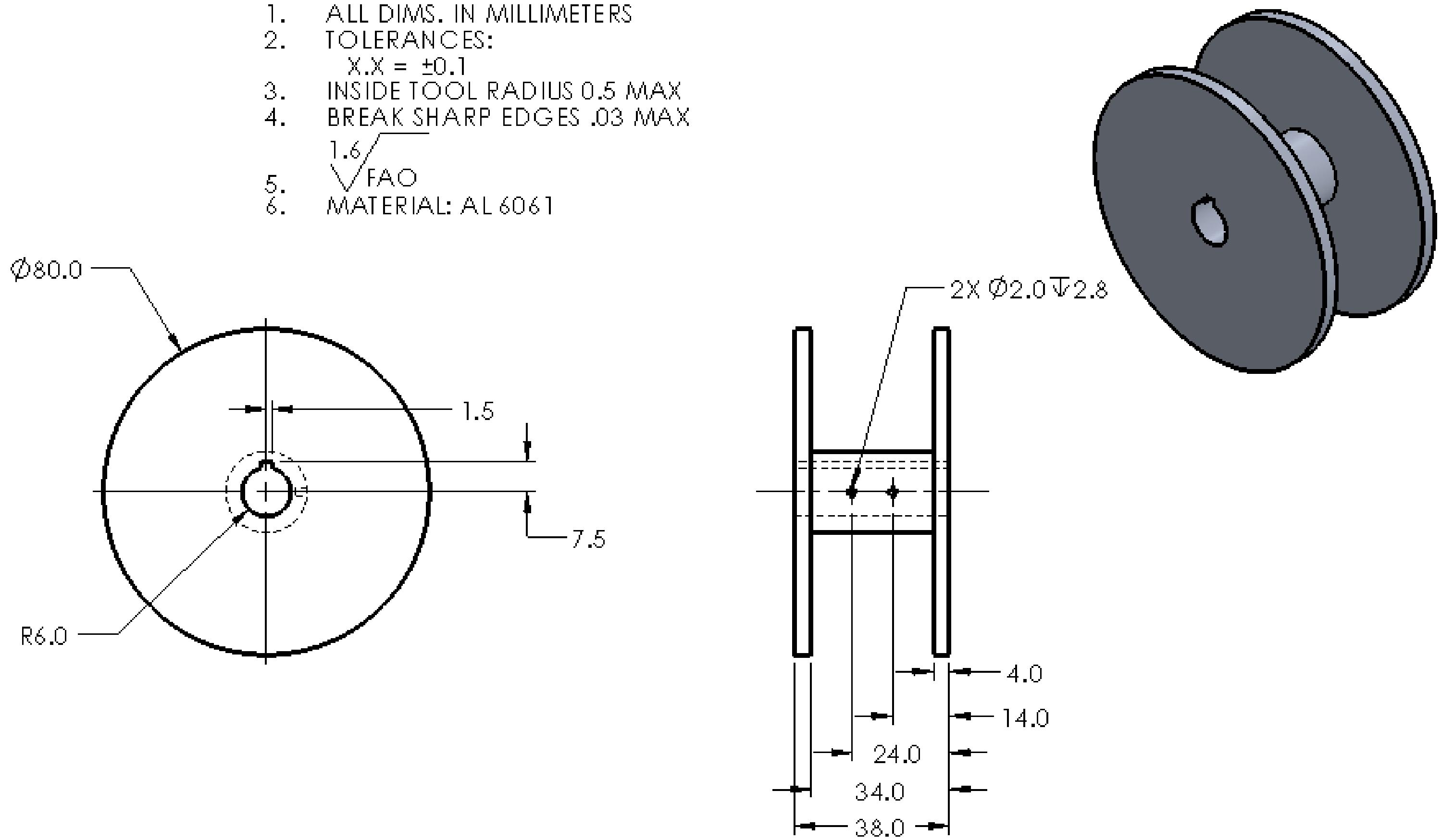
Cal Poly Mechanical Engineering ME 429 SENIOR PROJECT	Part/Dwg. #: 301-ST		Title: Deployer Casing (String Tensioners)		Drwn. By: CALEB BARBER
	Team: STELLAR	Lab Section: 07	Date: 2/8/17	Scale: 2:3	DEPLOYABLE ANTENNA PROJECT

NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: ABS



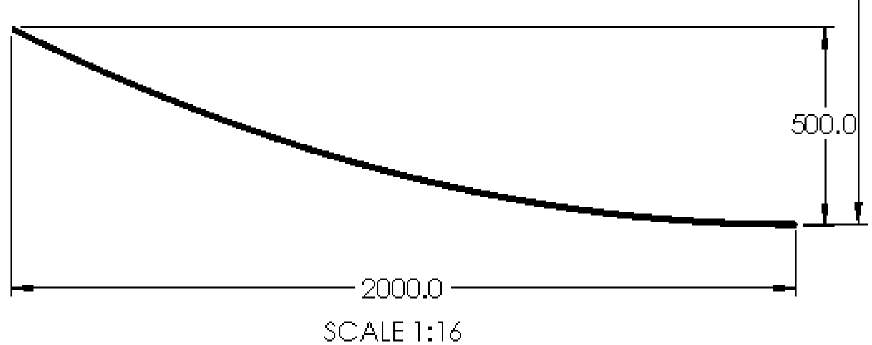
Cal Poly Mechanical Engineering ME 429 SENIOR PROJECT	Part/Dwg. #: 302	Title: Deployer Casing Cover	Drwn. By: CALEB BARBER
	Team: STELLAR / Lab Section: 07	Date: 2/8/17 / Scale: 2:3	DEPLOYABLE ANTENNA PROJECT

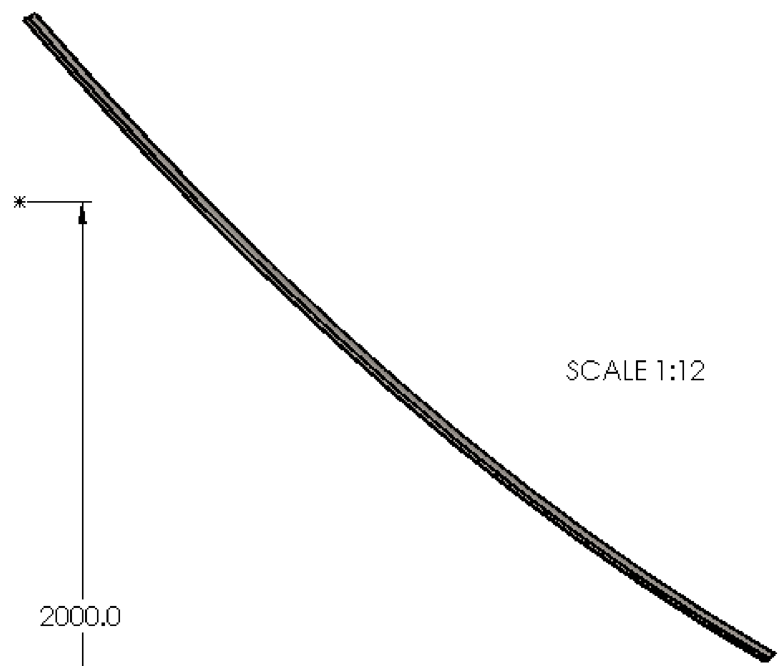
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: AL 6061

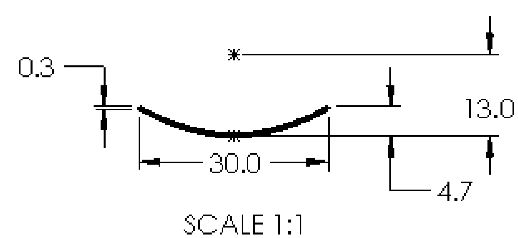


Cal Poly Mechanical Engineering	Part/Dwg. #: 303		Title: Spool	Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR	Lab Section: 07	Date: 2/8/17 / Scale: 2:3	DEPLOYABLE ANTENNA PROJECT

NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: 17-7 STEEL

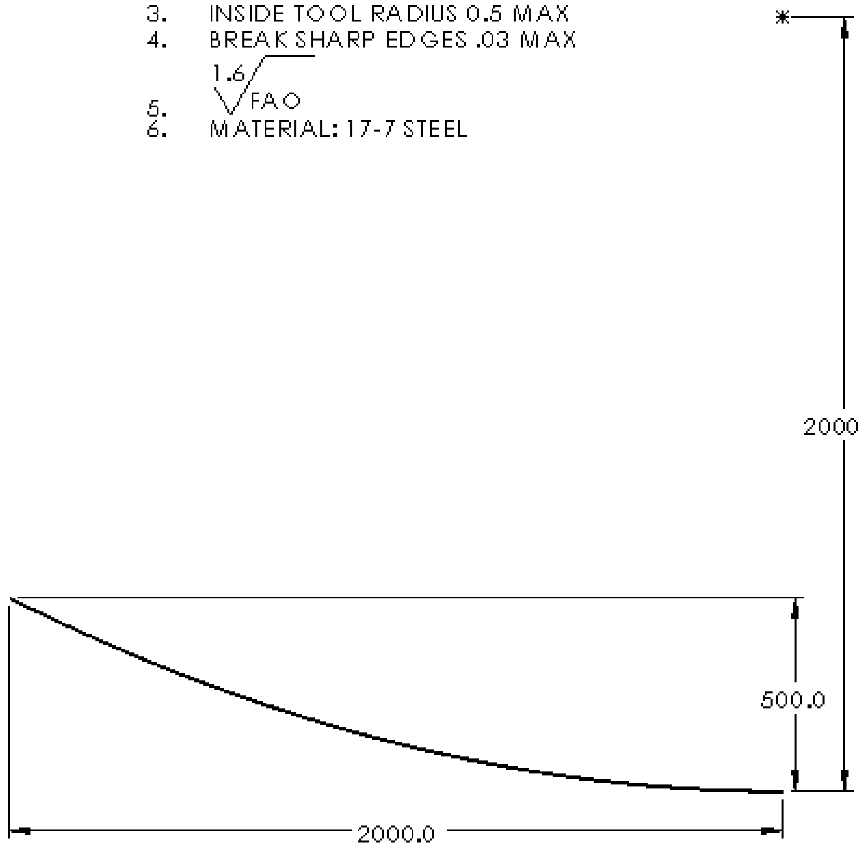




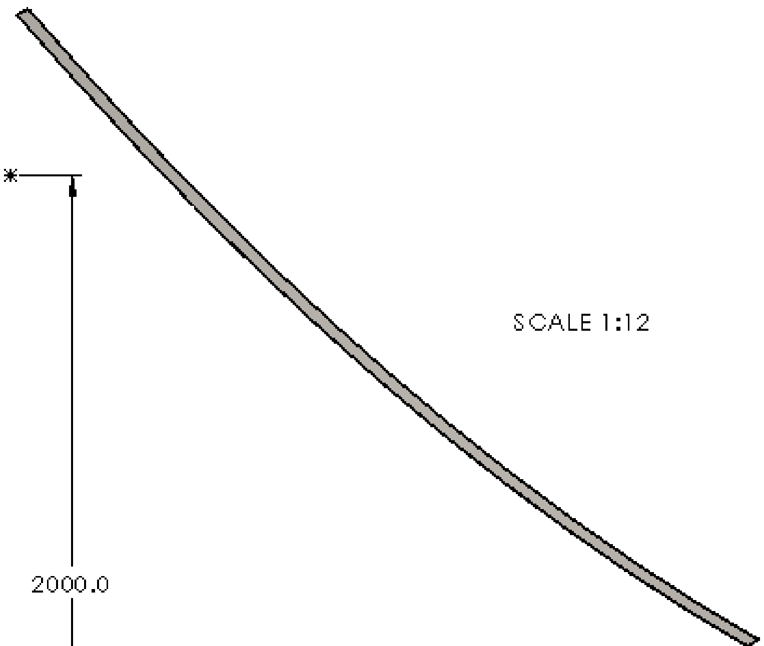


Cal Poly Mechanical Engineering	Part/Dwg. #: 304-HT		Title: Tape Measure Boom (HT)	Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR	Lab Section: 07	Date: 2/8/17 · Scale:	DEPLOYABLE ANTENNA PROJECT

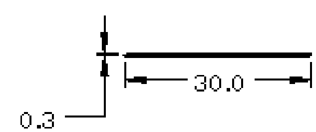
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: 17-7 STEEL



SCALE 1:16



SCALE 1:12



SCALE 1:1

Cal Poly Mechanical Engineering	Part/Dwg. #: 304-ST	Title: Tape Measure Booms (ST)	Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR / Lab Section: 07	Date: 2/8/17 / Scale:	DEPLOYABLE ANTENNA PROJECT

Steel Phillips Rounded Head Screw

M2 x 0.4 mm Thread, 3 mm Long

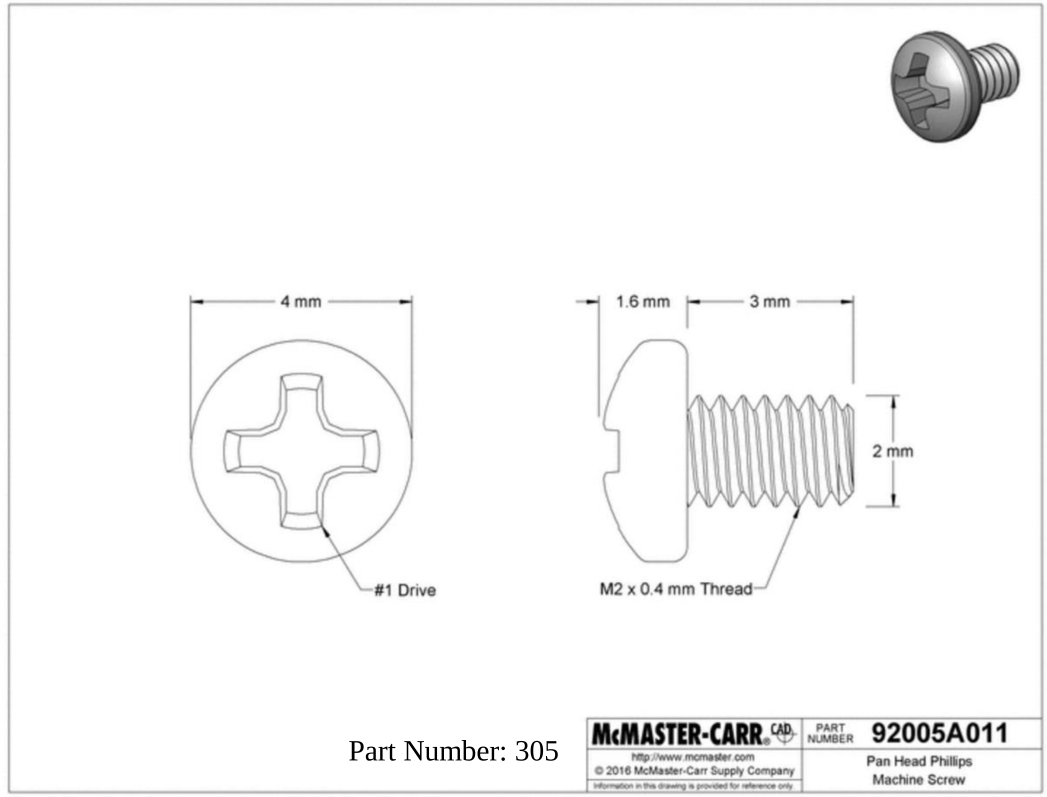
Packs of 100

ADD TO ORDER

In stock
$5.04 per pack of 100
92005A011

Thread Size	M2
Thread Pitch	0.4 mm
Length	3 mm
Threading	Fully Threaded
Head Diameter	4 mm
Head Height	1.6 mm
Drive Size	No. 1
Material	Zinc-Plated Steel
Hardness	Rockwell B71
Tensile Strength	60,000 psi
Thread Type	Metric
Thread Spacing	Coarse
Thread Fit	Class 6h
Thread Direction	Right Hand
Head Type	Rounded
Rounded Head Style	Pan
Rounded Head Profile	Standard
Drive Style	Phillips
Specifications Met	DIN 7985
System of Measurement	Metric
RoHS	Compliant

These pan head screws are zinc plated for corrosion resistance in wet environments. Length is measured from under the head.



Part Number: 305

The information in this 3-D model is provided for reference only. Details

Ball Bearing

Trade No. 6001, for 12 mm Shaft Diameter, 28 mm OD

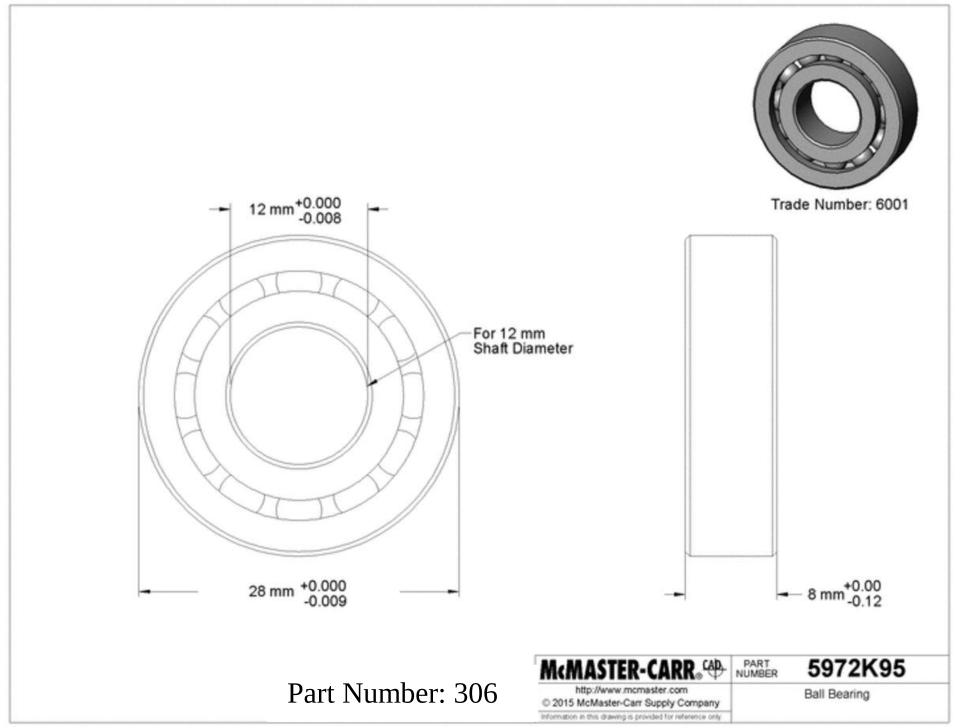
Each

ADD TO ORDER

In stock
$7.22 Each
5972K95

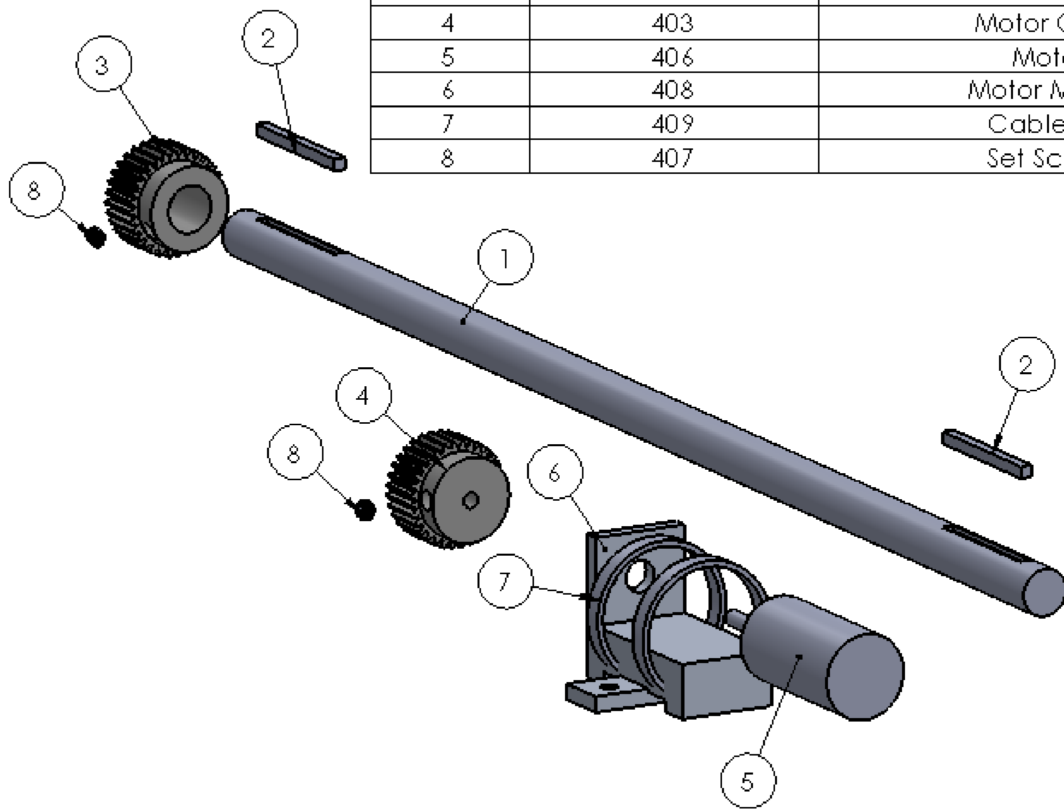
Bearing Type	Ball
For Load Direction	Radial
Ball Bearing Type	Standard
Construction	Single Row
Seal Type	Open
For Shaft Shape	Round
Trade No.	6001
For Shaft Diameter	12 mm
ID	12 mm
ID Tolerance	-0.008 to 0 mm
OD	28 mm
OD Tolerance	-0.009 to 0 mm
Width	8 mm
Width Tolerance	-0.12 to 0 mm
Material	52100 Steel
Ball Material	Steel
Cage Material	Steel
Radial Load Capacity, lbs.	
Dynamic	1,145
Static	530
Maximum Speed	32,000 rpm
Shaft Mount Type	Press Fit
Lubrication	Lubricated
Lubrication Method	Filled
Lubricant Type	Oil
Temperature Range	-20° to 230° F
ABEC Rating	ABEC-1
Radial Clearance Trade No.	C3
Radial Clearance	0.011 to 0.025 mm
RoHS	Compliant

Open bearings dissipate heat more efficiently than double-shielded and double-sealed bearings.

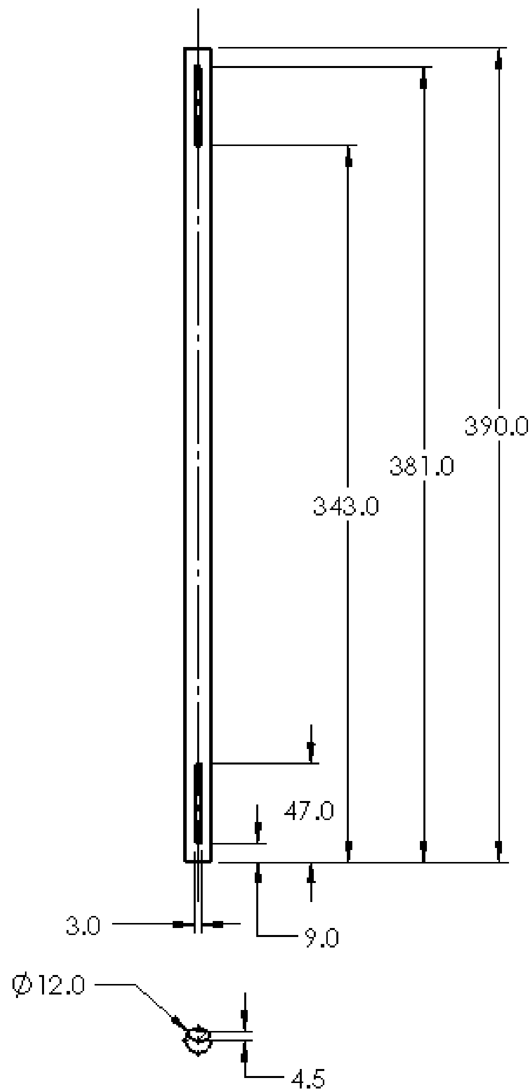


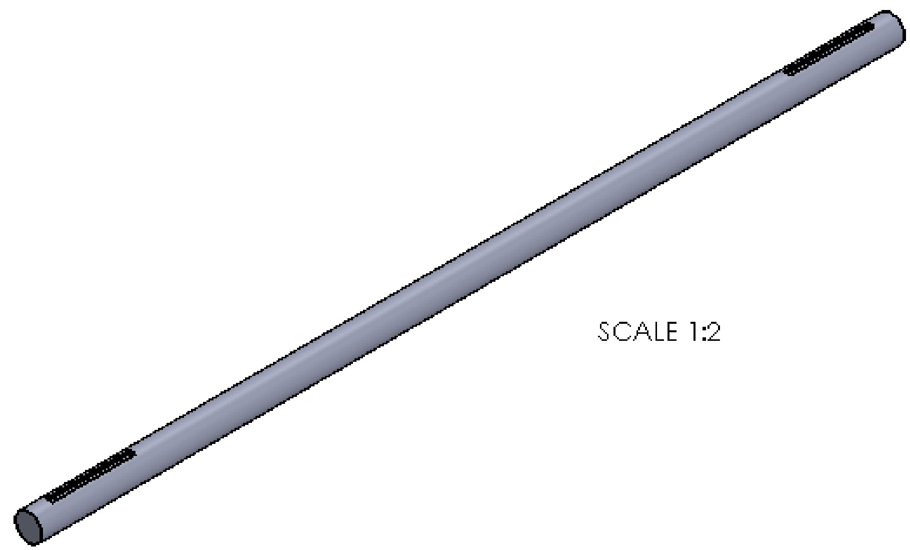
The information in this 3-D model is provided for reference only. Details

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	401	Main Shaft	Steel	1
2	402	Shaft Key	Steel	2
3	404	Main Shaft Gear	Gear Stk.	1
4	403	Motor Gear	Gear Stk.	1
5	406	Motor	-	1
6	408	Motor Mount	AL 6061	1
7	409	Cable Tie	Plastic	2
8	407	Set Screw	Steel	2



Cal Poly Mechanical Engineering ME 429 SENIOR PROJECT	Part/Dwg. #: 400	Title: Power Transmission Assembly	Drwn. By: CALEB BARBER
	Team: STELLAR / Lab Section: 07	Date: 2/8/17 / Scale: 2:3	DEPLOYABLE ANTENNA PROJECT





SCALE 1:2

NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: STEEL

Cal Poly Mechanical Engineering	Part/Dwg. #: 401		Title: Main Shaft		Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR	Lab Section: 07	Date: 2/8/17	Scale: 1:3	DEPLOYABLE ANTENNA PROJECT

Keyed Rotary Shaft

1045 Carbon Steel, 1/2" Diameter, 24" Long

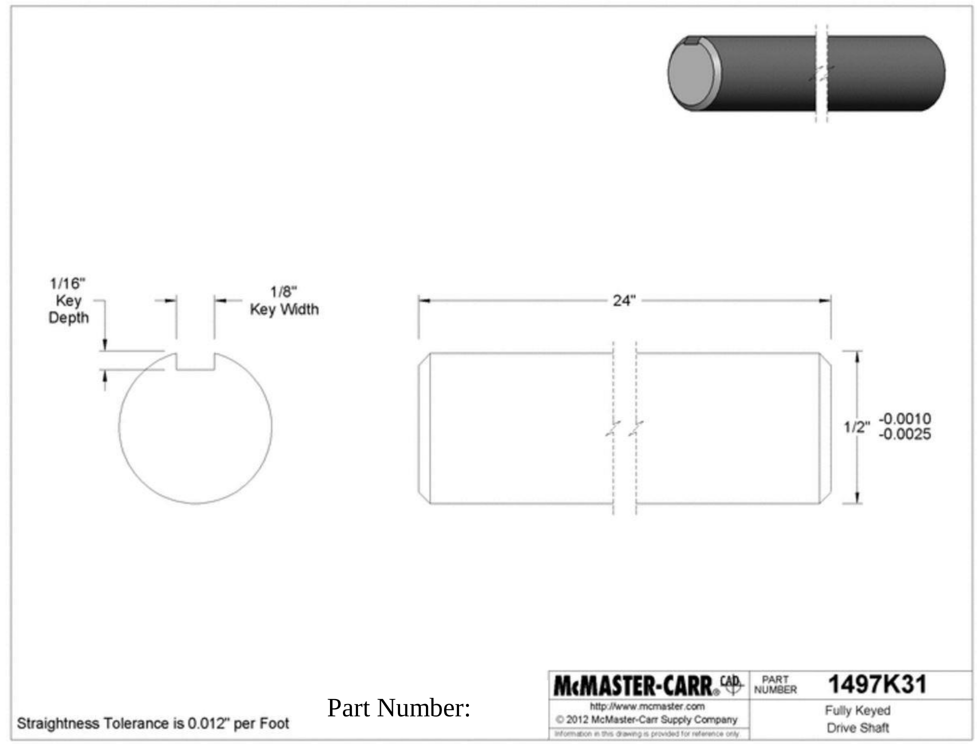
Each

ADD TO ORDER

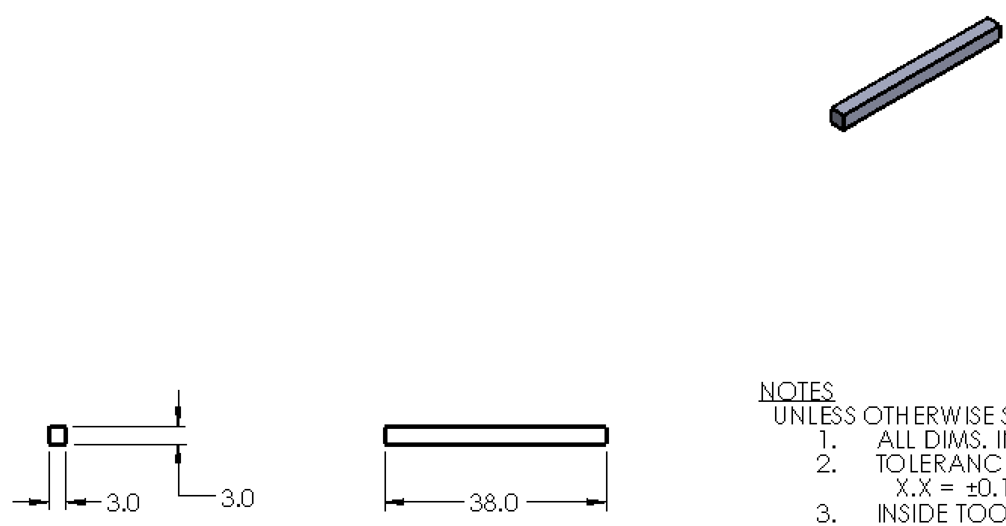
In stock
$29.37 Each
1497K31

Material	1045 Carbon Steel
Diameter	1/2"
Length	24"
Keyway	
Width	1/8"
Depth	1/16"
Length	24"
ANSI Keys Included	No
Diameter Tolerance	-0.0025" to -0.001"
Straightness Tolerance	0.012" per ft.
Length Tolerance	-0.0313" to 0.0313"
End Shape	Chamfered
Hardness Rating	Medium
Hardness	Rockwell B95
Yield Strength	75,000 psi
For Motion Type	Rotary
Shaft Type	Keyed
End Type	Straight
RoHS	Compliant

Made of carbon steel, these shafts are stronger than aluminum and stainless steel shafts. For a secure hold in high-torque applications, an ANSI keyway runs along the length of the shaft (keys not included; see our selection of key stock). Commonly known as drive shafts, rotary shafts are often used with gears, sprockets, rotary bearings and other power transmission components.

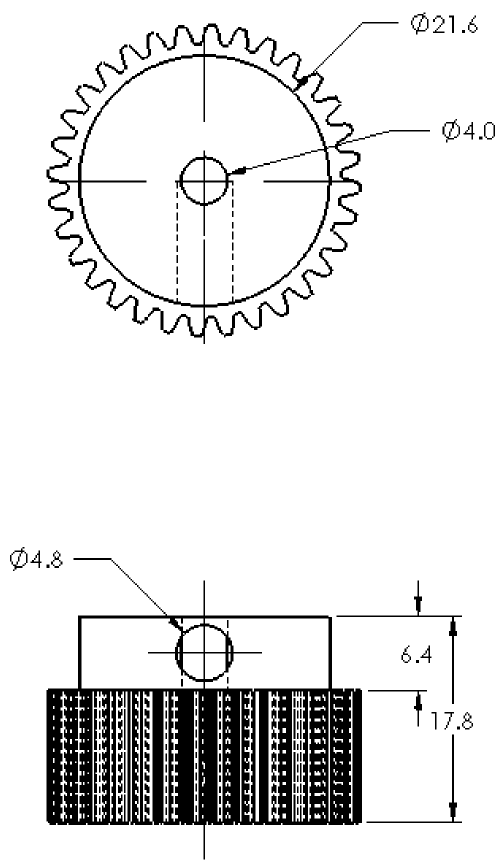


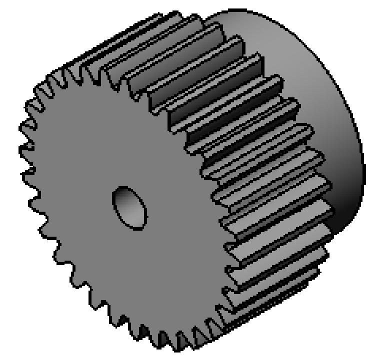
The information in this 3-D model is provided for reference only. Details



NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: STEEL

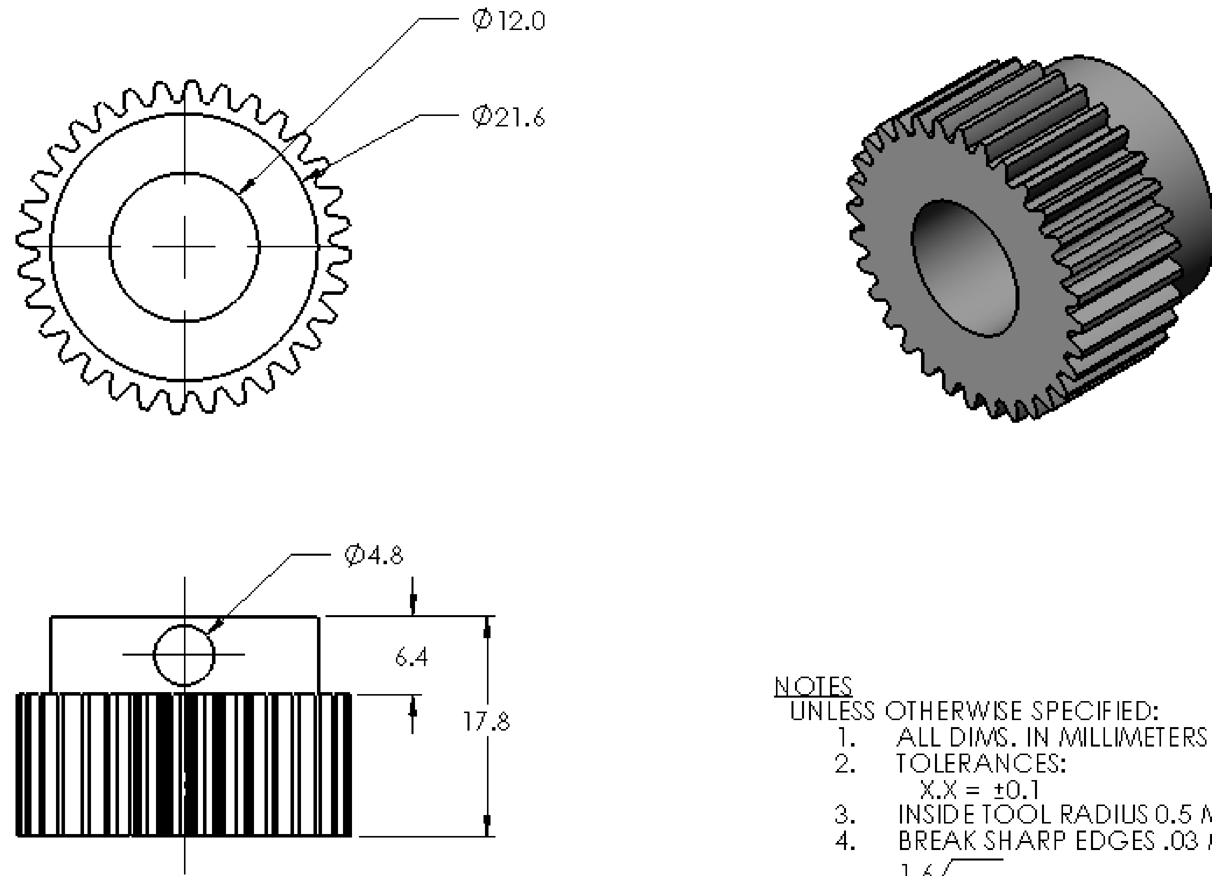
Cal Poly Mechanical Engineering	Part/Dwg. #: 402		Title: Shaft Key		Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR	Lab Section: 07	Date: 2/8/17	Scale: 1:1	DEPLOYABLE ANTENNA PROJECT





NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: STEEL

Cal Poly Mechanical Engineering	Part/Dwg. #: 403		Title: Motor Gear		Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR	Lab Section: 07	Date: 2/8/17	Scale: 2:1	DEPLOYABLE ANTENNA PROJECT

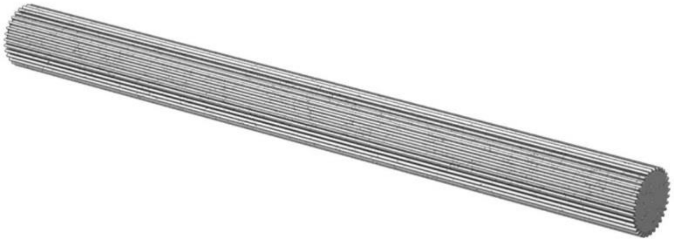


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: STEEL

Cal Poly Mechanical Engineering	Part/Dwg. #: 404	Title: Main Shaft Gear	Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR / Lab Section: 07	Date: 2/8/17 / Scale: 2:1	DEPLOYABLE ANTENNA PROJECT

High-Load Metal Gear Rod Stock

20 Degree Pressure Angle, 32 Pitch, 32 Teeth



Each

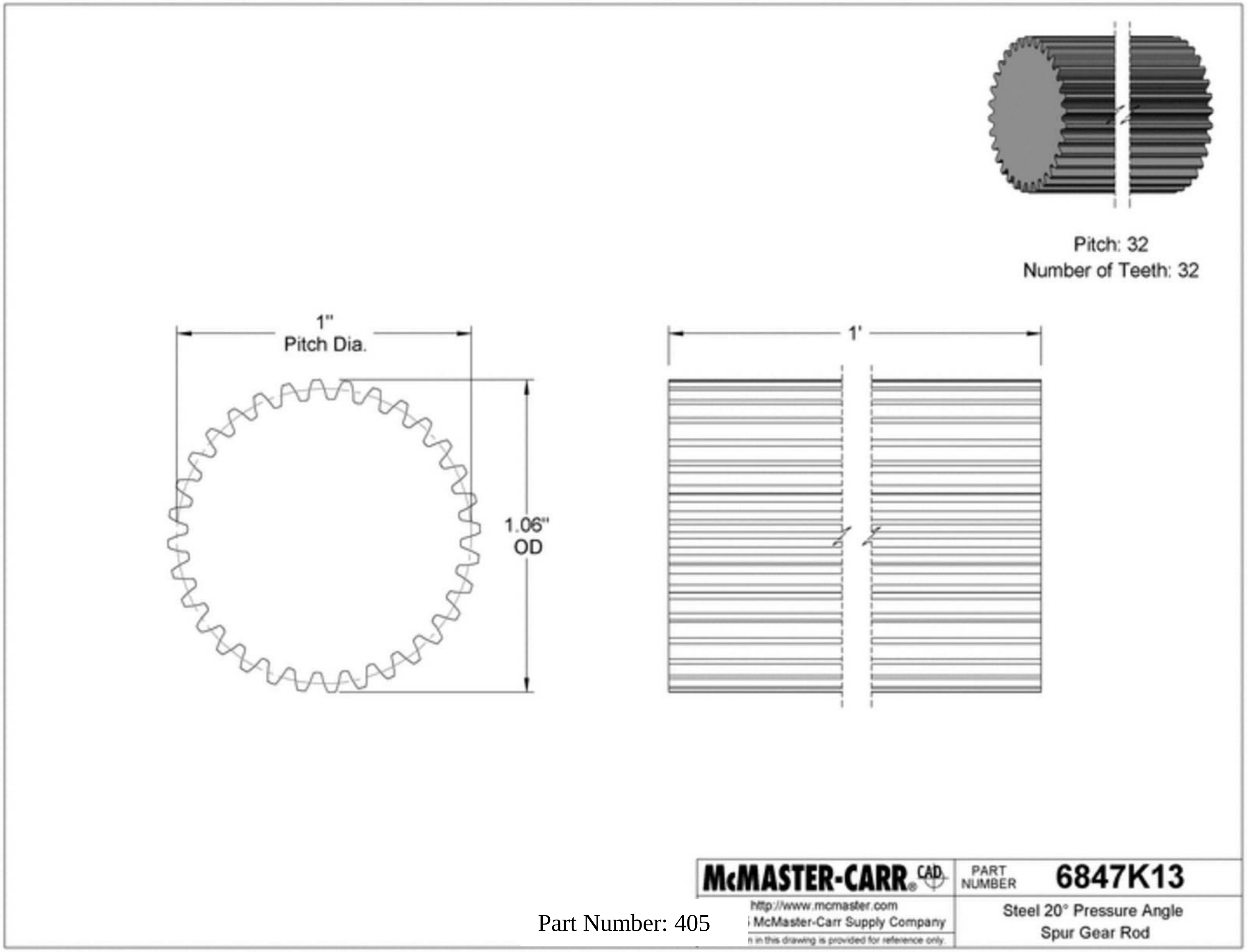
ADD TO ORDER

In stock
$44.91 Each
6847K13

Pressure Angle	20°
Pitch	32
Number of Teeth	32
Pitch Diameter	1"
OD	1.06"
Length	1 ft.
Material	Steel
RoHS	Compliant

Machine your own gears to fit the exact face widths and shaft diameters required. Rod stock has teeth with a 20° pressure angle, which have a wider profile than 14 1/2° teeth, so they have greater strength to handle high loads.

For gears and racks to mesh correctly, they must have the same pressure angle and pitch. Use gears made from this rod stock with other components that have a 20° pressure angle.



Part Number: 405

26 RPM Mini Econ Gear Motor

Part Number: 406

1 of 15

ADD TO WISHLIST | 1 | ADD TO CART

Price	$9.99 Sign up for Price Alert
Part	638380
Status	In stock

♥ This Product? Share It!

Voltage (Nominal)	12V
Voltage Range (Recommended)	6V -18V
Speed (No Load)*	26 rpm
Current (No Load)*	0.1A
Current (Max Load)*	0.35A
Current (Stall)*	1.5A
Torque (Stall)*	650.7 oz-in (46,858 kgf-cm)
Gear Ratio	488:1
Gear Material	Metal
Gearbox Style	Straight Cut Spur
Motor Type	Brushed DC
Output Shaft Diameter	4mm (0.1575”)
Output Shaft Style	D-shaft
Output Shaft Support	Bushing
Electrical Connection	Male Spade Terminal
Product Weight	1.65 oz

Alloy Steel Cup Point Set Screw

M5 Size, 6mm Long, 0.8mm Pitch

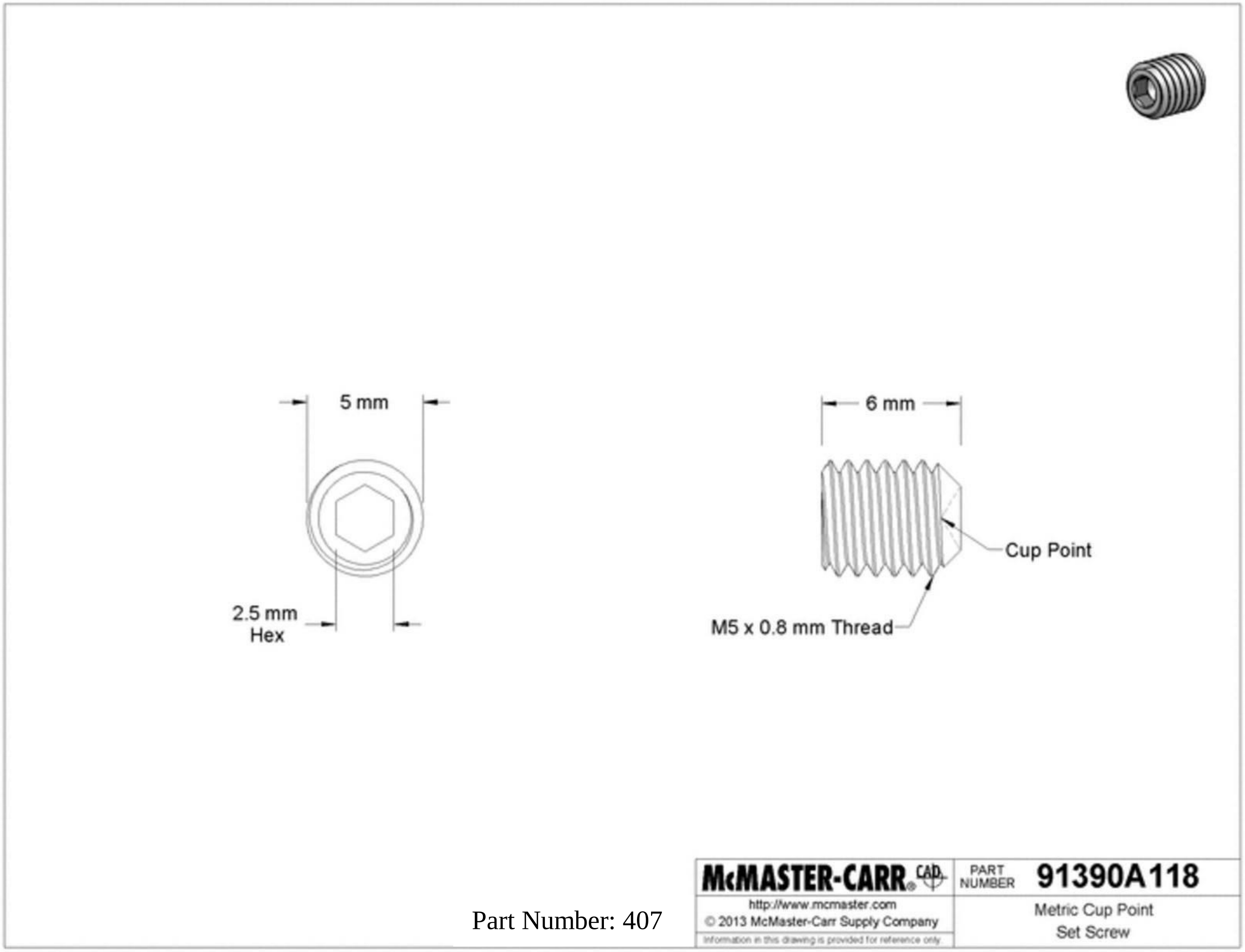
Packs of 100

ADD TO ORDER

In stock
$3.89 per pack of 100
91390A118

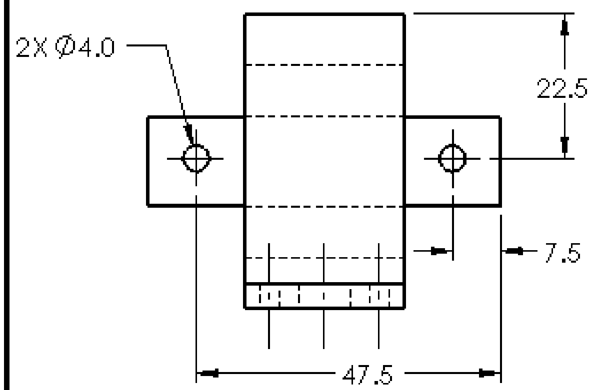
Material	Alloy Steel
Thread Size	M5
Thread Pitch	0.8 mm
Length	6 mm
Drive Size	2.5 mm
Hardness	Rockwell C45
Specifications Met	DIN 916, ISO 4029
Thread Type	Metric
Thread Spacing	Coarse
Thread Fit	Class 5g6g
Thread Direction	Right Hand
Drive Style	Hex
Tip Type	Cup
Head Type	Headless
System of Measurement	Metric
RoHS	Compliant

These alloy steel set screws have a thin edge that digs into hard surfaces for a secure hold. Length listed is the overall length.

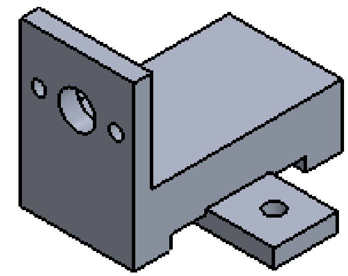


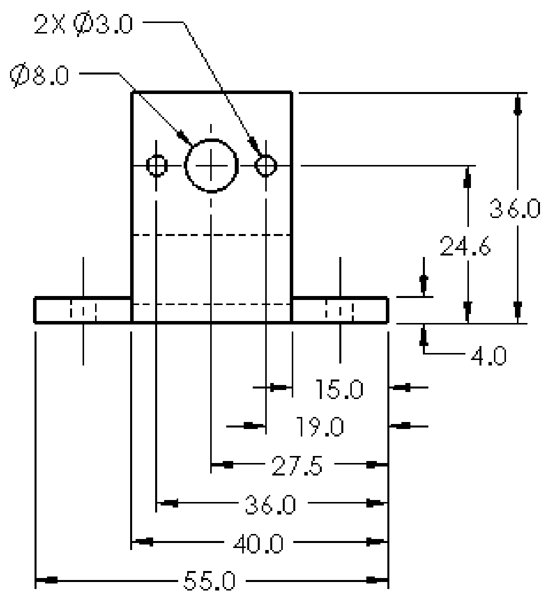
Part Number: 407

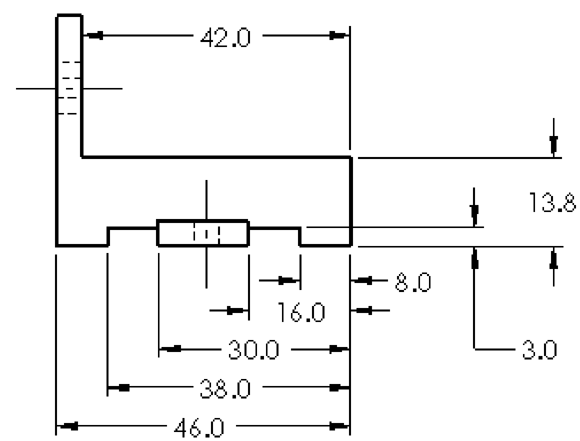
The information in this 3-D model is provided for reference only. Details



NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: AL 6061







Cal Poly Mechanical Engineering	Part/Dwg. #: 408		Title: Motor Mount	Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR	Lab Section: 07	Date: 2/8/17	Scale: 1:1	DEPLOYABLE ANTENNA PROJECT

Nylon Cable Tie Part Number: 409

8" Long, 2-1/8" Bundle Diameter, 10 lb. Break Strength, Black

Packs of 100

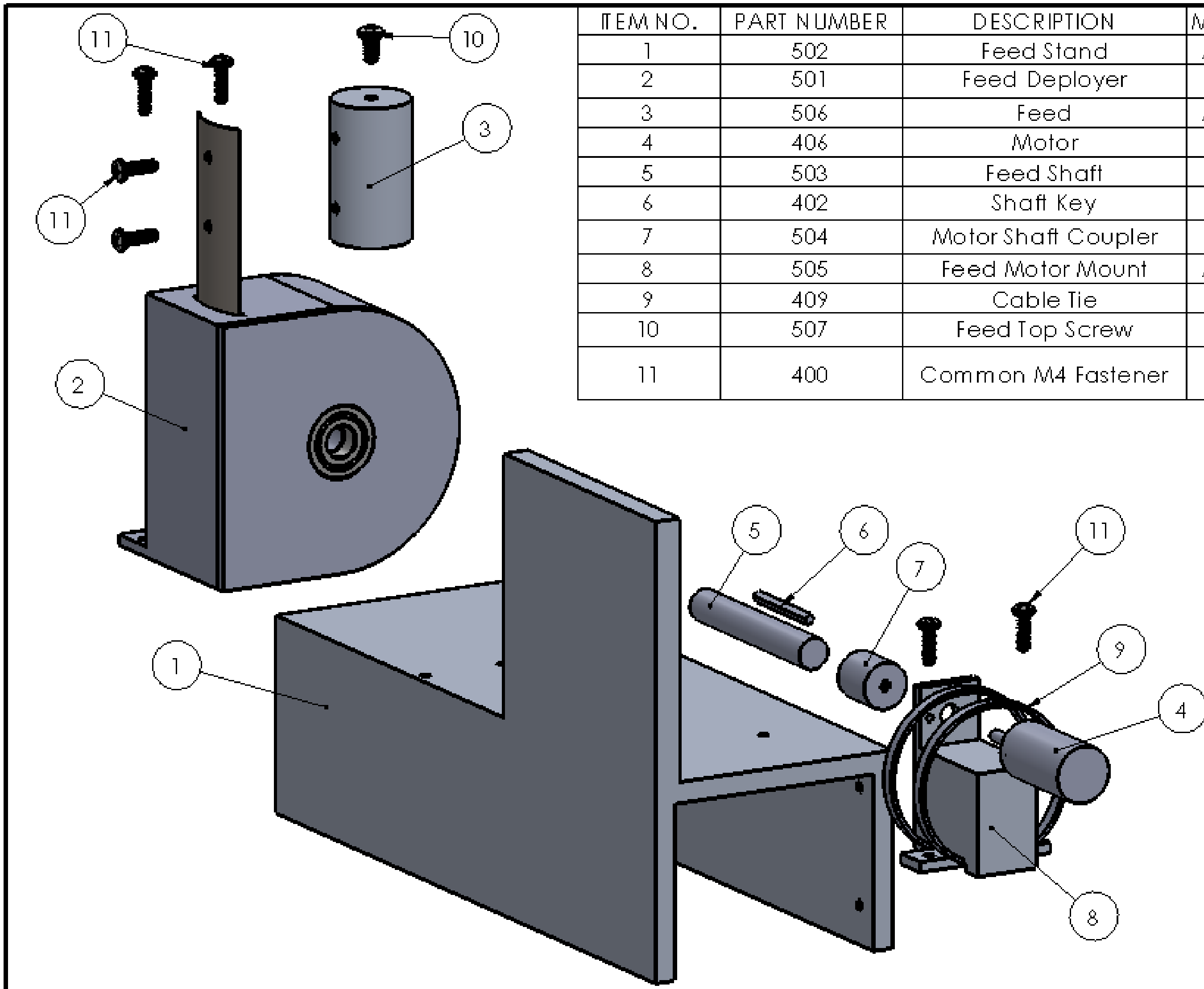
ADD TO ORDER

In stock
1-9 Packs $5.62
10 or more $4.61
7130K32

Cable Tie Style	Narrow
Overall Length	8"
For Maximum Bundle Diameter	2 1/8"
Breaking Strength	10 lbs.
Reusable	No
Width	0.10"
Thickness	0.04"
Material	Nylon
Closure Type	Lock
Body Style	Solid
For Use Outdoors	No
Specifications Met	MS 3367-4, UL 62275, UL 94V2
Temperature Range	32° to 180° F
Color	Black
RoHS	Compliant

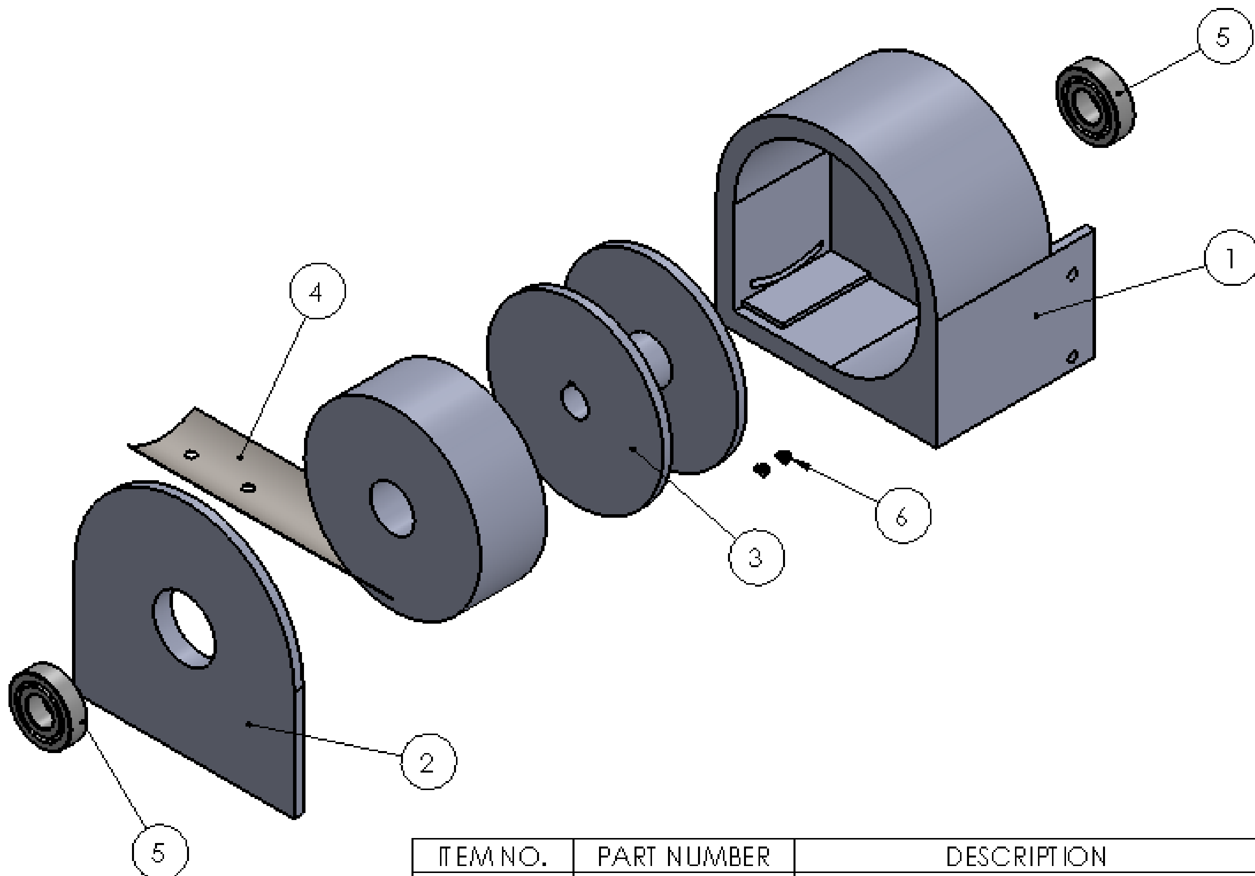
Bundle and secure your cable, wire, and hose. Also known as zip ties.

Narrow ties are highly flexible and conform to irregularly shaped material better than standard, wide, and extra-wide cable ties.



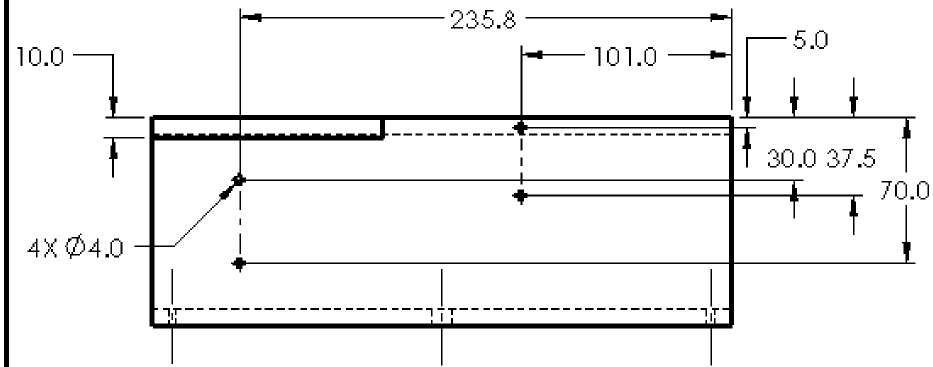
ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	502	Feed Stand	AL 6061	1
2	501	Feed Deployer	-	1
3	506	Feed	AL 6061	1
4	406	Motor	-	1
5	503	Feed Shaft	Steel	1
6	402	Shaft Key	Steel	1
7	504	Motor Shaft Coupler	Steel	1
8	505	Feed Motor Mount	AL 6061	1
9	409	Cable Tie	Plastic	2
10	507	Feed Top Screw	Steel	1
11	400	Common M4 Fastener	Steel	6

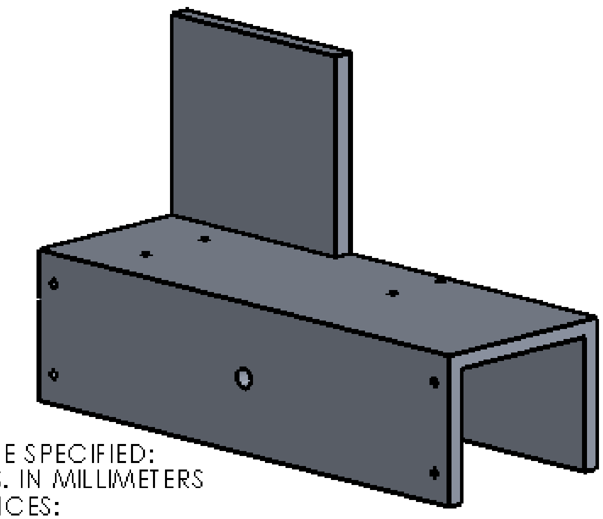
Cal Poly Mechanical Engineering ME 429 SENIOR PROJECT	Part/Dwg. #: 500 Team: STELLAR · Lab Section: 07	Title: Feed Deployment Assembly Date: 2/8/17 · Scale: 1:2	Drwn. By: CALEB BARBER DEPLOYABLE ANTENNA PROJECT



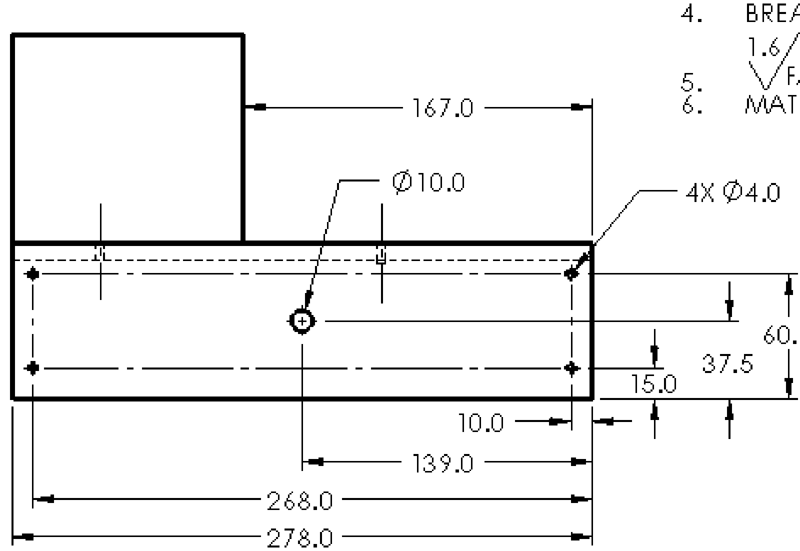
ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	501-1	Feed Deployer Casing	ABS	1
2	302	Deployer Casing Cover	ABS	1
3	303	Spool	AL 6061	1
4	501-2	Feed Boom	17-7 Steel	1
5	306	Bearing	Steel	2
6	305	M2 Boom Fastener	Steel	2

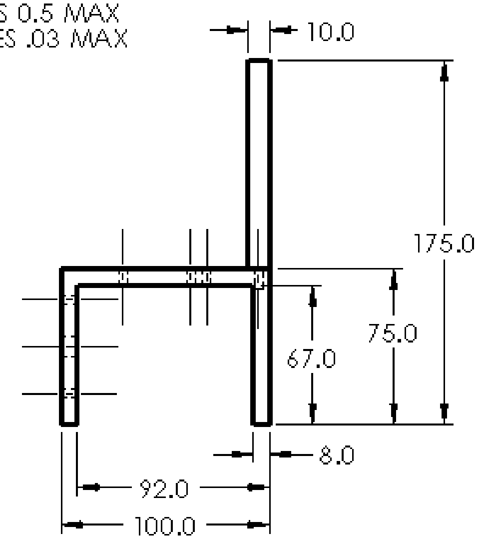
Cal Poly Mechanical Engineering	Part/Dwg. #: 501		Title: Feed Deployer Assembly	Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR	Lab Section: 07	Date: 2/8/17 / Scale: 1:2	DEPLOYABLE ANTENNA PROJECT



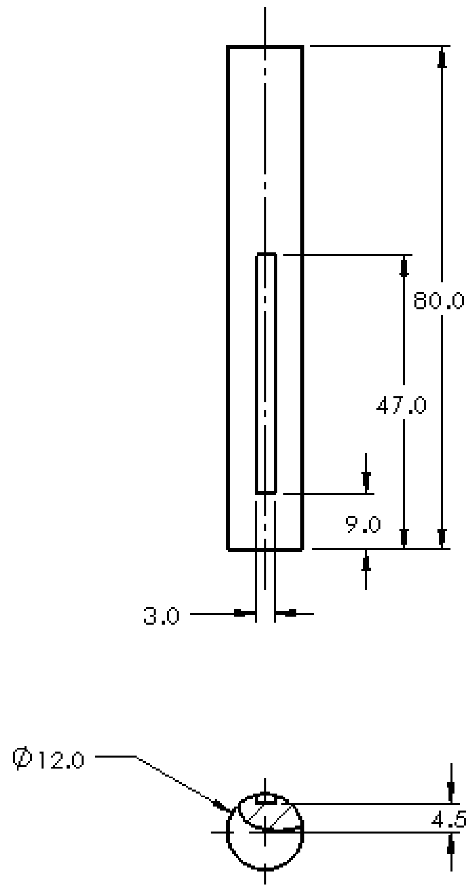


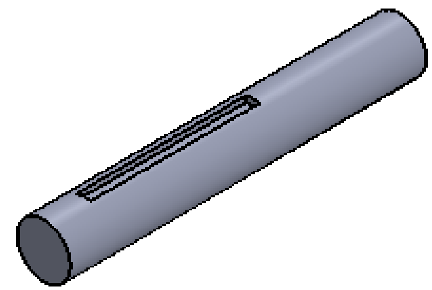
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: AL 6061





Cal Poly Mechanical Engineering ME 429 SENIOR PROJECT	Part/Dwg. #: 502 Team: STELLAR — Lab Section: 07	Title: Feed Stand Date: 2/8/17 — Scale: 1:3	Drwn. By: CALEB BARBER DEPLOYABLE ANTENNA PROJECT





NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: STEEL

Cal Poly Mechanical Engineering	Part/Dwg. #: 503		Title: Feed Shaft		Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR	Lab Section: 07	Date: 2/8/17	Scale: 1:1	DEPLOYABLE ANTENNA PROJECT

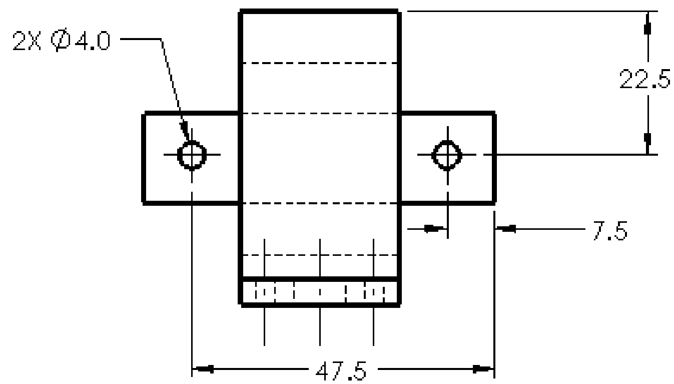
Set Screw Shaft Couplers

Part Number: 504

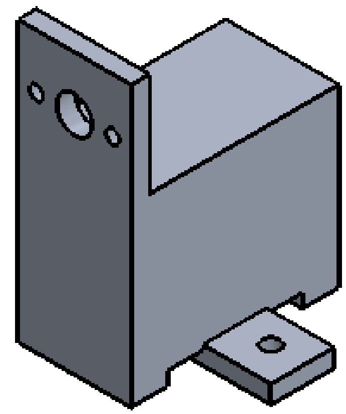
ADD TO WISHLIST 1 ADD TO CART

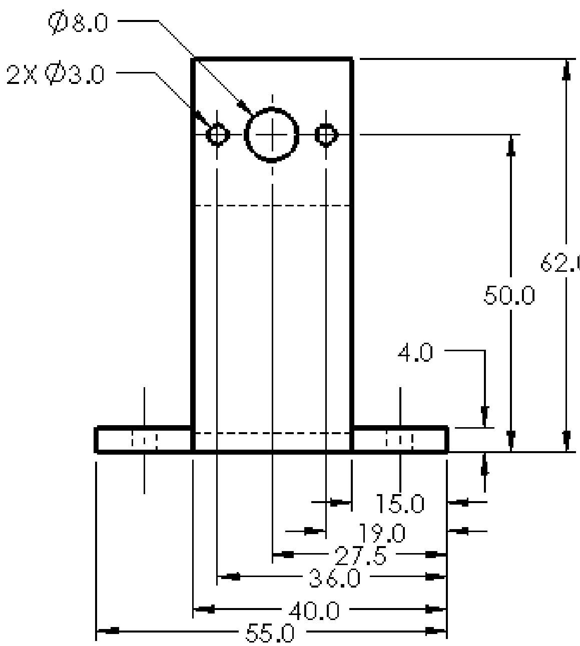
Price	$4.99 Sign up for Price Alert
Part	Set Screw Shaft Couplers
Status	In stock
Bore*	Choose an Option...

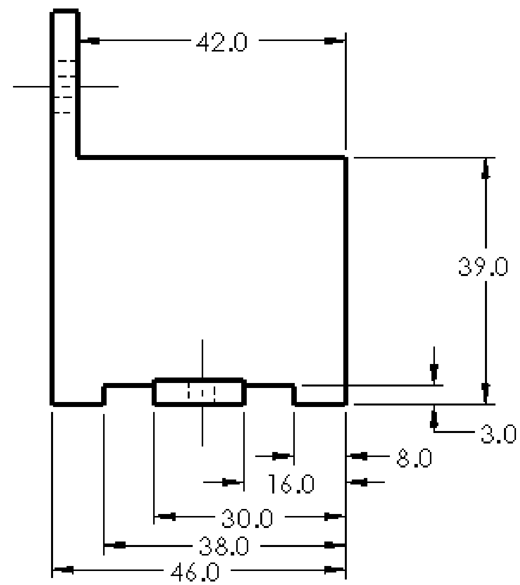
12mm to 4mm	.70"	625238



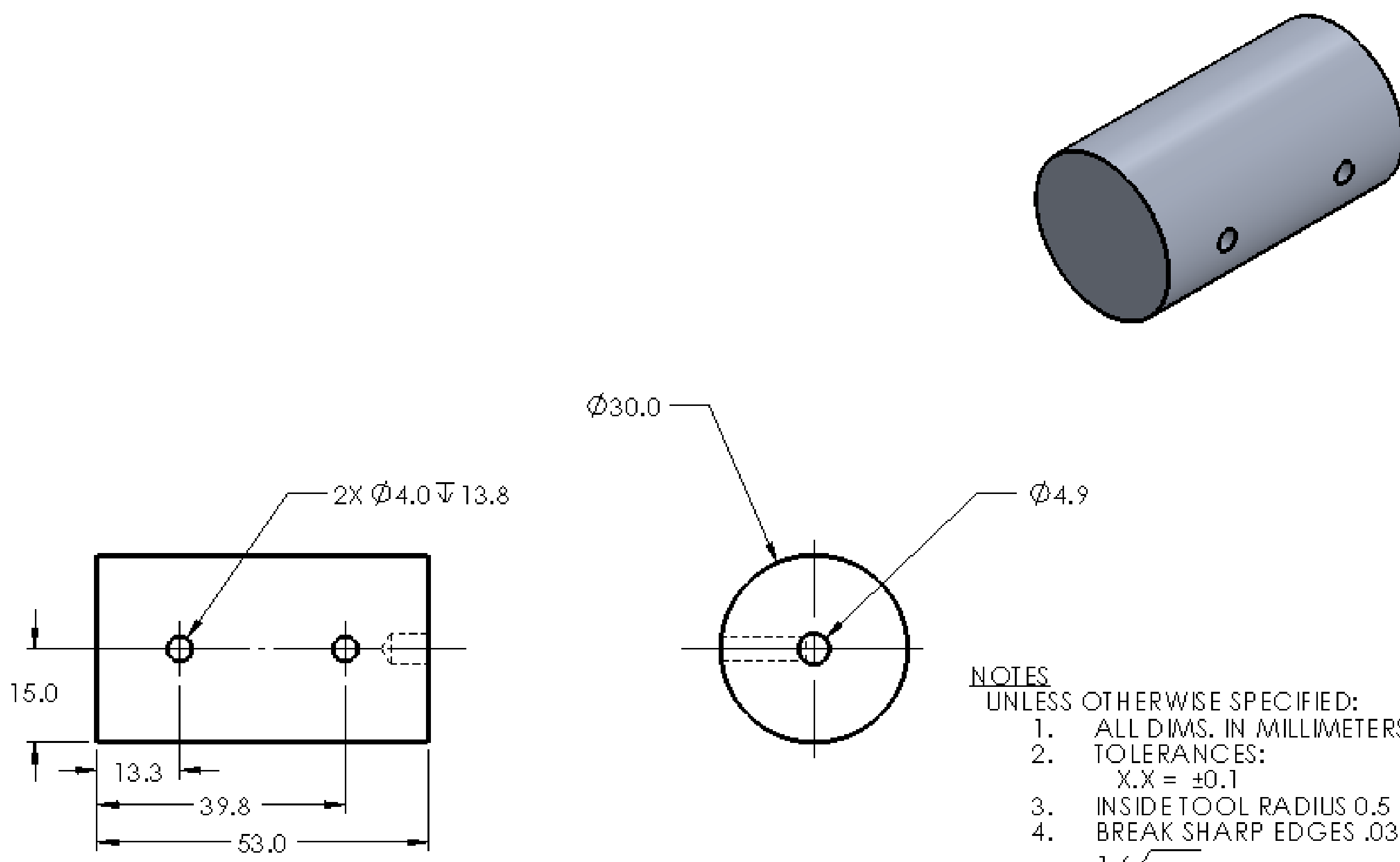
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: AL 6061







Cal Poly Mechanical Engineering ME 429 SENIOR PROJECT	Part/Dwg. #: 505 Team: STELLAR — Lab Section: 07	Title: Feed Motor Mount Date: 2/8/17 — Scale: 1:1	Drwn. By: CALEB BARBER DEPLOYABLE ANTENNA PROJECT



NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
X.X = ±0.1
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES .03 MAX
5. 1.6 √ FAO
6. MATERIAL: AL 6061

Cal Poly Mechanical Engineering	Part/Dwg. #: 506	Title: Feed	Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR / Lab Section: 07	Date: 2/8/17 / Scale: 1:1	DEPLOYABLE ANTENNA PROJECT

Steel Phillips Rounded Head Screws

10-24 Thread Size, 3/8" Long

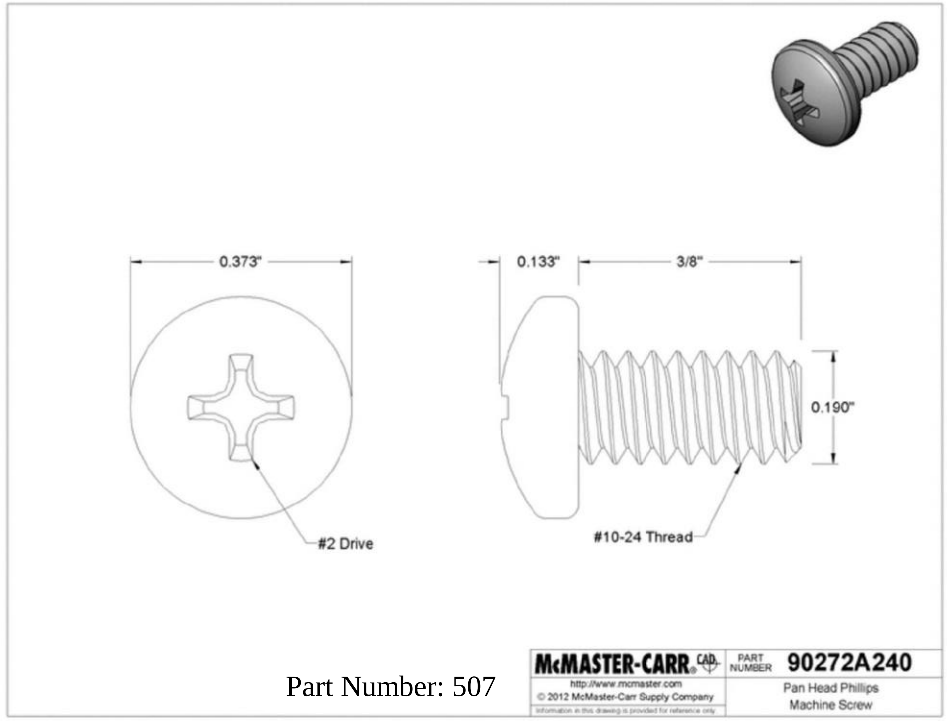
Packs of 100

ADD TO ORDER

In stock
$3.93 per pack of 100
90272A240

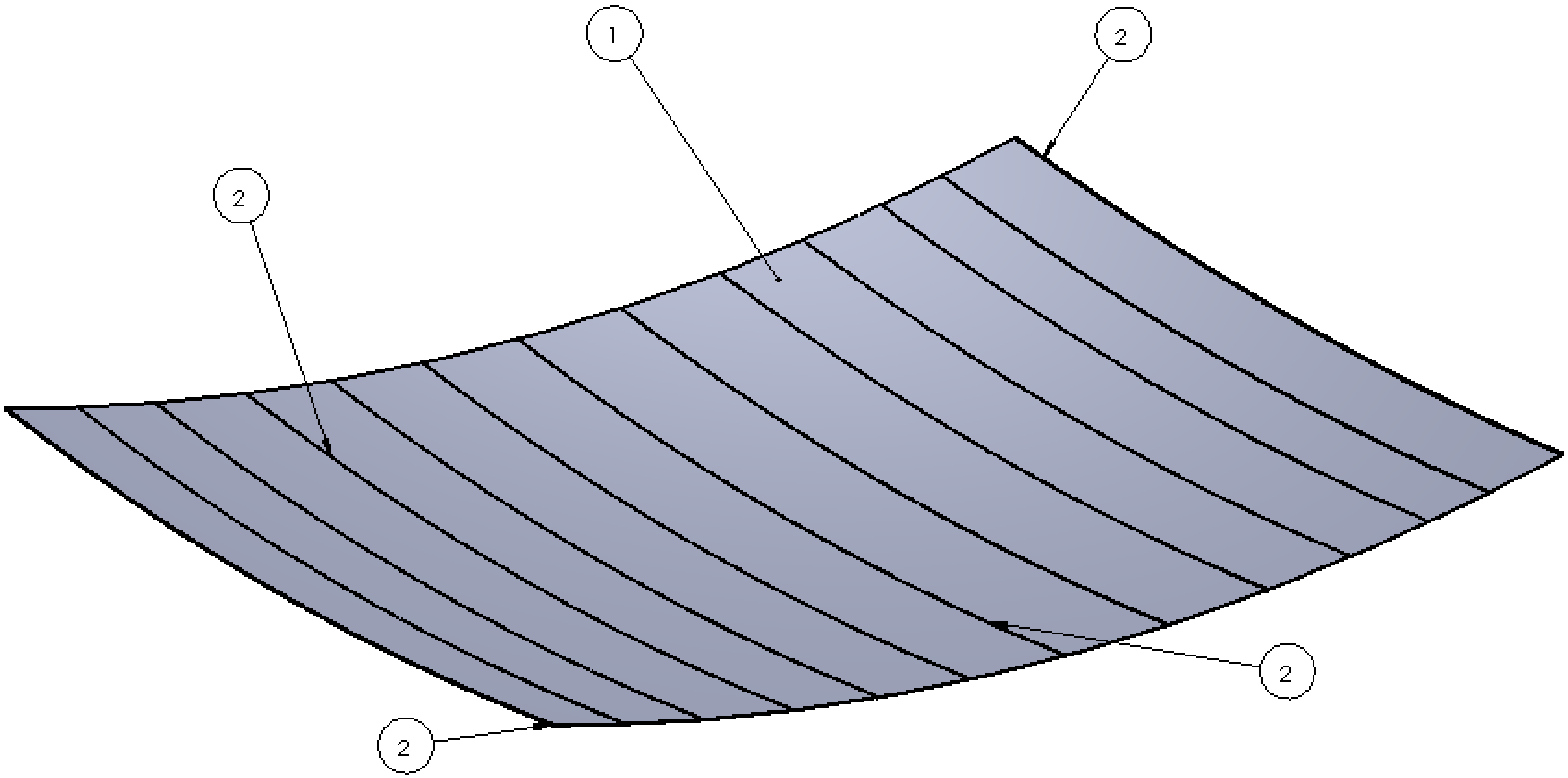
Thread Size	10-24
Length	3/8"
Threading	Fully Threaded
Head Diameter	0.373"
Head Height	0.133"
Drive Size	No. 2
Material	Zinc-Plated Steel
Hardness	Rockwell B70
Tensile Strength	60,000 psi
Screw Size Decimal Equivalent	0.190"
Thread Type	UNC
Thread Spacing	Coarse
Thread Fit	Class 2A
Thread Direction	Right Hand
Head Type	Rounded
Rounded Head Style	Pan
Rounded Head Profile	Standard
Drive Style	Phillips
System of Measurement	Inch
RoHS	Compliant

These pan head screws are zinc plated for corrosion resistance in wet environments. Length is measured from under the head.



Part Number: 507

The information in this 3-D model is provided for reference only. Details



ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	601	Mylar Reflector	Mylar	1
2	602	Nitinol Rib	Nitinol	13

Cal Poly Mechanical Engineering	Part/Dwg. #: 600	Title: Reflector Assembly	Drwn. By: CALEB BARBER
ME 429 SENIOR PROJECT	Team: STELLAR · Lab Section: 07	Date: 2/8/17 · Scale: 1:8	DEPLOYABLE ANTENNA PROJECT

Mylar Reflective Material, 4 Feet x 25 Feet, 2 Mil

Part Number: 601

by Earth Start

164 customer reviews | 90 answered questions

List Price: ~~$29.95~~
Price: $17.94 & **FREE Shipping**
You Save: $12.01 (40%)

i Your cost could be **$12.94**: Qualified customers get $5 in Gift Card funds on first $100 reload of their Amazon Gift Card Balance. Learn more

Note: Not eligible for Amazon Prime. Available with free Prime shipping from other sellers on Amazon.

In Stock.
Get it as soon as Feb. 16 - 22 when you choose **Standard** at checkout.
Ships from and sold by DCS Solutions.

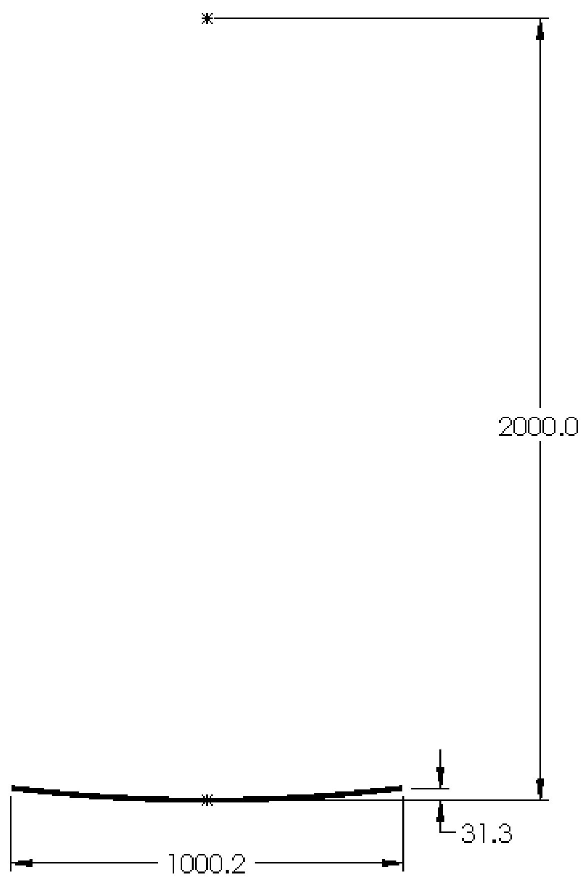
- 2 Mil Thick (Heavy Duty not 1mil like many on Amazon)
- 48
- 100% Light Tight
- Metalized on both sides
- Durable - Puncture/Tear Resistant

New (14) from $17.94 & FREE shipping.

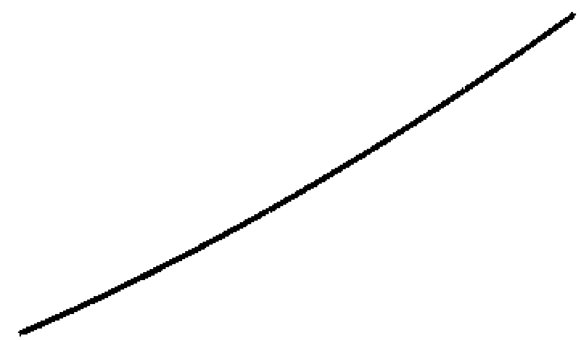
Report incorrect product information.

Technical Details

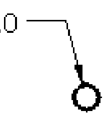
Item Dimensions	0.05 x 4.5 x 25 inches
Item Weight	5 pounds
Manufacturer Part Number	AZ-M001
Material Type	REFLECTIVE
Shipping Weight	2.4 pounds
UNSPSC Code	21101612



SCALE 1:16



NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN MILLIMETERS
2. TOLERANCES:
X.X = ±0.1
3. MATERIAL: NITINOL



SCALE 2:1

Cal Poly Mechanical Engineering	Part/Dwg. #: 602		Title: Nitinol Rib		Drwn. By: David Galvez
ME 429 SENIOR PROJECT	Team: STELLAR	Lab Section: 07	Date: 2/8/17	Scale: 1:8	DEPLOYABLE ANTENNA PROJECT

Steel Phillips Rounded Head Screw

M4 x 0.7 mm Thread, 14 mm Long

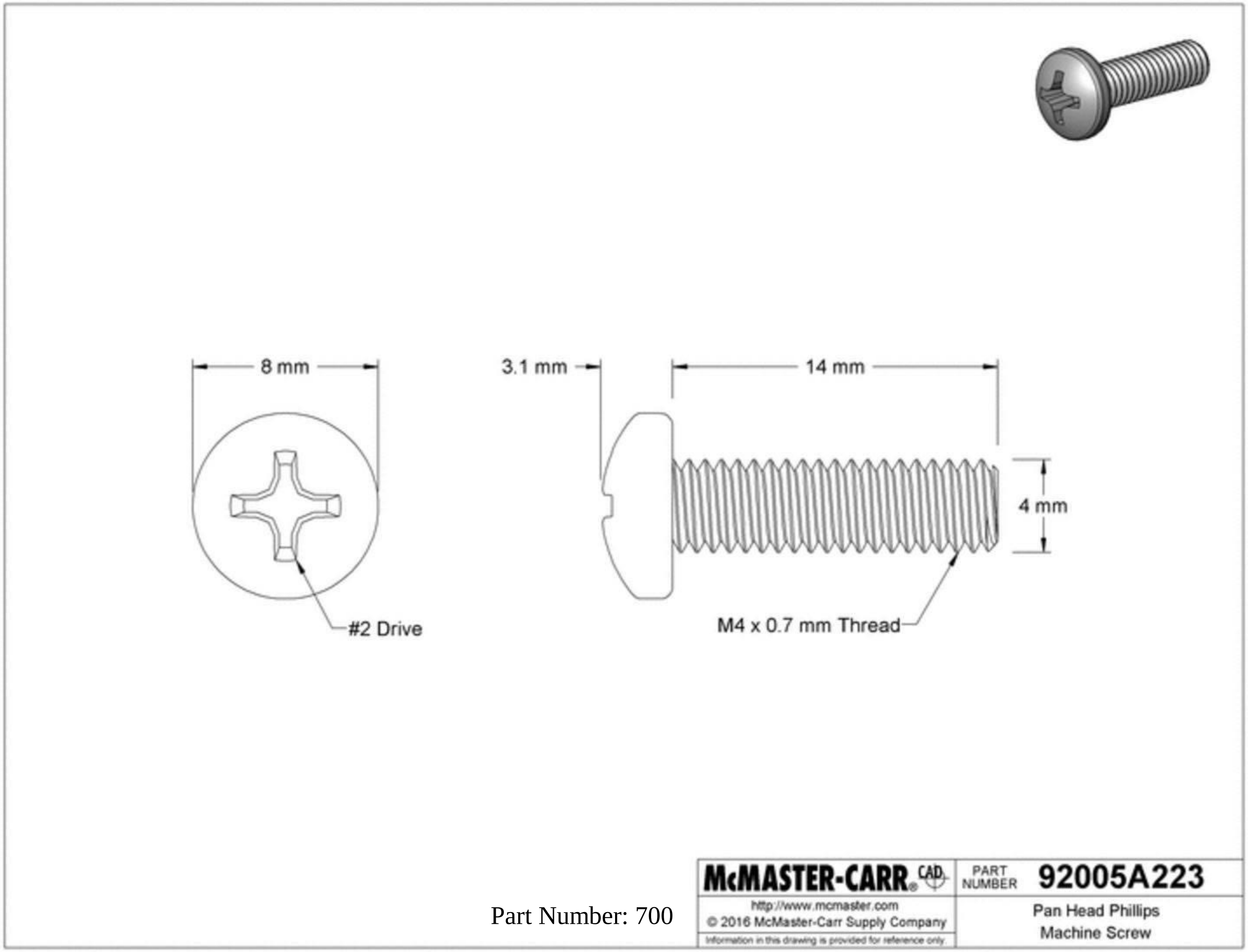
Packs of 100

ADD TO ORDER

In stock
$5.04 per pack of 100
92005A223

Thread Size	M4
Thread Pitch	0.7 mm
Length	14 mm
Threading	Fully Threaded
Head Diameter	8 mm
Head Height	3.1 mm
Drive Size	No. 2
Material	Zinc-Plated Steel
Hardness	Rockwell B71
Tensile Strength	60,000 psi
Thread Type	Metric
Thread Spacing	Coarse
Thread Fit	Class 6h
Thread Direction	Right Hand
Head Type	Rounded
Rounded Head Style	Pan
Rounded Head Profile	Standard
Drive Style	Phillips
Specifications Met	DIN 7985
System of Measurement	Metric
RoHS	Compliant

These pan head screws are zinc plated for corrosion resistance in wet environments. Length is measured from under the head.



Part Number: 700

Part Number: 701

Energizer 9V Alkaline Battery Retail Pack - 2-Pack

by Energizer

Be the first to review this item

Price: $7.52 & **FREE Shipping**

i Your cost could be **$2.52**: Qualified customers get $5 in Gift Card funds on first $100 reload of their Amazon Gift Card Balance. Learn more

Note: Not eligible for Amazon Prime.

In stock.

Usually ships within 4 to 5 days.

Want it Tuesday, Feb. 14? Order within **9 hrs 7 mins** and choose **Two-Day Shipping** at checkout. Details

Ships from and sold by MYBATTERYSUPPLIER.

Package Quantity: **1**

1	12
$7.52	$75.61

- Quantity Per Box/Pack - 2/Pack
- Type (Alkaline, Etc.) - Alkaline
- Size - 9V

Stren High Impact Fishing Line   Part Number: 702

by Stren

154 customer reviews | 3 answered questions

Price: $4.50 - $18.10

Sale: Lower price available on select options

Color: **Clear**

Size:

Select ▾

- Shock Resistant For Fighting Line-Punishing Gamefish
- Saltwater Tough For All Coastal And Offshore Fishing

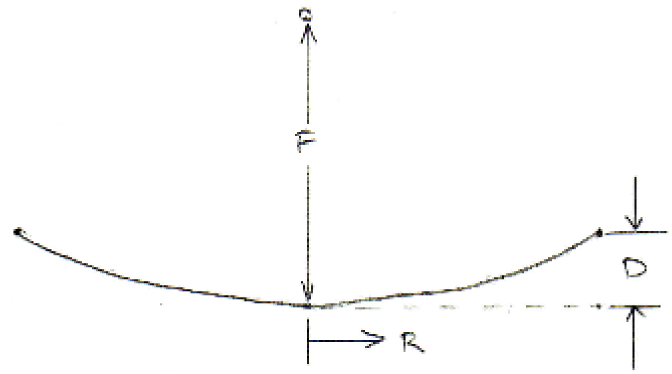
Report incorrect product information.

Appendix H.1: Detailed Supporting Analysis

APPENDIX H

BOOM AND NITINOL LENGTH CALCULATIONS

IDEAL PARABOLIC REFLECTOR SHAPE:



IDEAL PARABOLIC EQUATION: $4FD = R^2$

TO FIND THE LENGTH OF AN ARC OF THE PARABOLA, WHICH IS HOW MUCH MATERIAL TO PURCHASE, WE FOLLOW:

$$h = \frac{p}{2}$$

$$q = \sqrt{f^2 + h^2}$$

$$s = \frac{hq}{f} + f \ln\left(\frac{h+q}{f}\right)$$

WHERE f = FOCAL LENGTH, $p = R_{MAX}$

ARC LENGTH OF BOOM:

$f = F = 2m$

$p = R_{MAX} = 2m$

$h = 2m / 2 = 1m$

$q = \sqrt{(2m)^2 + (1m)^2} = 2.236\ m$

$$s = \frac{(1m)(2.236m)}{2m} + 2m \ln\left(\frac{1m + 2.236m}{2m}\right)$$

$S_{BOOM} = 2.08\ m$ ⟵

ARC LENGTH OF RIBS:

$f = 2m, \quad p = 0.5m$

$h = 0.5m / 2 = 0.25m$

$q = \sqrt{(2m)^2 + (0.25m)^2} = 2.016\ m$

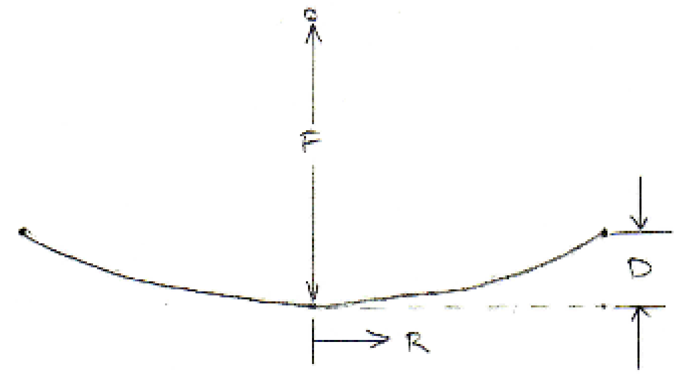
$$s = \frac{(0.25m)(2.016m)}{2m} + 2m \ln\left(\frac{0.25m + 2.016m}{2m}\right)$$

$S_{RIBS} = 0.501\ m$ ⟵

APPENDIX H

BOOM AND NITINOL LENGTH CALCULATIONS

IDEAL PARABOLIC REFLECTOR SHAPE:



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TO FIND THE LENGTH OF AN ARC OF THE PARABOLA, WHICH IS HOW MUCH MATERIAL TO PURCHASE, WE FOLLOW:

$$h = \frac{p}{2}$$

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$s_{BOOM} = 2.08\ m$ ←

ARC LENGTH OF RIBS:

$f = 2m, \quad p = 0.5m$

$h = 0.5m/2 = 0.25m$

$q = \sqrt{(2m)^2 + (0.25m)^2} = 2.016\ m$

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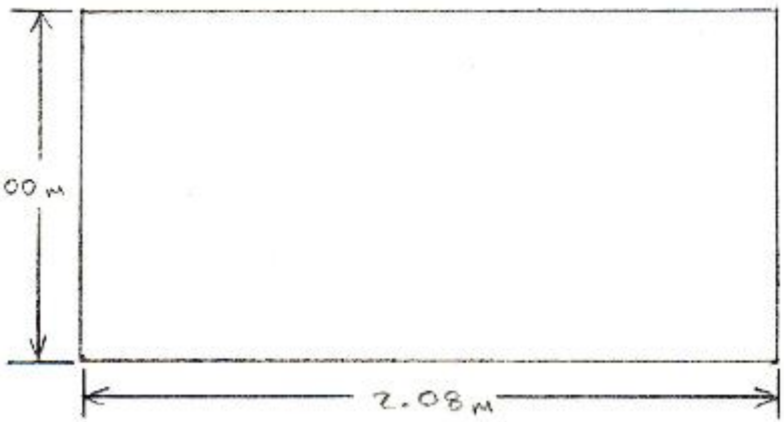
$s_{RIBS} = 0.501\ m$ ←

APPENDIX H

WEIGHT OF MYLAR CALCULATION

FLAT PATTERN OF MYLAR:



TYPICAL MYLAR THICKNESS: 2 mil ≡ 50.8 μm

$$\forall_{mylar} = (100\,cm)(208\,cm)(50.8 \times 10^{-4}\,cm)$$

$$= 105.7\,cm^3$$

$$m_{mylar} = \rho_{mylar} \forall_{mylar}$$

$$= \left(1.39\,\frac{g}{cm^3}\right)(105.7\,cm^3)$$

$$= 146.9\,g$$

$$m_{mylar} = 0.1469\,kg \leftarrow$$

$$W_{total} = m_{mylar}\,g$$

$$= (0.1469\,kg)(9.81\,m/s^2)$$

$$= 1.44\,N \text{ TOTAL}$$

THE LOAD ON EACH BOOM WOULD BE $\frac{1}{2} W_{total}$

$$W_{boom} = \frac{1}{2} W_{TOTAL}$$

$$W_{boom} = 0.72\,N / BOOM \leftarrow$$

THIS WOULD PROVIDE A DISTRIBUTED LOAD PER BOOM OF:

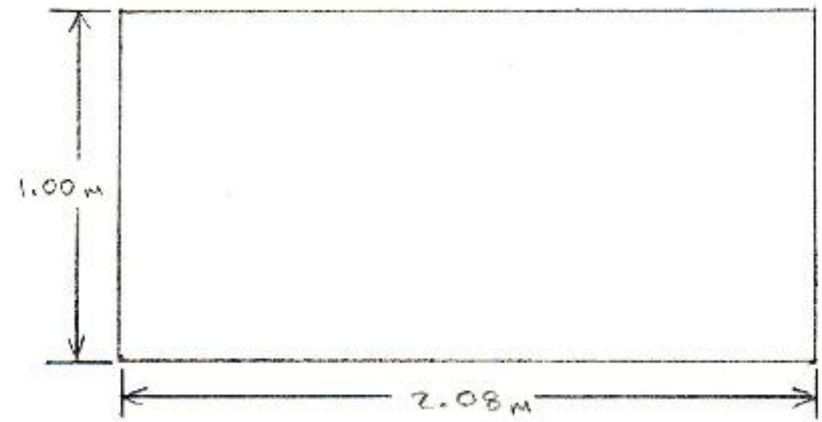
$$W_{dist} = 0.72\,N / BOOM / 2\,m$$

$$W_{DIST} = 0.36\,N/m / BOOM \leftarrow$$

APPENDIX H

WEIGHT OF MYLAR CALCULATION

FLAT PATTERN OF MYLAR:



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$= 105.7\,cm^3$

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$= (1.39\,\frac{g}{cm^3})(105.7\,cm^3)$

$= 146.9\,g$

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$= (0.1469\,kg)(9.81\,m/s^2)$

$= 1.44\,N$ TOTAL

THE LOAD ON EACH BOOM WOULD BE $\frac{1}{2} W_{total}$

$W_{boom} = \frac{1}{2} W_{total}$

$W_{boom} = 0.72\,N$ / BOOM ⟵

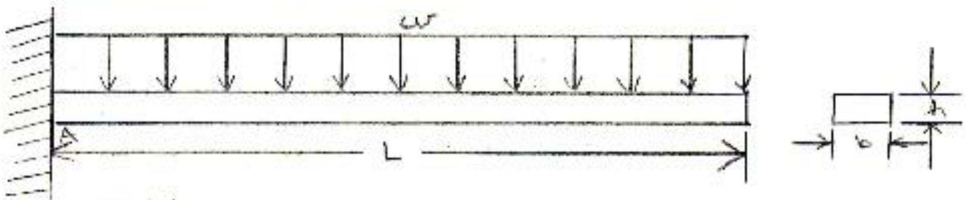
THIS WOULD PROVIDE A DISTRIBUTED LOAD PER BOOM OF:

$W_{dist} = 0.72\,N$ / BOOM / 2 m

$W_{dist} = 0.36\,N/m$ / BOOM ⟵

APPENDIX H

BOOM STRESS CALCULATION



FOR EACH BOOM

$$I = \frac{1}{12} b h^3$$

$$= \frac{1}{12}\left(1\text{in.}\left(\frac{0.0254\text{ m}}{1\text{ in.}}\right)\right)\left(0.010\text{ in.}\left(\frac{0.0254\text{ m}}{1\text{ in.}}\right)\right)^3$$

$$= 3.469 \times 10^{-14}\ m^4$$

$$F_R = \omega L$$
$$= \left(0.36\ \frac{N}{m}\right)\left(2.08\ m\right)$$

$= 0.749\ N$ APPLIED $\frac{L}{2}$ AWAY FROM SUPPORT

$$M_A = F_R \frac{L}{2}$$
$$= (0.749\ N)(1.04\ m)$$
$$= 0.779\ N\cdot m$$

$$\sigma_A = \frac{M_A c}{I}$$

$$= \frac{(0.779\ N\cdot m)\left(0.5 \cdot 0.010\text{ in.}\left(\frac{0.0254\text{ m}}{1\text{ in.}}\right)\right)}{3.469 \times 10^{-14}\ m^4}$$

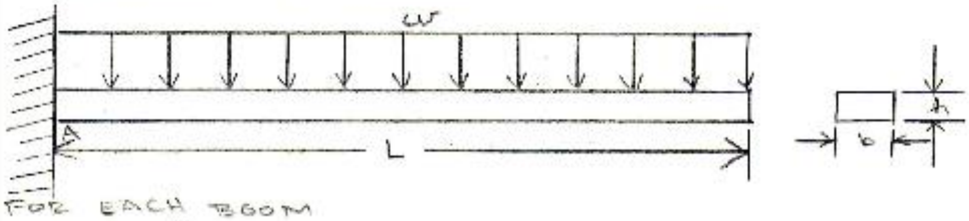
$$\sigma_A = 2.85 \times 10^9\ Pa$$

$\sigma_A = 2.85\ GPa$ ←

NOTE: ALTHOUGH THIS EXCEEDS THE YIELD STRENGTH OF MOST STEELS, OUR BOOMS ARE NOT GOING TO BE STRAIGHT CANTILEVER BEAMS. THE CURVATURE OF OUR BOOMS WILL DEFINITELY IMPROVE THE MOMENT OF AREA OF THE BEAM CROSS SECTION, WHICH WILL ULTIMATELY DECREASE THE STRESS. FURTHER ANALYSIS AND TESTING IS NEEDED

APPENDIX H

BOOM STRESS CALCULATION



FOR EACH BOOM

$$I = \frac{1}{12} b h^3$$

$$= \frac{1}{12}\left(1\,in.\left(\frac{0.0254\,m}{1\,in.}\right)\right)\left(0.010\,in.\left(\frac{0.0254\,m}{1\,in.}\right)\right)^3$$

$$= 3.469 \times 10^{-14}\ m^4$$

$$F_R = \omega L$$

$$= \left(0.36\ \frac{N}{m}\right)\left(2.08\ m\right)$$

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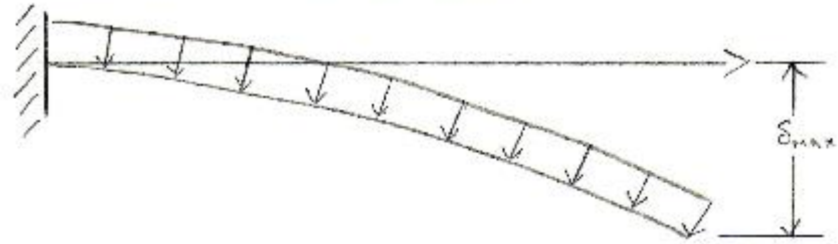
$$\sigma_A = 2.85\ GPa \leftarrow$$

NOTE: ALTHOUGH THIS EXCEEDS THE YIELD STRENGTH OF MOST STEELS, OUR BOOMS ARE NOT GOING TO BE STRAIGHT CANTILEVER BEAMS. THE CURVATURE OF OUR BOOMS WILL DEFINITELY IMPROVE THE MOMENT OF AREA OF THE BEAM CROSS SECTION, WHICH WILL ULTIMATELY DECREASE THE STRESS. FURTHER ANALYSIS AND TESTING IS NEEDED

APPENDIX H

BEAM DEFLECTION CALCULATION



FOR A CANTILEVER BEAM

$$\delta_{max} = \frac{wl^4}{8EI}$$

USING $E_{STEEL} = 150$ GPa

$w = 0.36$ N/m

FROM OUR SOLIDWORKS MODEL OF THE BOOM,

$I = 703.77547874\ mm^4$

THE MAXIMUM DEFLECTION OF THE BOOM WILL BE

$$\delta_{max} = \frac{\left(0.36\frac{N}{m}\right)(2.08m)^4}{8\left(150\times10^9\ \frac{N}{m^2}\right)\left(703.78\ mm^4\right)\left(\frac{1m}{1000mm}\right)^4}$$

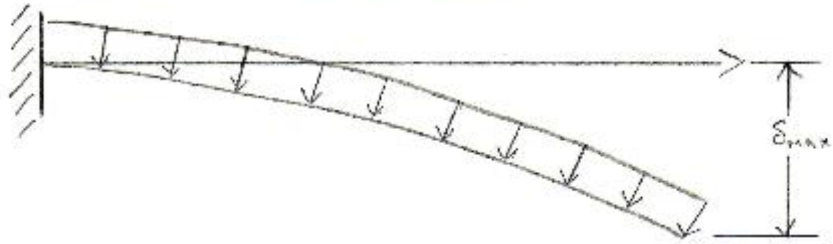
$= 0.00798$ m

$\delta_{MAX} = 8.0$ mm ←

NOTE: THIS DEFLECTION CALCULATION WAS PERFORMED WITH THE AREA MOMENT OF INERTIA OF AN AXIALLY CURVED BOOM. THIS GIVES A REASONABLE ESTIMATE FOR THE DEFLECTION OF A STRAIGHT OUT TAPE MEASURE.

APPENDIX H

BEAM DEFLECTION CALCULATION



FOR A CANTILEVER BEAM

$$\delta_{max} = \frac{\omega l^4}{8EI}$$

USING $E_{steel} = 150$ GPa

$\omega = 0.36$ N/m

FROM OUR SOLIDWORKS MODEL OF THE BOOM,

$I = 703.77547874 \text{ mm}^4$

THE MAXIMUM DEFLECTION OF THE BOOM WILL BE

$$\delta_{max} = \frac{\left(0.36 \frac{N}{m}\right)(2.08 m)^4}{8\left(150 \times 10^9 \frac{N}{m^2}\right)\left(703.78 \text{ mm}^4\right)\left(\frac{1 m}{1000 mm}\right)^4}$$

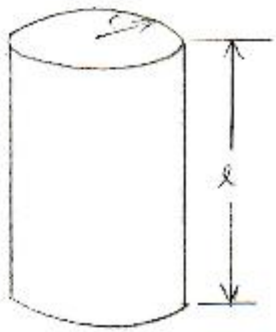
$= 0.00798$ m

$\delta_{max} = 8.0$ mm ←

NOTE: THIS DEFLECTION CALCULATION WAS PERFORMED WITH THE AREA MOMENT OF INERTIA OF AN AXIALLY CURVED BOOM. THIS GIVES A REASONABLE ESTIMATE FOR THE DEFLECTION OF A STRAIGHT OUT TAPE MEASURE.

APPENDIX H

FEED GEOMETRY CALCULATION



FEED MODELLED AS A CYLINDER

WE WILL MODEL THE FEED USING ALUMINUM

THE FEED SHOULD HAVE A MASS OF 100g TO SIMULATE THE MASS OF AN ACTUAL FEED

WE CHOSE THE DIAMETER OF THE CYLINDER TO BE 30mm

$\rho_{Al} = 2.70 \ g/cm^3$

$m_{cyl} = \rho_{Al} V_{cyl}$

$= \rho_{Al} \pi r^2 \ell$

$\ell = \frac{m_{cyl}}{\rho_{Al} \pi r^2}$

$= \frac{100 g}{2.70 \frac{g}{cm^3} \pi \left(15 mm \cdot \frac{1 cm}{10 mm}\right)^2}$

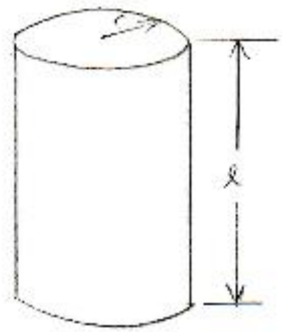
$\ell = 5.24 \ cm$

$\ell = 52.4 \ mm$ ←

NOTE: SINCE THE FEED WILL HAVE SOME HOLES IN IT TO ALLOW FOR FASTENING, WE WILL USE AN ALUMINUM CYLINDER LENGTH OF $\ell = 53$ mm

APPENDIX H

FEED GEOMETRY CALCULATION



FEED MODELLED AS A CYLINDER

WE WILL MODEL THE FEED USING ALUMINUM

THE FEED SHOULD HAVE A MASS OF 100g TO SIMULATE THE MASS OF AN ACTUAL FEED

WE CHOSE THE DIAMETER OF THE CYLINDER TO BE 30 mm

$\rho_{Al} = 2.70\ g/cm^3$

$$m_{cyl} = \rho_{Al} V_{cyl}$$
$$= \rho_{Al} \pi r^2 l$$

$$l = \frac{m_{cyl}}{\rho_{Al} \pi r^2}$$

$$= \frac{100\ g}{2.70\ \frac{g}{cm^3}\ \pi \left(15\ mm \cdot \frac{1\ cm}{10\ mm}\right)^2}$$

$l = 5.24\ cm$

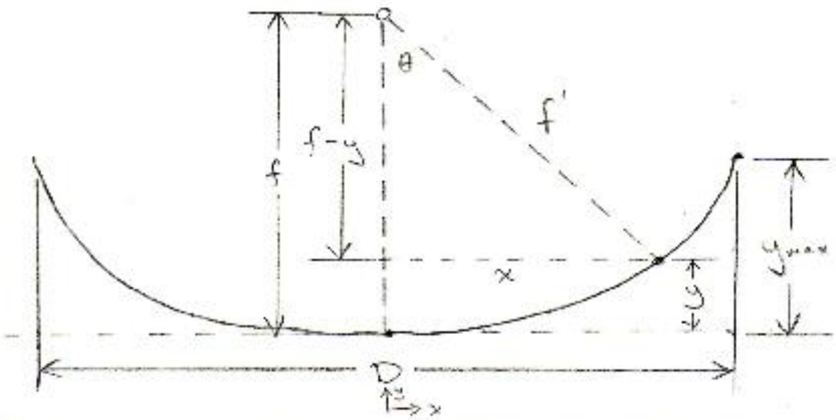
$l = 52.4\ mm$ ⟵

NOTE: SINCE THE FEED WILL HAVE SOME HOLES IN IT TO ALLOW FOR FASTENING, WE WILL USE AN ALUMINUM CYLINDER LENGTH OF $l = 53$ mm

APPENDIX H

PARABOLOID SURFACE PLOT CALCULATION

EXAGGERATED PARABOLIC REFLECTOR SHAPE [TO ILLUSTRATE GEOMETRIC RELATIONSHIPS]



FOR THE LONGITUDINAL PARABOLIC DEFINITION

$D = 400$ cm
$\frac{f}{D} = 0.5$ } REQUIRED BY SPECIFICATIONS
$f = 200$ cm

$4 y_{max} f = x_{max}^2$ EDGE EXTREME VALUES

$$y_{max} = \frac{x_{max}^2}{4f}$$

$$= \frac{(200 \text{ cm})^2}{4\,(200 \text{ cm})}$$

$$= \underline{50 \text{ cm}}$$

THE GENERAL EQUATION FOR THE PARABOLIC REFLECTOR IS:

$$4yf = x^2$$

THE FOCAL LENGTH OF THE WIDTHWISE PARABOLAS CHANGE AS THE DISTANCE GETS FURTHER FROM THE VERTEX. WE WILL DENOTE THESE UNIQUE FOCAL POINTS AS f'

$$f' = \sqrt{x^2 + (f - y)^2}$$

APPENDIX H

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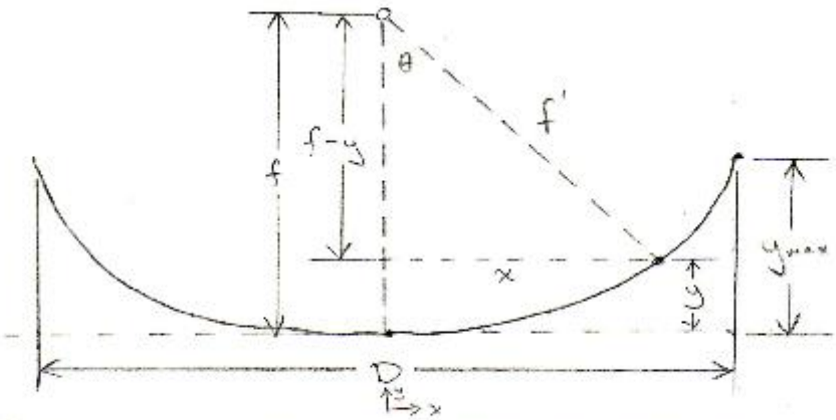
EXAGGERATED PARABOLIC REFLECTOR SHAPE [TO ILLUSTRATE GEOMETRIC RELATIONSHIPS]



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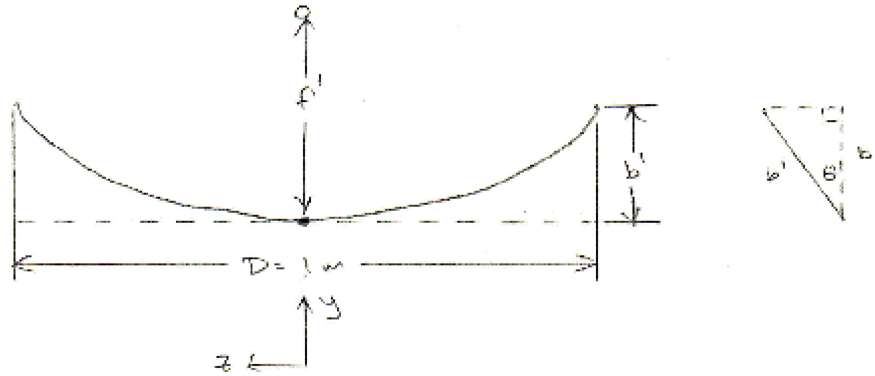
APPENDIX H

PARABOLOID SURFACE PLOT CALCULATION CONT'D

FROM THE POINT OF VIEW OF THE WIDTHWISE PARABOLAS



FOR THE WIDTHWISE PARABOLIC DEFINITION

$$4b'f' = z^2$$

$$b' = \frac{z^2}{4f'}$$

$$b' = \frac{z^2}{4\sqrt{x^2 + (f-y)^2}}$$

$$b = b' \cos\theta$$

$$b = \frac{z^2}{4\sqrt{x^2 + (f-y)^2}} \cos\theta$$

$$\theta = \tan^{-1}\left(\frac{x}{f-y}\right)$$

$$b = \frac{z^2}{4\sqrt{x^2 + (f-y)^2}} \cos\left[\tan^{-1}\left(\frac{x}{f-y}\right)\right]$$

THE LOCATION OF THE PARABOLOID WILL BE THE ADDITION OF THE HEIGHTS DEFINED BY BOTH THE LONGITUDINAL AND WIDTHWISE PARABOLAS

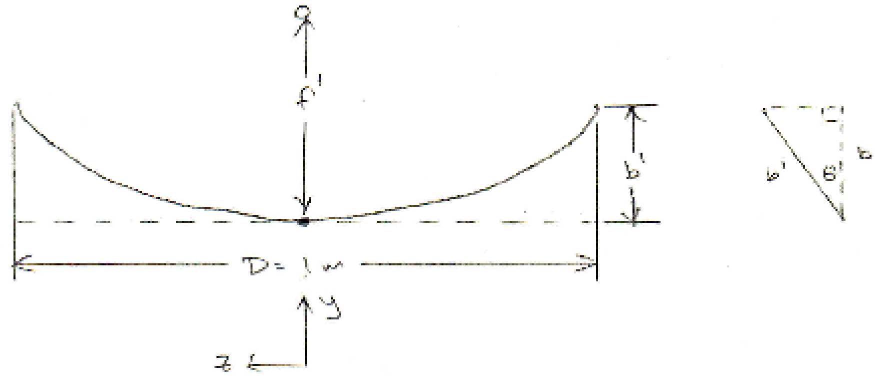
$$\text{HEIGHT} = \frac{x^2}{4f} + \frac{z^2}{4\sqrt{x^2 + (f-y)^2}} \cos\left[\tan^{-1}\left(\frac{x}{f-y}\right)\right]$$

→ SEE ATTACHED MATLAB CODE AND 3D PLOT

APPENDIX H

PARABOLOID SURFACE PLOT CALCULATION CONT'D

FROM THE POINT OF VIEW OF THE WIDTHWISE PARABOLAS



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APPENDIX H

Measuring Horizontal Resistance on Tape Measure for Motor Selection

☆ This resistance is used to estimate the Torque needed to unroll the horizontal deployers

$K_{Avg} = 78.283\ kg/s^2$

$X_1 = 3.2\ cm \quad X_2 = 10.5\ cm$

$F_H = KX$

$F_H = 78.283\ kg/s^2\ (.105\ m - .032\ m)$

$F_H = 5.71\ N$ ☆ in english 1.284 lbf

Torque calculation r = radius of tape measure spool

☆ Calculated in english because Motor specs are in english units.

$T_{reqd} = F_H\ r$

$= 1.284\ lbf\ (1.535\ in)$

$\boxed{T_{reqd} = 1.971\ lbf\ in}$

Beause there are two horizontal deployers driven by one motor, this torque is doubled

$\boxed{T_{reqd_H} = 3.942\ lbf\cdot in}$

$\approx 4.54\ KgFcm$

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APPENDIX H

GEAR SELECTION

Motor shaft Inner diameter = 4 mm
Deployer shaft Inner diameter = 12 mm

1:1 Gear Ratio

Factor of Safety = 2

σ_{all} = 15 kpsi

Steel S_{ut} = 55 kpsi
S_y = 30 kpsi

F = .5

Pressure angle 20°

P = 32 in

N = 32 teeth

P_d = 1"

OD = 1.06"

Spur Gear Bending

$$d_P = \frac{N_P}{P_d} = \frac{32}{1} = 32$$

Velocity $$V = \frac{\pi(1")(32)}{12} = 6.81 \text{ fpm}$$

Speed of selected Motor N = 26 rpm

N = .433 rps

Hp needed

= .0032 Hp

$$W^t = \frac{33000(.0032\ HP)}{6.81} = 15.271$$

Gear bending stress equation

$$\sigma = W^t K_o K_v K_s \frac{P_d}{F} \frac{K_m K_B}{J}$$

Overload factor $K_o = 1$

Dynamic Factor $K_v = 1.1$ → Low speed

Size Factor $K_s = \frac{1}{K_b} = \left(\frac{F(\sqrt{Y})}{P}\right)^{0.535}$

$K_b = (d/.3)^{-0.107} = .879$ in

$K_s = 1.1375$

$P_d = 1"$

$F = .5"$

$Y = .365$

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APPENDIX H

Load distribution Factor K_m

$K_m = 1 + C_{mc}(C_{pf} C_{pm} + C_{ma} C_e)$

$= 1 + .8\left(\left(\frac{.5}{10(1)} - 0.025\right)(1) + (.247 + .0167(0.5))\right)$

$K_m = 1.22$

Rim Thickness $K_B = 1$

Geometry Factor $J = .35$

$\sigma = W^t K_o K_v K_s \frac{P_d}{F} \frac{K_m K_B}{J}$

$= 15.271(1)(1.1)(1.1375)\left(\frac{1}{.5}\right)\left(\frac{1.22(1)}{.35}\right)$

$\sigma = 133.208$ psi

$\sigma_{all} = \frac{S_t}{S_F} \frac{Y_N}{K_T K_R}$ $S_t = 45{,}000$ psi

Bending stress-strength Repeated Factor $Y_N = 4.498(1000)^{-.0140}$

$Y_N = 3.4$

Temp. Factor $K_T = 1$

Reliability Factor .999

$K_R = 0.658 - 0.079(\ln(1-R))$

$K_R = 1.0075$

$SF = \frac{\frac{45000(3.4)}{1.0075}}{133.208 \text{ psi}} = \boxed{1140}$ Bending Factor of Safety

* Because our speeds + loads are quite small Gear Bending is not a concern

* Because of our small amount of actual usage, Gear wear is not a concern.

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APPENDIX H

Spring Constant Calibrations

* Using springs to estimate starting torque required by Motor using known masses

$m_1 = 159.45\,g = .15945\,kg$ $m_2 = 187.5\,g = .1875\,kg$ $m_3 = 229.05\,g = .2291\,kg$

$F_1 = (.15945\,kg)(9.81\,m/s^2) = 1.564\,N$ $F_2 = (.1875\,kg)(9.81\,m/s^2) = 1.839\,N$ $F_3 = (.2291\,kg)(9.81\,m/s^2) = 2.25\,N$

* Assuming a linear spring, the ΔX was measured from a tension spring using known masses

$$F = KX$$

TRIAL 1: $X_1 = 3.2\,cm$ $X_2 = 4.9\,cm$

$$K = \frac{F_1}{X}$$

$$K = \frac{1.564\,N}{.049\,m - 0.032\,m}$$

$$\boxed{K_1 = 92\ kg/s^2}$$

TRIAL 2: $X_1 = 3.2\,cm$ $X_2 = 5.6\,cm$

$$K = \frac{F_2}{X}$$

$$K = \frac{1.839\,N}{.056\,m - .032\,m}$$

$$\boxed{K_2 = 76.64\ kg/s^2}$$

TRIAL 3: $X_1 = 3.2\,cm$ $X_2 = 6.6\,cm$

$$K = \frac{F_3}{X}$$

$$K = \frac{2.251\,N}{.066 - 0.032}$$

$$\boxed{K_3 = 66.21\ kg/s^2}$$

$$K_{AVG} = \frac{K_1 + K_2 + K_3}{3} = \frac{92\,kg/s^2 + 76.64\,kg/s^2 + 66.21\,kg/s^2}{3}$$

$$\boxed{K_{AVG} = 78.283\ kg/s^2}$$

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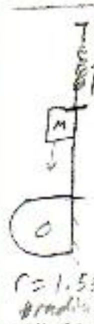
APPENDIX H

Measuring Vertical Resistance on Tape Measure For Feed Motor Selection



$M = 229.1\,g \qquad K_{Avg} = 78.283\ kg/s^2$

$X_1 = 3.2\ cm \qquad X_2 = 13.2\ cm$

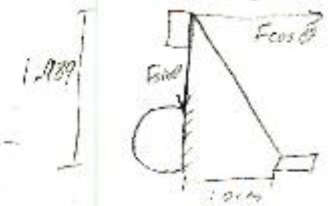
$F = K_{Avg}(X_2 - X_1)$

$F_V = 78.283\ kg/s^2\ (.132\ m - .032\ m)$

r = 1.535 in # radius of TM spool

$\boxed{F_{req} = 7.783\ N} \approx 1.753\ lbs$

* A retractable reel was added to maintain the stiffness of the boom, so the added force must be accounted for.



Tensioning force $F = 0.5\ lbf$

$a^2 + b^2 = c^2$

$1.989^2 + .1^2 = c^2$

$c = 1.991\ m$

$F\cos\theta = .5\left(\frac{.1}{1.991}\right) = .025\ lbf$

$F\sin\theta = .5\left(\frac{1.989}{1.991}\right) = .499$

$F_{req} = 1.753\ lbf + .499\ lbf$

$F_{req} = 2.253\ lbf$

$T_{req} = F_{req}(r)$

$= 2.253\ lbf\ (1.535\ in)$

$\boxed{= 3.458\ lb\ in}$

$\approx 3.98\ kgf\,cm$

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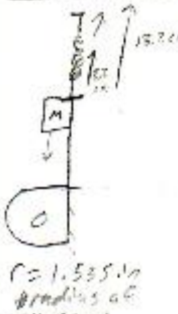

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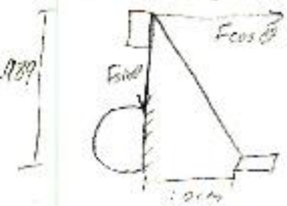

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APPENDIX H

SHAFT SIZING

* Because required horsepower of the motor is so low, the power used in this calculation is an estimate 0.01HP. Giving a larger safety margin

Motor Specs

$P = 0.01$ hp

$N = 26$ rpm

$\varnothing_{shaft} = 12$ mm

Factor of Safety $n = 2$

$$T_{rq} = \frac{63000\,(P)}{N} = 24.23 \text{ in-lb}$$

converted $T_{rq} = 2.738$ N-m.

$$F = \frac{2T}{d\cos\theta} = \frac{2\,(2.73 \text{ N-m})}{.012\text{ m}\,(\cos 20°)}$$

$F = 595$ N

$M = F\,d$

$M = 595\text{N}\,(0.195\text{ m})$

$M = 116.15$ N-m

Theoretical stress concentration factor

Bending $K_t = 2.14 \rightarrow$ End mill Keyseat

Torsion $K_{ts} = 3.0$

Notch sensitivity Factors

$q_s = 0.9 \qquad q = 0.8$

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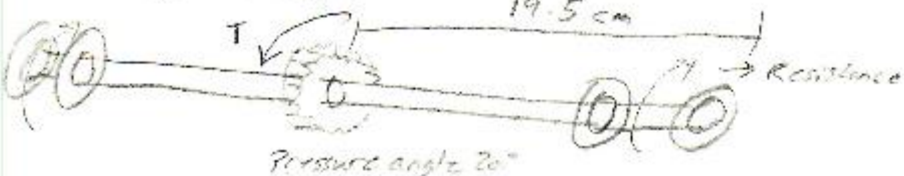

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Torsion $K_{ts} = 3.0$

Notch sensitivity factors

$q_s = 0.9$ $\quad q = 0.8$

APPENDIX H

Fatigue Stress Concentration Factor

Bending $K_f = 1 + q(K_t - 1)$

$= 1 + .08(2.14 - 1)$

$K_f = 1.912$

Torsion $K_{fs} = 1 + q_s(K_{ts} - 1)$

$K_{fs} = 1 + 0.9(3 - 1)$

$K_{fs} = 2.8$

Min diameter equation for Von Mises compared to Yeild Strength

$$d = \left[\frac{16n}{\pi S_y}\left[4(K_f M)^2 + 3(K_{fs} T)^2\right]^{1/2}\right]^{1/3}$$

$$= \left[\frac{16(2)}{\pi(450\,MPa)}\left[4(1.912 \times 116.15\,Nm)^2 + 3(2.8(7.738\,Nm))^2\right]^{1/2}\right]^{1/3}$$

$d = 2.18$ mm

APPENDIX H

Fatigue Stress Concentration Factor

Bending $K_f = 1 + q(K_t - 1)$

$= 1 + .08(2.14 - 1)$

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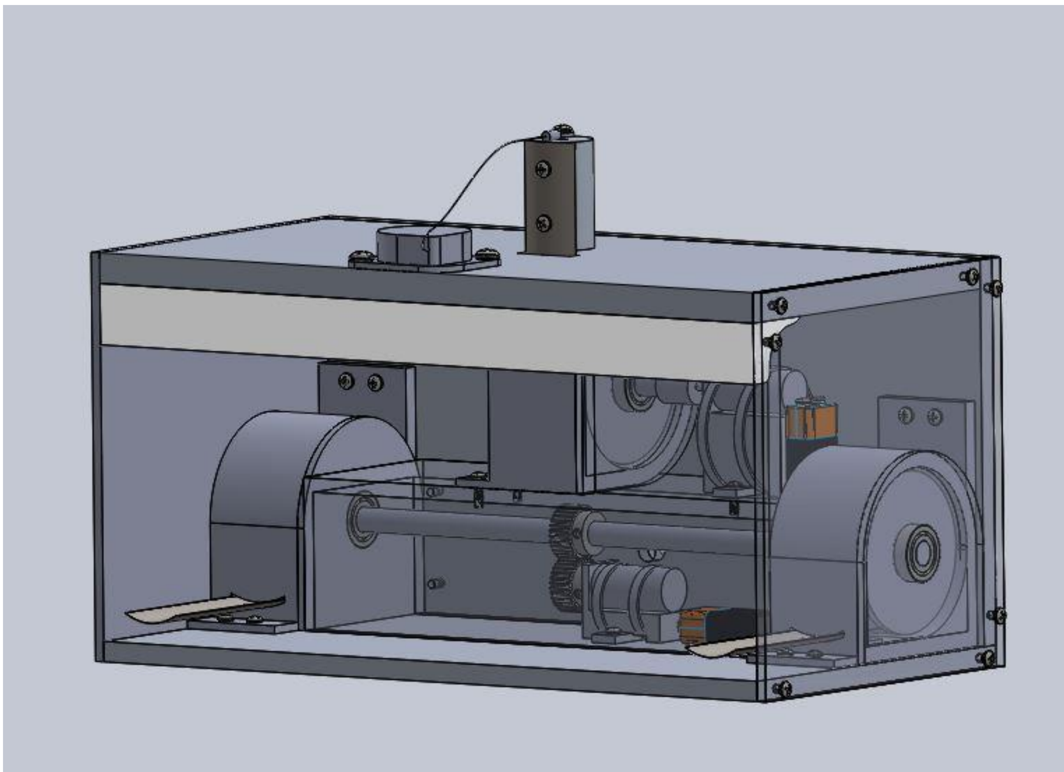
$$= \left[\frac{16(2)}{\pi(450\,MPa)}\left[4(1.912 \times 116.15\,Nm)^2 + 3(2.8(7.738\,Nm))^2\right]^{1/2}\right]^{1/3}$$

d = 2.18 mm

```
% Appendix H.2

% Senior Project
% SolidWorks Data Script for Reflector

% Stellar Dudes: David Galvez, Mack Lennon, Caleb Barber

% Alright dudes, here's what's up. This code ultimately outputs height values
% of our ideal reflector at various structured x,z positions. We can adjust
% how fine we want these x,z positions to be by making Nx and Nz bigger.
% The final matrix that we care about is yq. We will compare the ideal yq
% with our measure yq that we will hopefully get from a 3D scan.

% Update - the scan sucked. We are better off measuring by hand and seeing
% what we get.

% ReflectorLocations_5cmSpacing.csv is the saved values we took from
% SolidWorks using a mesh of 5 cm. We can make that smaller if we want but
% it will take more time.

clc
clear all
close all

fileID = fopen('ReflectorLocations_5cmSpacing.csv'); % Open data file

% scan text file: specify format, skip header lines, specify delimiter
C = textscan(fileID, '%d %f %f %f %f %s','HeaderLines',9,'Delimiter',',');

fclose(fileID);                   % Close data file

[N,d,x,y,z,Comp] = C{1,:};        % Define variables stored in cell array

% Number of points in x and z directions ( probably as accurate as we'll
% get from a 5 cm mesh spacing in SolidWorks
Nx = 20; Nz = 40;

% maximum values for x and z directions
xmin = min(x);
xmax = max(x);
zmin = min(z);
zmax = max(z);

% Spatial Step Sizes
dx = (xmax-xmin)/Nx;
dz = (zmax-zmin)/Nz;

% Here, we turn our wacky mesh locations into something structured
xgv = xmin:dx:xmax;             % regular mesh vector in x-direction
zgv = zmin:dz:zmax;             % regular mesh vector in z-direction
[xq, zq] = meshgrid(xgv, zgv);  % create regular mesh arrays

% Find y values at locations xq,zq from scattered data of y located at x,z
yq = griddata(x,z,y,xq,zq);       % interpolate nodal data onto regular mesh
```

```
% Plot Data
y1 = min(y);
y2 = max(y);
Nc = 100; % Number of Contours (change to make best plot)
dy = (y2 - y1)/Nc;
v = y1:dy:y2;
colormap(jet)
contourf(xq,zq,yq, v, 'Linestyle', 'none'); % contour plot of data
ymax = max(y1,y2);
ymin = min(y1,y2);
caxis([ymin, ymax])
axis equal tight
title('Contour Plot of y values') % title needs to be at bottom
xlabel('x [m]')
ylabel('z [m]')
%

height_matrix = [0 10 40 60 15 40 200 260 150 140 110 100];

% Based off the matrix produced above, I probed values of theoretical
y_values = [17.2862 48.6721 48.6721 130.8299 163.098 163.098 ...
    293.0256 424.5632 390.4169 424.5632 259.7957 293.0256];

lhm = length(height_matrix);

height_difference = zeros(1,lhm);
height_difference_squared = zeros(1,lhm);

for p = 1:lhm
    height_difference(p) = height_matrix(p) - y_values(p);
    height_difference_squared(p) = (height_difference(p))^2;
end

% rms in mm
rms = sqrt((1/length(height_matrix))*sum(height_difference_squared));
rms = rms/10;

% Let's hope for the best
```

Appendix I: Operator's Manual: Deployable Cubesat Antenna
Team: Stellar Dudes
Sponsor: Dr. Tomas Svitek, Stellar Exploration Inc.
Advisor: Professor Rossman, Cal Poly, San Luis Obispo



I. Pre-Folding and Deployment Preparation

A. Before operation of the deployable antenna, the reflector and reflector material must be folded and stowed properly.

B. With the booms fully extended the reflector and rib material must be folded in the manner shown below in Figure 1.

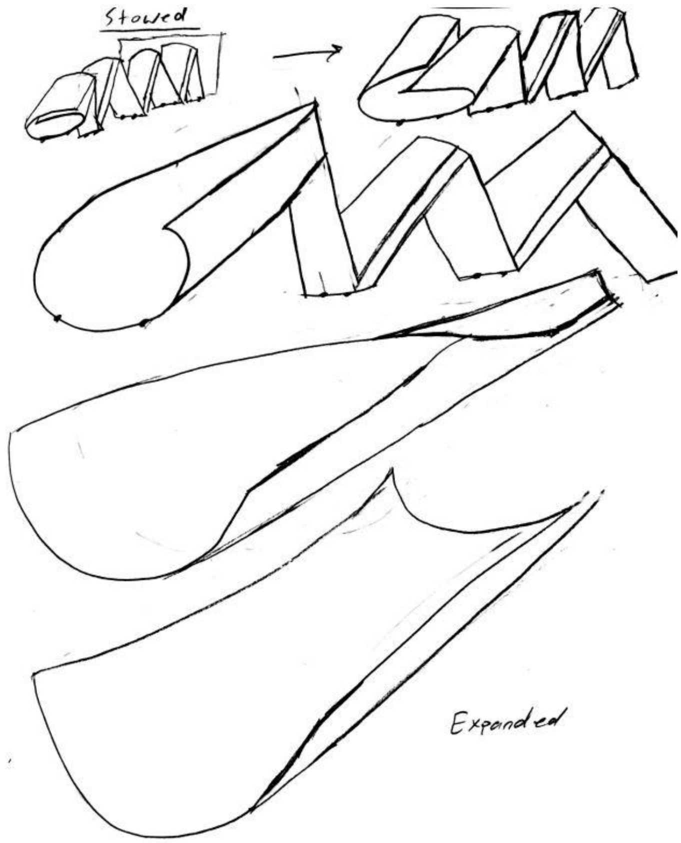


Figure 1. Proper folding method of ribbed reflector (starting from the bottom)

C. The reflector and folded ribs must be stowed behind the stopper, as seen in Figure 2 to constrain the top of the reflector folds and prevent unwanted deployment.

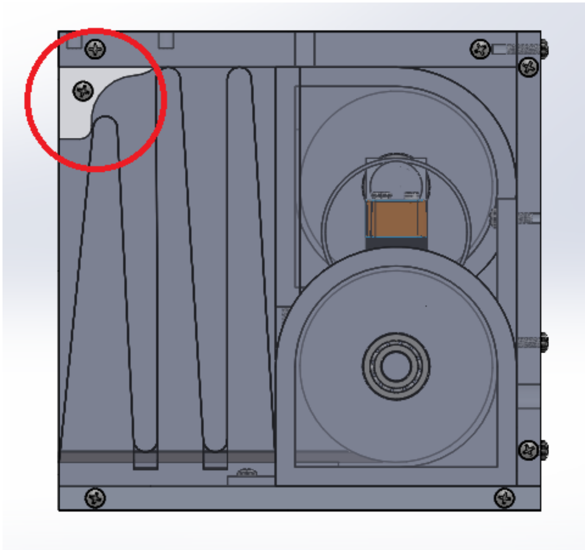


Figure 2. Proper stowing behind stopper

D. Roll up booms by flipping switch to reverse position until reflector is placed behind stopper.

II. Operation

A. Reflector should only be deployed from a flat table and in a location that allows for at least 2m x 1m of open space in front of the deployment unit.
B. Before deployment reflector should be checked for tears and tangles that may prevent deployment.
C. It is preferable to deploy the reflector and feed separately (not at the same time) to prevent the motion of one from affecting the other.
D. Once the booms are fully extended, the switches should be flipped to the off position.
E. The reflector will remain open until properly stowed as explained in the above section.
F. A proper deployment should look like Figure 4 shown below.

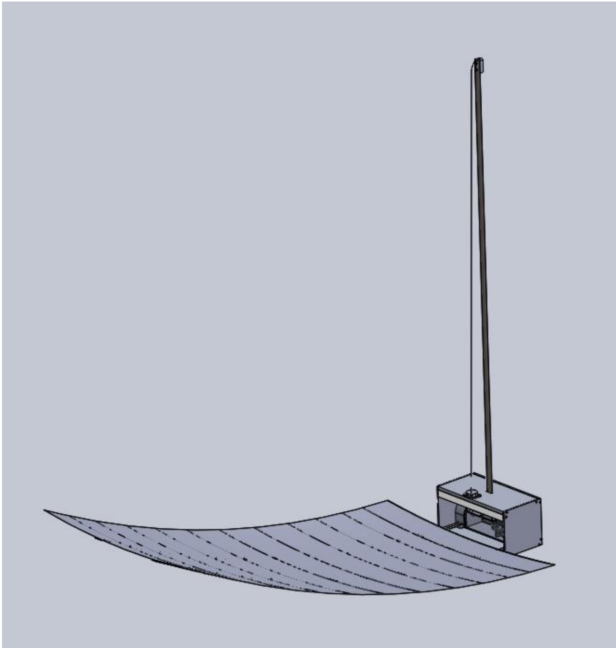


Figure 4. Fully Deployed Reflector

III. Safety Concerns

A. Deployer unit must be set on a sturdy table to avoid unwanted movement during deployment.

B. Fingers and loose articles of clothing must be kept away from deployer during operations.

C. Reflector must be checked for tears and tangles before operation to assure a proper deployment.

D. Power source and wiring must be properly insulated and checked for any loose metal that may cause any fire danger.

E. The deployer unit must have at least 2m x 1m of space in front of it before deployment.

F. Due to the use of highly elastic materials, sudden motions may occur when reflector is deployed. Stand clear of reflector as it deploys.

G. Safety glasses will be worn when handling highly elastic components such as the ribbed reflector to prevent any accidental injury.

Appendix J: List of Edits from PDR to CDR

Report Edit Log

Team: Stellar Dudes

Edits for Report: (Check box)		
	PDR	
	CDR	
	FDR	X

Report Section #	Source of recommended edit (Sponsor, Advisor, Team, Reviewer)	Brief description of edit
Ch.5	Team	Added detail and prototype design to Manufacturing section
Ch.5. *11*	Team/Advisor	Updated costs and shipping
Ch.4	Advisor	Reorganization Final Design, added pics, reduced paragraphs and labels
Ch.6	Team	Discussed Test Results
Ch.6	Advisor	Added new specs table addressing if pass/fail
Ch. 7	Team	Discussed improvements needed and overall conclusion
Gantt Chart	Team	Updated Gantt Chart and reorganized planned and actual
Throughout	Advisor	Correctly labeled and introduced Figures
Throughout	Team	Improved readability and flow/ removed contractions
Thoughout	Advisor	Mention Figure then show it