Boom Stability Control
Final Project Report

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## Change Log

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Executive Summary

The BOOMStiC Gravity Gradient Boom and Turnstile Antenna project was developed to provide a passive attitude control system and better communications for future CubeSat satellites developed by California Polytechnic State University. The system utilizes the energy from a coilable metal spring to deploy a tip mass to a length of one meter from the side of the satellite. Calculations show the resulting gravity gradient torque causes the satellite to settle two degrees from normal to the earth’s surface.
1. Introduction

The Cal Poly PolySat project has expressed a need for a passive attitude control system using a gravity gradient boom and an accompanying antenna. Such a device would provide future CubeSat satellites from Cal Poly and other institutions around the world with the ability to maintain a constant orientation relative to Earth and more reliable communication. PolySat and the Mechanical Engineering Senior Project group consisting of Michael Barnes, Justin Carnahan, Daniel Fluitt, and Alicia Johnstone have agreed to develop a gravity gradient boom and antenna combination that will meet the goals and requirements presented in the Boom Stability Control Proposal Document and in Section 3, Objectives. Five gravity gradient boom concepts were considered and modeled, one of which has been selected for production. This chosen concept, the reasoning behind its selection, the structural and orbital analyses, and validation testing are presented in this report.

2. Background

While PolySat does not have any experience developing gravity gradient booms, the technology has been used in aerospace industry since the beginning of space flight. Deep space satellites such as Voyager and Cassini, as well as many other earth orbiting satellites, have used deploying booms for orientation adjustment and other science missions. While these designs are on a much larger scale, the lessons learned from their experience will aid us in creating a successful product. In the CubeSat community, institutions including Stanford University, Montana State University, and Surrey Satellite Communications have used gravity gradient booms on triple CubeSats. These designs will be studied heavily, as they are the most applicable to our project. Website links about these satellites are provided in Appendix A for additional information. A patent search yielded no patents on CubeSat Gravity Gradient Booms.

Our product will have to meet a number of specifications in order for it to be marketable. Most important, the design standard of a CubeSat presented in the CubeSat Design Specification will need to be followed if our product is to be used on Cal Poly’s satellites. This document presents a conceptual design that will be able to meet PolySat’s product requirements, as well as the technical requirements that must be met in order for a CubeSat to be eligible to launch in the Poly Pico-satellite Orbital Deployer (P-POD).

2.1. Gravity Gradient Analysis

Analysis was performed to determine how the proposed boom length and tip mass would stabilize the satellite. A model was analyzed using a typical Low Earth Orbit (LEO) of 500 km. The boom was considered to be of negligible mass, and to be completely rigid. The model analyzed can be seen in Figure 1. This model was analyzed statically and the restoring moment was plotted against satellite orientation. The drag force was also computed to make sure that the restoring torque could overcome the drag force moment and stabilize the satellite. The results of this analysis are given in Figure 2 and Table 1. All of the calculations performed are given in Appendix F.
What causes the gravity gradient boom to self-orient the satellite is the unbalance between the gravitational force and the centripetal force. Looking at the equations for each force, it can be seen that the gravitational force is proportional to the orbiting radius squared, while the centripetal force is proportional to the square root of the orbiting radius squared. This creates a non-linear relationship between the two forces. Since the CubeSat and tip mass are rigidly connected, and the whole unit orbits about its center of mass, all of the components orbit at the same rate. This causes the CubeSat to orbit faster than required for its altitude, in turn causing the centripetal force to be larger than the gravitational force. The tip mass will then orbit more slowly than required for its altitude, causing the gravitational force to overcome the centripetal force. These coupled forces cause a restoring moment that will stabilize the satellite with the boom unit, aligning itself perpendicularly to the orbit path.

<table>
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Figure 1: Model Analyzed
After completing the analysis, the proposed boom length of 1 meter and tip mass of 100g were found to be theoretically appropriate for stabilizing a 1U CubeSat. When comparing the maximum torque that the drag produces to the restoring torque, a theoretical settling position of about 0.1° is expected. This analysis was performed on a very simple model, and further analysis will need to be performed in order to fully validate the gravity gradient boom design.

### 2.2. Existing Deployable Mast Technologies

As stated in the beginning of Section 2, there have been successful gravity gradient boom deployers incorporated on spacecraft in the past. This section will identify and explain a few of the deployable mast technologies that have already been developed.

#### 2.2.1. Thin-Walled Tubular Booms

Thin-walled tubular booms are elastically deformable due to their thin-walled shells. This makes them rigid while deployed, and malleable while stored (see Figure 3).
2.2.2. Coilable Masts

Figure 4 is a picture of a coilable mast. The major advantage of this concept is its ability to compress down to a small volume, while having the ability to deploy to a significant length. It will be rigid near the base but will lose rigidity as the mast increases in length. This concept is best for shorter masts.
2.2.3. Telescopic Mast
A telescopic mast consists of concentric cylindrical tubes nested inside each other, as seen in extendable car radio antennas. The telescopic mast typically requires a motor to facilitate extension (Figure 5). This concept will produce a rigid mast but will require an unfavorable stored volume to deployed length ratio.

![Figure 5. Telescopic Mast Deployment (Gunnar Tibert Doctoral Thesis, Appendix A)](image)

2.2.4. Articulated Trusses
An articulated truss mast has more rigidity and efficiency than the other mast types in this section. There are a number of different configurations for these trusses. A folding articulated square truss mast is shown in Figure 6.

![Figure 6. Folding Articulated Square Truss Mast (Gunnar Tibert Doctoral Thesis, Appendix A)](image)
3. Objectives

Listed below are the project requirements which our design will adhere to. QFD was performed and the resulting House of Quality is given in Appendix B. The House of Quality showed that one or more of our engineering requirements satisfy each customer requirement. A comprehensive table of all specifications complete with projected methods of compliance is also given in Appendix C.

3.1. Boom Unit

3.1.1. Boom Length
The length of the boom shall be substantial enough to produce reliable attitude control while in orbit. A tentative goal of a 1 meter boom has been set.

3.1.2. Tip Mass
The tip mass shall be optimized to produce reliable attitude control while in orbit, while not infringing significantly on the mass margin prescribed by CubeSat standards. The tip mass remains a function of the boom length, and shall be designed in parallel with the boom length. A tentative goal to use electronics such as a tri-axis magnetometer as the tip mass has been set.

3.1.3. Positioning Of Boom Unit
Because the antenna placement is most critical, the boom shall be designed to function and fasten to the structure in many different orientations and positions. The boom unit shall be able to fit on a few, preferably all, faces of the CubeSat structure to maximize placement options. The boom unit shall also be able to be fastened in different orientations on each face of the CubeSat structure. The boom unit shall have minimal impact on the amount of solar panel surface area. The boom shall be oriented to produce optimal gain, wave pattern, etc. for the antenna.

3.1.4. Size Requirements
The size of the boom unit is limited to the internal volume of the CubeSat structure, and the 6.5mm envelope that is permitted outside of the CubeSat structure as specified in the CubeSat Developers Specifications Document (Appendix A). The boom unit shall occupy no more than ¼ U of satellite space. The volume of the boom unit and boom length ratio shall be optimized.

3.1.5. Storage Requirements
The boom unit design shall take into consideration storage of up to six months. Design considerations to minimize or preferably eliminate creep of any component shall be taken.
3.2. Antenna Unit

3.2.1. Antenna Type
The antenna shall be designed as a Turnstyle or Dipole type antenna capable of receiving and transmitting in circular waveforms. The deployed antenna shall be as close to perfectly straight as possible.

3.2.2. Antenna Length
The antenna shall be designed to function in the 437 MHz band.

3.2.3. Antenna Location
The antenna must be mounted on the “Top Hat” of the new PolySat structure. The antenna placement must be optimized with respect to the Boom and CubeSat structure.

3.2.4. Storage Requirements
The antenna unit design shall take into consideration storage of up to six months. Design considerations to minimize or preferably irradiate creep of any component shall be taken.

3.3. Kinematics

3.3.1. Deployment
The boom shall deploy to a final length equal to that specified in Section 3.1.1. The boom will not deploy until actuated. The faster the boom deploys the better, but structural integrity takes precedence over speed (i.e. the boom will not deploy faster than material properties allow).

3.3.2. Torquers
The system may include torquers for the purpose of re-settling the satellite. The torquers will not interfere with any of the other satellite or boom components.

3.3.3. Settling
Once the boom is fully deployed, the satellite shall settle. The time needed to settle is a function of other design requirements (i.e. boom length, tip mass, etc.).

3.4. Forces and Environment

3.4.1. During Launch
The system shall survive +3dB higher than NASA’s General Environmental Verification Specification (GEVS) for qualification vibrations. These levels will be tested and verified at Cal Poly.

3.4.2. During and Post-Boom Deployment
The boom shall be designed to withstand the dynamic loads encountered during deployment. During deployment and after, the boom shall be rigid enough to resist buckling. The entire system shall withstand the environmental effects found in low earth
orbit (i.e. gravity gradient, magnetic torques, thermal, etc.) with a minimum service life of five years.

3.4.3. **Environment**
The product shall be designed to operate in a low earth orbit environment.

3.5. **Energy**

3.5.1. **During Launch**
No electronics shall be active during launch to prevent any electrical or RF interference with the launch vehicle and primary payloads (See Section 2.3.1 of Cal Poly’s CubeSat Design Specification Rev. 12, Appendix A).

3.5.2. **During and Post-Boom Deployment**
The boom may implement a small electric motor, shape memory alloy, or stored potential energy to achieve full deployment. The system will be passive once fully deployed.

3.6. **Material**

3.6.1. **Composition**
The boom shall be made of a non-ferrous material. Once in orbit, the selected material will stay non-ferrous for the extent of the minimum CubeSat service life (five years). The material shall be coatable and/or paintable.

3.6.2. **Conductivity**
The antenna shall be made of a conductive material. The boom may also be conductive as long as it is grounded to the CubeSat structure. Conductivity of the material will be greater than or equal to carbon steel.

3.7. **Electronics**

3.7.1. **Boom Tip Electronics**
The tip mass of the boom may be designed to accommodate electronics. Refer to Section 3.1.2.

3.8. **Safety**

3.8.1. **Safety Standards**
The boom and antenna design must not violate any of the specifications provided in the CubeSat Developers Specifications document (Appendix A) or the NASA Educational Launch of Nano-Satellites (ELaNa) initiative, LSP-REQ-317.01.

3.8.2. **Deployment Safety**
Deployment design must not have any risk of damaging other systems of the satellite including solar panels, structure, and sensors.
3.9. Manufacturing

3.9.1. Manufacturing
Manufacturing will be performed by the BOOMStiC team at Cal Poly, or by a commercial machinist.

3.10. Assembly

3.10.1. Assembly
Flight unit of product must be assembled in a clean room environment. Proper assembly procedures shall be provided with the final product.

3.11. Quality Control

3.11.1. Design Reviews
Design reviews will be required at each major milestone of the project.

3.12. Schedules

3.12.1. Major Goals and Milestones
All major goals and milestones are outlined in the Method of Approach section of this report.

3.12.2. Weekly Meetings
Weekly meetings shall take place in order to keep project progress on track and to ensure PolySat is involved in the design process.

3.12.3. Testing
After construction, the boom apparatus will be integrated into the HyperCube, the current PolySat CubeSat structure. The deployment will be tested a sufficient number of times to establish that the deployment is reliable.

It will then be put into a 1U test pod provided by the CubeSat Program and tested on a vibration slip table to levels specified in Section 3.4.1. The mechanism will then go through functional testing again to determine if it survived the vibrations testing.

It will also undergo thermal vacuum testing which will ensure that the deployment apparatus will not be adversely affected by the temperatures and vacuum it is expected to experience in space.
4. Project Management

The responsibilities of the team are divided evenly according to each member’s strengths. A list of each team member and their responsibilities can be found below:

Alicia Johnstone: Sponsor-Team communication, documentation of project progress, thermal analysis, prototype fabrication,
Primary Subsystem: Boom/Antenna Control

Daniel Fluitt: Electrical analysis, design lead/solid modeling, manufacturing considerations, anechoic chamber testing
Primary Subsystem: Antenna-Structure Interface

Justin Carnahan: Information gathering, vibration analysis, antenna design considerations, vibrations testing,
Primary Subsystem: Boom Storage and Deployment

Michael Barnes: Material analysis, testing plans, thermal-vacuum chamber testing,
Primary Subsystem: Boom-Structure Interface

Outstanding tasks include but are not limited to: finalizing satellite settle duration estimates, building and testing a prototype boom, rapid prototyping the “top hat” and boom structure, deciding materials, working out a heat treatment schedule (if Beryllium-Copper is chosen), fabricating components, and building/testing final boom.

The outstanding tasks will be completed by the group member with an appropriate responsibility or strength.

For a list of the milestones and design flowchart see Figure A.1 and Table A.1 in the Appendix.
5. Design Development

5.1. Initial Design Concepts
After a number of brainstorming and ideating sessions, five boom deployment methods were chosen for further investigation. A rough model was built for each concept to better determine their feasibility.

Three of the five concepts were rejected after trials with the models. A Pugh Matrix (See Appendix E) was developed, however sponsor input was the deciding factor. The two concepts chosen for development were the tape measure boom, Figure 10, and the scissor lift boom, Figure 11. Ultimately, the tape measure boom concept was chosen to be prototyped.

![Spring Boom Concept](image)

**Figure 7. Spring Boom Concept**

The Spring boom concept, Figure 1, would essentially consist of a spring mounted to a side panel. Ideally, the spring would be compressed to a length of 6.5mm for launch and extend to one meter once actuated, which may prove difficult with our volume constraints. This design would require sacrificing the solar panel on that face. The spring would need to be highly specialized to fit our design requirements which may prove to be expensive. Finally, the deployment would result in longitudinal oscillations. For these reasons, the Spring boom concept was rejected.
The “Tent Pole” boom concept, Figure 8, works much like a standard tent pole. When in launch configuration, the links would lie side by side along the face of the satellite. In an ideal deployment, the links would rotate and lock into place without contacting each other or the satellite. The probability of an ideal deployment happening is low. These links would be connected by some type of space grade elastomer. Finding an appropriate elastomer for this application would be difficult if not impossible. Additionally, deployment of this boom would be unreliable and violent when compared to the other designs. For these reasons, the “Tent Pole” boom concept was rejected.

The Justin’s Ladder boom concept, Figure 9, consists of a series of panels stacked together. It is unique among the five concepts in the fact that it has the potential to double as additional solar panels for the satellite. When actuated, torsion springs connecting the panels would force them to un-stack and align end-to-end. One foreseeable complication with this design is the drag created by its large surface area. The drag on the panels created by the upper atmosphere could affect the orientation which would defeat the purpose of having the boom. For these reasons, the “Justin’s Ladder” boom concept was rejected.
The Tape Measure boom concept, Figure 10, was selected for further analysis. See Section 4.2 for additional information.

The Scissor Lift boom concept, Figure 11, was also selected for further analysis. See Section 4.3 for additional information.
5.2. Runner-up Concept: The “Scissor Lift” Boom

Figure shows a sketch of the “scissor lift” boom concept. It is made up of a simple scissor lift structure with a tension spring at the bottom to actuate deployment. A burn wire will hold it in the stowed position until deployment. The boom will be located on the outside of the structure and under the outer panel.

![Figure 12. Scissor Lift Concept integrated onto PolySat CubeSat structure](image)

As seen in Figure, the tension spring will cause the unfixed end point of the apparatus to slide to the fixed point when the free end is released by the burn wire. This will cause the boom to extend.

![Figure 13. Scissor Lift extension process](image)
5.2.1. Volume / Length
The boom will not be inside the structure, so virtually none of the internal volume of the CubeSat will be used. According to the CubeSat specifications, the satellite may use an extra 6.5 mm beyond the structure and between its rails. This concept will need to be less than 6.5 mm thick, less if there is to be a solar panel covering it. The length of the boom is expected to be approximately 1 meter as seen in Figure 12.

5.2.2. Positioning
The boom and deployer may be positioned on any side face of the CubeSat structure. The stowed configuration can be seen in Figure 13, and extended in Figure .

5.2.3. Resist Buckling Forces / Rigidity
The boom is expected to be sufficiently rigid to maintain its shape and not be susceptible to significant oscillations during or after deployment.

5.2.4. Composition / Nonferrous
The boom will likely be made of aluminum or plastic strips and nonferrous fasteners at the joints to meet the nonferrous requirement.

5.2.5. Deployment Reliability
The scissor lift is expected to deploy reliably with sufficiently frictionless joints. The fasteners will most likely be nonferrous screws and nuts. The nuts will be put on with zero torque and LOCTITE will be used to hold them in place.

5.2.6. Storage
It is expected that this design will be functional after having been stored for six months or longer, but will require testing to verify.

5.2.7. Tip Mass / Electronics
It is expected that this design will be able to accommodate a magnetometer at the tip, along with extra mass if it is deemed necessary for satellite alignment. The wiring will be affixed along the length of the boom.

5.2.8. Energy
Electrical power will not be required until deployment. At that time, electricity will flow through a resistor which will sever the burn wire holding the boom in the stowed position.
5.2.9 Safety to the Satellite and Launch Vehicle
It is expected that the launch vehicle and CubeSat will not be damaged during or after deployment. Deployment will not occur until a sufficient amount of time has passed as to assure that the CubeSat is too far from the launch vehicle to affect it. The concept is designed to deploy linearly away from the CubeSat, and should not be a danger to the outer components of the satellite.

5.2.10 Construction
The prototype parts will likely be cut from plastic sheeting by the BOOMStiC team using the Cal Poly laser cutter. The final iteration will be made in the same fashion if plastic is determined to be the best material. If the parts are aluminum, they will be machined by the BOOMStiC team or a commercial machinist.

5.3. Chosen Concept: The “Tape Measure” Boom
Figure 15 Error! Reference source not found. shows a CAD model of the expected final product. The actual solar panel area that will be needed for deployment may be larger due to the tip mass and magnetometer. The overall concept utilizes the same spring action used in a common tape measure. The key difference is that the coiled spring used to retract the measuring tape in a standard tape measure is reversed to propel the tape out of its coiled, stowed configuration.
Figure 15. Tape Measure Concept integrated into the PolySat CubeSat structure

Figure 13. Boom stowed in the deployer with dimensions
Figure 14. Mounted deployer configuration, side view

Figure 18. Mounted deployer configuration, top view
5.3.1. **Volume / Length**  
This concept will take up a small volume in its stowed configuration, detailed in Error! Reference source not found., while having the ability to deploy to 0.5 meter in boom length. It will also require only a small amount of surface area of the satellite, so it won’t greatly impact the amount of solar cells the satellite can accommodate.

5.3.2. **Positioning**  
The boom and deployer will be attached to the underside of the “top hat” of the HyperCube structure, so that the boom may deploy from any X or Y axis face of the CubeSat structure. It will be dependent upon which face the developer would like to face toward, or away from the Earth. The mounted deployer unit can be seen in Error! Reference source not found. and Error! Reference source not found..

5.3.3. **Resist Buckling Forces / Rigidity**  
To increase rigidity, two curved strips of non-ferrous metal, resembling a tape measure, are be aligned so the concave sides face each other. This will also create an outer surface that will be less likely to be affected by drag.

5.3.4. **Composition / Nonferrous**  
To meet the requirement that the boom be made of non-ferrous material, the “tape measure” will need to be manufactured specifically for this project. Commercially available tape measures are made of steel. One tape measure made of fiber reinforced plastic was found, but the exact materials are proprietary to the manufacturer and the outgassing properties are unknown. The tape is made from Phosphor-Bronze spring hardened sheet metal.

5.3.5. **Deployment Reliability**  
Given that a “tape measure” concept has been tested as a deployable for other spacecraft, such as PolySat’s CP5, the deployment of this concept is expected to be reliable. It is also expected that the deployment will not damage any outer components of the satellite.

5.3.6. **Storage**  
It is expected that this design will be functional after having been stored for six months or longer due to the consistent reliability of standard tape measures, which share the same components and similar design concepts. This will be verified with testing.

5.3.7. **Tip Mass / Electronics**  
It is expected that this design will be able to accommodate a magnetometer at the tip, along with extra mass if it is deemed necessary for satellite alignment. The wiring will be affixed within the length of the boom.
5.3.8. Energy
Electrical power will not be required until deployment. At that time, electricity will flow through a resistor which will sever the burn wire holding the boom in the stowed position.

5.3.9. Safety to the Satellite and Launch Vehicle
It is expected that the launch vehicle and CubeSat will not be damaged during or after deployment. Deployment will not occur until a sufficient amount of time has passed as to assure that the CubeSat is too far from the LV to affect it. The concept is designed to deploy linearly away from the CubeSat, and should not be a danger to the outer components of the satellite.

5.3.10. Construction
The boom itself will be constructed at Cal Poly by the BOOMStiC team out of Phosphor-Bronze sheeting. A half-inch strip will be run through an English Wheel to create the curved shape that will give the tape rigidity, while allowing it to be coiled for stowage. If the team is unable to procure a long enough single piece of copper, smaller strips will be joined together through welding, brazing, or possibly aluminum rivets.

The deployment apparatus will likely contain a coiled spring from a tape measure, adapted to force the boom out of the satellite. The tape will be coiled around this coiled spring assembly. The enclosure prototype will likely be made using the rapid prototype machines in Cal Poly’s Mechanical Engineering department. The final iteration of the enclosure will likely be machined out of aluminum by the BOOMStiC team or by a commercial machinist.
6. Final Design

6.1. Design Description
After much deliberation, the decision was made to pursue the Tape Measure deployer as the final design. As described in Section 4.3, this design is essentially a tape measure with the coiled internal spring reversed. The mechanism will be housed by two aluminum plates called the Boom Deployer Base and the Boom Deployer Top (see Figure 19).

![Boom Deployer Assembly](image)

**Figure 19.** Boom Deployer Assembly

These plates separate all moving parts of the mechanism from the rest of the satellite, protecting the electronics. They will be fixed to the satellite structure by 4-40 bolts and mounting points called Connecting Blocks (see Figure 19). The entire assembly will not exceed an envelope of 100mm X 100mm X 20.55mm. See the Appendix for detailed drawings with exact dimensions.

The moving parts of the mechanism consist of the Spindle, the four Tensioners, the Wire Spool, and the Boom itself. The Spindle is the internal anchor for the boom and is allowed to spin freely with the use of two thrust bearings. These bearings fit inside seats cut into the Spindle, the Boom Deployer Base, and the Boom Deployer Top. The Tensioners are spring loaded “pinball style” arms with rolling points of contact on their tips (see Figure 20).

![Tensioner](image)

**Figure 20.** Tensioner

![Internal workings of assembly](image)

**Figure 21.** Internal workings of assembly
The pressure applied to the Boom by these arms will keep the Boom from unwinding inside the Cubesat throughout its storage, launch, and deployment. The circuitry on the tip mass requires power, ground, and various other inputs and outputs. To house these wires, they will be wound around the Wire Spool to mitigate the chance of a tangle. The wires will be firmly attached to the tip mass and will be drawn out with the boom during deployment. The remaining bolts in the deployment structure (see Figure 21) are used to guide the Boom during deployment and structural support. Additional analysis has gone into adding ribs to the upper and lower plates to add strength and rigidity. After running FEA models on both designs, the benefit of the ribs appears to be minimal. See Section 5.2 for FEA results and discussion.

External to the structure of the satellite is the Tip Mass Assembly (see Figure 22). In addition to serving as the tip mass of the boom, the assembly also contains the Instrument Bracket to mount various electronics. The design requirement for the mass of the tip mass is 100 grams. Initial designs have used aluminum as the material; however the size of an aluminum mass weighing 100 grams might not fit in the given envelope. To fix this problem, a denser material, such as lead, will be used. There will be a tri-axis magnetometer mounted to the Instrument Bracket for measuring the strength and/or direction of the magnetic field in the vicinity of the mass. There will be room for other components which can be mission specific depending on the customer’s desires.

The boom itself could be made of either Phosphor-Bronze or Beryllium-Copper. Both are nonferrous which satisfies one of the primary design requirements (see Section 3.1.18). The benefit of using Phosphor-Bronze is it comes in a spring temper. This is beneficial because it helps deploy the boom as well as adds to the rigidity of the system. Beryllium-Copper can be heat treated to a spring temper; however after testing in the MATE 215 laboratory, our samples warped considerably (see Figure 23).
A potential solution is to heat treat the material while clamped into a press, however this has not been attempted. An additional drawback to the Beryllium-Copper is the fact that beryllium dust is poisonous if inhaled. More precisely, it leads to Chronic Beryllium Disease. Therefore accurate cutting (with power tools for example) is out of the question. Finally, the heat treatment of a Beryllium-Copper strip that measures 1 meter (see Section 3.1.1) will have to be done outside of Cal Poly since the biggest furnace on campus has about 2 feet of usable space. Outsourcing the heat treatment would not be impossible, but it is highly undesirable. To form the material into the necessary shape for the reverse coiled spring, a pair of steel pipes are used with the inside diameter of the first equaling the outside diameter of the second. The first pipe is cut in half along its length, and the other fits inside the resulting pieces. The boom material is sandwiched in between the pipes and clamps are used to form the curve. Any excess material is removed with a high speed cutting tool, leaving the desired form factor for our design.

6.2. Analysis Results

6.2.1. Settling Time
Basic analysis has gone into tip mass and boom length. There is currently not enough information about the Cubesat’s projected orbit environment to be able to give a definitive time to settle. This value will depend largely on altitudes, pressures, and boom drag, as well as other various unknowns. Magnetorquers will be necessary for satellite detumbling before the gravity gradient boom can be deployed. This does not change the design of the boom since magnetorquers are compact and already come standard on most Cubesat structures. See Appendix F for analysis on theoretical settle angles and restoring torques.

6.2.2. Finite Element Analysis
Finite element analysis was used to analyze the structure that would enclose the BOOMStiC unit. The CAE software package used was NX Nastran 6.0. The first design was simple and met specifications, and the first iteration of the design reduced displacements by 16% and allowed for more components. Both of the CAD models can be seen below in Figures 21 and 22.

Figure 24. Initial Design of Boom Package  Figure 25. First Iteration of Boom Package
In order to mesh the parts effectively certain geometry idealizations were made. Such idealizations include: removing small holes that are not in direct shear, making edges uniform and flat, removing filets and rounds, and converting internals into concentrated masses. The idealized models can be seen below in Figures 23 and 24.

![Idealized Initial Boom Package](image)

**Figure 26.** Idealized Initial Boom Package

![Idealized Ribbed Boom Package](image)

**Figure 27.** Idealized Ribbed Boom Package

The FEA models were then meshed using 3D solid elements. Linear 4-node brick elements were used for the initial boom package design because the simple geometry allowed for easy meshing. The ribbed model posed some meshing issues, so quadratic 10-node tetrahedrons were used. A point mass as used to model the spindle and stowed tape measure. The ribbed model used a larger concentrated mass. This point mass was then connected to the assembly by creating a wagon wheel connection using ridged 1D bar elements. Convergence studies were preformed for both models to ensure that sufficient element quality was achieved while optimizing run times for the simulations. The meshed designs are shown below in Figures 25 and 26.

![Meshed Initial Boom Package](image)

**Figure 28.** Meshed Initial Boom Package

![Meshed Ribbed Boom Package](image)

**Figure 29.** Meshed Ribbed Boom Package

Once the models were idealized and meshed, boundary conditions and loads were applied to the model to prepare it for submission to the solver. For both of the models, the faces where mounting holes would usually reside were fully fixed about their 6 DOF. A gravity load was applied to the system. The gravity load was 30 g’s with a FOS of 2, or 60 g’s, in all 3 directions. A modal analysis was also preformed, but the model did not include any sort of mechanical loading. Tables outlining the results are given below in Tables 2 and 3. A sample of the post-processed plots are also given below in Figures 27-32.
Table 2. Finite Element Stress Analysis Results

<table>
<thead>
<tr>
<th>Loading Case</th>
<th>Load</th>
<th>Max Stress (Mpa)</th>
<th>Max Displacement (mm)</th>
<th>Ult. Strength (Mpa)</th>
<th>Margin of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X Direction</td>
<td>60 g's</td>
<td>1.0</td>
<td>9.34E-04</td>
<td>310</td>
<td>&gt;300</td>
</tr>
<tr>
<td>Y Direction</td>
<td>60 g's</td>
<td>1.0</td>
<td>9.27E-04</td>
<td>310</td>
<td>&gt;300</td>
</tr>
<tr>
<td>Z Direction</td>
<td>60 g's</td>
<td>10.0</td>
<td>6.71E-02</td>
<td>310</td>
<td>30</td>
</tr>
<tr>
<td>First Iteration of Model, Ribbed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X Direction</td>
<td>60 g's</td>
<td>3.5</td>
<td>6.64E-04</td>
<td>310</td>
<td>88</td>
</tr>
<tr>
<td>Y Direction</td>
<td>60 g's</td>
<td>3.5</td>
<td>6.62E-04</td>
<td>310</td>
<td>88</td>
</tr>
<tr>
<td>Z Direction</td>
<td>60 g's</td>
<td>20.0</td>
<td>5.62E-02</td>
<td>310</td>
<td>14.5</td>
</tr>
</tbody>
</table>

Table 3. Finite Element Modal Analysis Results

<table>
<thead>
<tr>
<th>Model</th>
<th>First Natural Frequency</th>
<th>Second Natural Frequency</th>
<th>Third Natural Frequency</th>
<th>Fourth Natural Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-Ribbed</td>
<td>499 Hz</td>
<td>1420 Hz</td>
<td>2200 Hz</td>
<td>2300 Hz</td>
</tr>
<tr>
<td>Ribbed</td>
<td>531 Hz</td>
<td>xxx</td>
<td>3000 Hz</td>
<td>3200 Hz</td>
</tr>
</tbody>
</table>
Figure 30. Z-Direction Displacement Results for the Un-Ribbed Model, 60 g loading

Figure 31. Z-Direction Displacement Results for the Ribbed Model, 60 g loading
Figure 32. Z-Direction Stress Results for the Un-Ribbed Model, 60 g loading

Figure 33. Z-Direction Stress Results for the Ribbed Model, 60 g loading
While the ribbed design does experience higher stresses, the stresses did not yield critical margin of safety. The stresses arise from an increased concentrated mass load, and load paths that flow through the ribs. The ribbed design effectively reduces displacement 16%, even at the larger loads. The resonant frequencies are well above 200 Hz, which is the minimum desired value and the first resonant mode similar to loading in the Z direction.

6.2.3. Spindle Diameter
The spindle needed to be designed so that the tape measure would not yield and deform when stowed. A stress calculation based on curvature was used to determine the spindle diameter. This calculation can be seen below.

\[
 Minimum \ Diameter = \frac{t}{\varepsilon_{y\text{ield}}} \\
 t = \text{Thickness} = 0.005 \text{ in} \\
 \varepsilon_{y\text{ield}} = \frac{\sigma_{y\text{ield}}}{E} \\
 \sigma_{y\text{ield}} = 80 \text{ ksi} \\
 E = 16 \times 10^3 \text{ ksi} \\
 Minimum \ Diameter = \frac{0.005 \text{ in} \times (16\times10^3 \text{ ksi})}{80 \text{ ksi}} = 1 \text{ in} \\
\]

Since the calculations yielded a minimum diameter of 1 in, we picked a diameter of 30 mm, or 1.2 in.
### 6.3. Cost Analysis

**Table 4. Bill of Materials and Cost Break-Down**

<table>
<thead>
<tr>
<th>Raw Materials</th>
<th>Expected Cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Ferrous Spring Metal</td>
<td>20</td>
</tr>
<tr>
<td>Housing Components (Aluminum)</td>
<td>50</td>
</tr>
<tr>
<td>Fasteners</td>
<td>10</td>
</tr>
<tr>
<td>Tip Mass Material</td>
<td>10</td>
</tr>
<tr>
<td><strong>Magnetometer</strong></td>
<td>Mission Dependent</td>
</tr>
<tr>
<td><strong>Prototyping</strong></td>
<td></td>
</tr>
<tr>
<td>RP Housing Components</td>
<td>100</td>
</tr>
<tr>
<td>RP “Top Hat”</td>
<td>50</td>
</tr>
<tr>
<td>RP Other</td>
<td>50</td>
</tr>
<tr>
<td><strong>Fabrication</strong></td>
<td></td>
</tr>
<tr>
<td>Machine Housing Components</td>
<td>Free (Machine on campus)</td>
</tr>
<tr>
<td>Machining “Top Hat”</td>
<td>50</td>
</tr>
<tr>
<td><strong>Coatings</strong></td>
<td></td>
</tr>
<tr>
<td>Anodization (PCA)</td>
<td>50</td>
</tr>
<tr>
<td>Thermal</td>
<td>TBD</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td>~400</td>
</tr>
</tbody>
</table>

### 6.4. Safety considerations

It should be noted that if the Beryllium-Copper is ever used for the boom material, it should not be put through any processes that will produce beryllium dust. If inhaled beryllium dust can lead to Chronic Beryllium Disease.

Additionally, if the Phosphor-Bronze is used, a respirator should be used when cutting in order to mitigate the inhalation of harmful particles.
7. **Project Realization**

7.1. **Manufacturing Processes**

7.1.1. **Housing and Tip Mass**
The housing pieces were machined from aluminum by BOOMStiC members and a Cal Poly shop tech. The top and bottom plates and the spindle were made with a CNC machine by Cal Poly shop tech, John Gorski. The other parts were machined by BOOMStiC with equipment in the Cal Poly machine shop and CubeSat/PolySat lab. Total machining cost was $50.

7.1.2. **Tape**
Phosphor-Bronze sheets of 0.005 inches thickness were ordered from McMaster-Carr. The approximate width of the tape was cut from the sheets by hand, using tin snips. The tape measure like radius was achieved by compressing the tape between a pipe of the same radius and a tube of slightly larger radius cut in half longitudinally. This radius adds rigidity to the boom, as well as provides the spring force required to deploy the boom.

![Figure 36. Creating the Curve in the Non-Ferrous Tape](image)

The tape was cut down to the specific width with a lathe. The approximate sized tape was wrapped around a spindle-sized aluminum rod, secured, and cut to size.

7.2. **Prototype versus Production Model**
The prototype model was rapid prototyped using the Cal Poly ME Department’s facilities. This model allowed us to fit-check the design and make sure we would be able to install it into the HyperCube structure.
8. Design Verification

8.1. Vibration Test

8.1.1 Test Description and Levels
The BOOMStiC system was assembled and integrated onto the HyperCube structure, then inserted into a CubeSat Test Pod provided by the CubeSat Program at Cal Poly. The integrated Test Pod was attached to the testing surface of the Cal Poly Aero Department’s Unholtz Dickie vibration table, in accordance with verified procedures. The table was run at 3dB above the standard NASA GEVS random vibration levels in each axis. Before and after each random vibrations test, an up and down sine sweep was also performed.

8.1.2 Results
Vibration test results are given below in Figures 37 through 42. The BOOMStiC system passed +3 dB NASA GEVS qualification testing without any damage. Looking at the pre and post sine sweeps, the similarity in response spectrums give a clear indication that no damage was sustained during testing in the X and Y orthogonal orientations. Although the pre and post sine sweeps from the Z orientation do not match as well as X and Y, the fundamental peaks are similar, and the post vibe inspection showed no damage to the unit. This change in response is attributed to the unconstrained nature of the boom itself, making the system more dynamic. It important to note that the amplification we see in the higher frequencies is a result of testing hardware, and not a result of excitation of the BOOMStiC structure.

![X Axis Pre/Post Sine Sweep](image)

Figure 37. Pre and Post X-Axis Sine Sweep (0-2000Hz)
Figure 38. X-Axis Random Vibe (+3dB NASA GEVS levels)

Figure 39. Pre and Post Y-Axis Sine Sweep (0-2000Hz)
Figure 40. Y-Axis Random Vibe (+3dB NASA GEVS levels)

Figure 41. Pre and Post Z-Axis Sine Sweep (0-2000Hz)
8.2. Thermal Vacuum Test

The BOOMStiC system, integrated onto the HyperCube structure, would be thoroughly cleaned and placed in the TVAC chamber at Cal Poly. The chamber simulates expected thermal and pressure environments in low earth orbit. The levels are derived from NASA Program Level Requirements, LSP-REQ-317.01. The temperature cycles will range from -15 to +70 degrees C at a pressure of $1 \times 10^{-4}$ torr.

The BOOMStiC assembly did not go through thermal vacuum testing due to lack of funds. But if the assembly is selected for a mission, the TVAC test will be performed.

8.3. Deployment Test

8.3.1 Test Description and Levels

After environmental testing, a deployment test was performed to verify that all mechanisms perform as expected after deployment from the launch vehicle. The BOOMSTIC system and HyperCube structure were placed in a well-lit area, where the boom and antenna were able to deploy unhindered. The “burn wire” was cut and the boom deployment was observed.
8.3.2 Results
The boom deployed as expected. The boom deployed smoothly and quickly to its full length. This proves the system will deploy even after experiencing launch environments.

<table>
<thead>
<tr>
<th>Test</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration Test</td>
<td>Unholtz Dickie (Cal Poly AERO Dept)</td>
</tr>
<tr>
<td></td>
<td>CubeSat Test Pod (provided by CubeSat, Cal Poly)</td>
</tr>
<tr>
<td>Thermal Vacuum Test</td>
<td>Thermal Vacuum Chamber (CubeSat, Cal Poly facility)</td>
</tr>
<tr>
<td>Deployment Test</td>
<td>High Speed Camera (provided by CubeSat/PolySat, Cal Poly)</td>
</tr>
</tbody>
</table>

The Specification Verification checklist can be found in Appendix J.

9. Conclusions and Recommendations

9.1. Conclusions
The Tape Measure design satisfies all of the customer requirements, with the exception of being able to deploy from any face. The current design will only deploy from an X or Y face. The designed structure is robust enough to withstand expected vibration levels as shown in Section 8 of this report.

According to analysis, a boom length of 0.7 meters will be sufficient to stabilize the deployment of a 1U CubeSat.

A prototype was built for a turnstyle antenna which did not prove to be feasible. The radius of curvature on the modified HyperCube structure was too small and resulted in permanent deformation of the antenna.

9.2. Recommendations
Phosphor-Bronze should be used rather than the Beryllium-Copper for the boom material. As described in the sections above, there is little advantage to using the Beryllium-Copper over the Phosphor-Bronze, and one significant disadvantage; beryllium dust is poisonous. This should be enough to create doubt in even the finest satellite developers.

Magnetorquers should be used to de-tumble the satellite before deploying the gravity gradient boom. This recommendation should not be hard to accomplish since magnetorquers take up no internal volume and come standard on most Cubesats.

Due to the extreme temperature gradients in space environments, we recommend coating the boom with Aeroglaze A276 Polyurethane Coating, to avoid unwanted thermal expansion and buckling of the boom.
The design should be modified to accommodate missions that require a Z-face of the satellite to face toward or away from the surface of the earth.

For the antenna concept, two possible courses of action can be taken: 1) use a different, more elastic material, and 2) increase the radius of curvature.

If this design is used on a flight mission, the manufacturing of parts should be done by professional fabricators to ensure all parts are properly machined to specification.
10. APPENDICES

A. Links to Additional Information
B. House of Quality
C. Design Specifications with Compliance
D. Design Process Flow Chart & List of Milestones with Deadlines
E. Pugh Matrix
F. Gravity Gradient Analysis
G. List of Vendors, Contact information, and pricing
H. Vendor Supplied Component Specifications and Data Sheets
I. Gantt Chart
J. Specification Verification Checklist
K. Part Drawings
Appendix A. Links to Additional Information
NASA’s ATS series of satellites
http://msl.jpl.nasa.gov/Programs/ats.html

NASA’s Space Mechanisms Handbook – Lessons Learned Document
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050192114_2005191102.pdf

NASA’s LACE Satellite
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930015538_1993015538.pdf

Department of Defense Gravity Gradient Experiment (DODGE)
http://space.skyrocket.de/doc_sdat/dodge.htm

Montana State Firebird CubeSat

University of Tokyo Prism Cubesat
http://www.space.t.u-tokyo.ac.jp/prism/subsystem/faq_index-e.html

Stanford University QuakeSat

Surrey Satellite Communications Gravity Gradient Boom
http://microsat.sm.bmstu.ru/e-library/SSTL/Boom_HQ.pdf

Gunnar Tibert Doctoral Thesis regarding spacecraft deplovers

List of CubeSats and mission descriptions
http://mtech.dk/thomsen/space/cubesat.php

CubeSat Developers Specifications document
Appendix B. House of Quality
### Engineering Requirements

#### BOOM StiC

**House of Quality**

<table>
<thead>
<tr>
<th>Customer Requirements</th>
<th>Weighting (Total 100)</th>
<th>Engineering Requirements</th>
<th>Benchmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appropriate Boom Length</td>
<td>X X</td>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>Appropriate Tip Mass</td>
<td>X</td>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>Fit In a Small Area</td>
<td>7.5 \ \ \ \ X X</td>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>Non-Ferrous</td>
<td>5 X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>If Conductive, Grounded</td>
<td>4 \ \ \ \</td>
<td>X X</td>
<td>X</td>
</tr>
<tr>
<td>3-Axis Magnetometer At Tip</td>
<td>4 X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>No Solar Cell Interference</td>
<td>5 X X X O</td>
<td>X X</td>
<td>X X</td>
</tr>
<tr>
<td>Appropriate Antenna Length</td>
<td>7 X X</td>
<td>X</td>
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<tr>
<td>Simple Antenna Design</td>
<td>4 X X X X X</td>
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<td>X</td>
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<tr>
<td>Fits on New Structure</td>
<td>7 \ O \ \ \ \ X X</td>
<td>X</td>
<td>X X</td>
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<tr>
<td>Stored over time</td>
<td>3 X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Survive Space Conditions</td>
<td>6 \ \ \ \ \ \ X X</td>
<td>X</td>
<td>X X</td>
</tr>
<tr>
<td>Survive Launch Conditions</td>
<td>6 X</td>
<td>X</td>
<td>X X</td>
</tr>
<tr>
<td>Passive when deployed</td>
<td>5 X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Boom, coat or paintable</td>
<td>3 X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Boom, Low Payload Mass</td>
<td>6 X X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Re-orientation Capabilities</td>
<td>2.5 \ \ \ \ X</td>
<td>X</td>
<td>X</td>
</tr>
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<td>Adhere to CubeSat Standards</td>
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*X = 9 (Strong Correlation) \ = 3 (Medium Correlation) O = 1 (Small Correlation) Blank = 0 (No Correlation)*
Appendix C. Design Specifications with Compliance
<table>
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<td>Optimized</td>
<td>High</td>
<td>A, S</td>
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<td>Multiple Sides</td>
<td>Medium High</td>
<td>M</td>
<td>T, I</td>
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<td>Medium High</td>
<td>M</td>
<td>T, I</td>
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<td>High</td>
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<td>3.1.6</td>
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<td>6 Months</td>
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<td>H</td>
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<td>Antenna Type</td>
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<td>A, T</td>
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<td>H</td>
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<td>3.3.2</td>
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<td>3.3.3</td>
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<td>3.4.1</td>
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<td>NASA GEVS (+3 dB)</td>
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<td>3.4.2</td>
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<td>A, T</td>
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<td>High</td>
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<td>A, T</td>
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<td>No Operation During Launch</td>
<td>No Electronics Active</td>
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<td>H</td>
<td>A, T</td>
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<td>Passive Device</td>
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<td>A, T</td>
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<td>5 Year Life Span</td>
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<td>H</td>
<td>A, S</td>
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<td>T</td>
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<td>3.6.2.b</td>
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<td>3.6.2.c</td>
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<td>≥ Carbon Steel</td>
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<td>H</td>
<td>T, I</td>
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<td>3.7.1</td>
<td>Boom Tip Electronics</td>
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<td>ELaNa Standards</td>
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<td>H</td>
<td>A, T, S, I</td>
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<td>3.12.1</td>
<td>Goals and Milestones</td>
<td>Outlined in Report</td>
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<td>Meetings With Sponsor</td>
<td>Weekly</td>
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Key: Analysis (A), Test (T), Similarity to Existing Designs (S), Inspection (I)

High Risk (H), Medium Risk (M), Low Risk (L)
Appendix D. Design Process Flow Chart & List of Milestones with Deadlines
Table D.1 Milestones and Due Dates

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<thead>
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<td>Project Requirements Report</td>
<td>October 19, 2010</td>
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<tr>
<td>Conceptual Design</td>
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<tr>
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<td><strong>Winter Quarter 2010</strong></td>
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<tr>
<td>Design Report</td>
<td>February 1, 2011</td>
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</tr>
<tr>
<td>Critical Design Review</td>
<td>February 3, 2011</td>
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<tr>
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<td>Project Update Memo</td>
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<tr>
<td>Prototype Presentation</td>
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<tr>
<td><strong>Spring Quarter 2011</strong></td>
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<td>Hardware Demo</td>
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<td>Final Report</td>
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<td>Design Expo</td>
<td>June 2, 2011</td>
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Appendix E. Pugh Matrix
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<th>Criteria</th>
<th>Justin's Ladder</th>
<th>Spring Loaded</th>
<th>Scissor Lift</th>
<th>Tent Pole</th>
<th>Tape Measure</th>
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<td>S</td>
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</table>
Appendix F. Gravity Gradient Analysis
Gravity Gradient Analysis Calculations

\[ F_{ci} = M_i \cdot \omega_i \]

\[ \omega_i = \sqrt[3]{\frac{M_{\text{Earth}} \cdot G}{r_i^3}} \]

\[ F_{gi} = \frac{G \cdot M_{\text{Earth}} \cdot m_i}{r_i^2} \]

\[ L_{CM} = L - \frac{L}{\frac{m_2}{m_1} + 1} \]

\[ F_{ci} = M_i \cdot \frac{M_{\text{Earth}} \cdot G}{r_i^3} \]
Note: Since the satellite is treated as a ridged body and it orbits about its center of mass, both tip mass and CubeSat orbit at the same rate as the center of mass.

\[ M_{Earth} = 5.97 \times 10^{24} \text{ kg} \]
\[ m_1 = 1.2 \text{ kg} \]
\[ m_2 = 0.1 \text{ kg} \]
\[ G = 6.672 \times 10^{-11} \frac{m^3}{kg \cdot s^2} \]
\[ r_i = (\text{Orbit Height} + \text{Earth Radius}) + \left( \frac{L}{L_{cm}} \right) \cdot \cos \theta \]
\[ r_1 = (500 \text{ km} + 6378.1 \text{ km}) + L_{cm} \cdot \cos \theta \]
\[ r_1 = (6878.1 \times 10^3 \text{ m}) + 0.0769 \text{ m} \cdot \cos \theta \]
\[ r_2 = (500 \text{ km} + 6378.1 \text{ km}) - (L - L_{cm}) \cdot \cos \theta \]
\[ r_2 = (6878.1 \times 10^3 \text{ m}) - 0.9231 \text{ m} \cdot \cos \theta \]
\[ r_{cm} = (500 \text{ km} + 6378.1 \text{ km}) \]
\[ r_{cm} = (6878.1 \times 10^3 \text{ m}) \]
\[ \omega_{cm} = \sqrt{\frac{5.97 \times 10^{24} \text{ kg} \cdot 6.672 \times 10^{-11} \frac{m^3}{kg \cdot s^2}}{(6878.1 \times 10^3 \text{ m})^3}} \]
\[ \omega_{cm} = 0.00111 \frac{\text{rad}}{s} \]
\[ F_{c_1} = m_1 \cdot \omega_{cm} \quad F_{c_2} = m_2 \cdot \omega_{cm} \]
\[ F_{c_1} = 0.0013 \text{ N} \quad F_{c_2} = 1.11 \times 10^{-4} \text{ N} \]
\[ F_{g1} = \frac{G \cdot M_{Earth} \cdot m_1}{r_1^2} \]
\[ F_{g2} = \frac{G \cdot M_{Earth} \cdot m_2}{r_2^2} \]

\[ F_{g1} = \frac{6.672 \times 10^{-11} \frac{m^3}{kg \cdot s^2} \cdot 5.97 \times 10^{24} kg \cdot 1.2 kg}{(6878.1 \times 10^3 m + 0.0769 m \cdot \cos \theta)^2} \]
\[ F_{g2} = \frac{6.672 \times 10^{-11} \frac{m^3}{kg \cdot s^2} \cdot 5.97 \times 10^{24} kg \cdot 0.1 kg}{(6878.1 \times 10^3 m - 0.9231 m \cdot \cos \theta)^2} \]

\[ \phi \text{ Moment} = (F_{g1} - F_{c1}) \cdot L_{CM} \cdot \sin \theta + (F_{c2} - F_{g2}) \cdot (L - L_{CM}) \cdot \sin \theta \]

Drag force torque calculation

\[ f_D = \frac{1}{2} C_D \rho A v^2 \]

\[ C_D = 1.05 \quad \rho = 1.9 \times 10^{-12} \frac{kg}{m^2} \]
\[ A = 0.0001 \ m^2 \quad v = 7.611 \times 10^3 \ \frac{m}{s} \]

\[ f_D = 5.78 \times 10^{-9} \ N \]

\[ T_D = f_D \cdot L_{cm} \]
\[ T_D = 4.45 \times 10^{-10} \ N \cdot m \]
MATLAB Code:

\[
\theta = (-\pi/4); \quad \% \text{Specify Theta Range}
\]

\[
m1 = 1.2; \quad \% \text{mass of CubeSat}
m2 = .1; \quad \% \text{mass of Tip Mass}
mE = 5.97*10^{24}; \quad \% \text{mass of earth}
G = 6.673*10^{-11}; \quad \% \text{gravitational constant}
L = 1.0; \quad \% \text{Length of boom}
Lcm = L - (L/((m2/m1)+1)); \quad \% \text{Computes location of CM}
\]

\% Orbit hight of cubesat and tip mass with respect to center of earth

\[
r1 = 6878.1*10^3 + \text{abs}(Lcm.*\cos(\theta));
r2 = 6878.1*10^3 - \text{abs}((L-Lcm).*\cos(\theta));
rcm = 6878.1*10^3;
\]

\% centrifugal forces on cubesat and tip mass

\[
Fc1 = m1.*(\sqrt{(mE*G)/(rcm.^3))};
Fc2 = m2.*(\sqrt{(mE*G)/(rcm.^3))};
\]

\% Gravitational forces on cubesat and tip mass

\[
Fg1 = (((G*mE*m1)./(r1.^2));
Fg2 = (((G*mE*m2)./(r2.^2));
\]

\% Moment generated from gravity gradient.
\% Negative Moment on positive theta is a restoring force.

\[
M = (((Fg1-Fc1).*Lcm.*\sin(\theta)) + ((Fc2-Fg2).*(L-Lcm).*\sin(\theta)));
\]

\% plots theta vs. moment

plot(theta,M)

\% NOTE: Aerodynamic drag moment : \(4.45 \times 10^{-10} \text{ N} \cdot \text{m}\)
Appendix G. List of Vendors, Contact Information, and Pricing
## Shim & Bushing Stock

### Bronze Shim Stock
High strength makes this nonmagnetic corrosion-resistant material ideal for applications requiring good resistance to repetitive stress. It is cold rolled.

#### Alloy 510 Bronze Rolls—Spring Temper

<table>
<thead>
<tr>
<th>Thick.</th>
<th>Tolerance</th>
<th>Each</th>
<th>6&quot; Wd.x50&quot; Lg.</th>
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<td>0200K44</td>
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<tr>
<td>0.010&quot;</td>
<td>-0.00004&quot;</td>
<td>0200K38</td>
<td>32.66</td>
<td>0.028</td>
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</table>

### Alloy 510 Bronze Strips—Spring Temper

<table>
<thead>
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<th>Thick.</th>
<th>Tolerance</th>
<th>Each</th>
<th>6&quot; Wd.x50&quot; Lg.</th>
<th>Each</th>
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<td>0.000&quot;</td>
<td>-0.00004&quot;</td>
<td>0200K44</td>
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<td>0.005&quot;</td>
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<td>0.010&quot;</td>
<td>-0.00004&quot;</td>
<td>0200K38</td>
<td>32.66</td>
<td>0.028</td>
</tr>
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</table>

### Plastic Shim Stock
Made of molded high-impact polystyrene, plastic shim stock is lightweight, corrosion resistant, and economical.

#### Sheets
- **Thickness:** 0.00005" to 0.006" thick are carboarded for shipping. 6" Wd.x50" Lg. for maximum temperature. Sheets may be gray, black, or white. Width and length tolerances are ±1/16. Sold in packages of 6.

#### Color-Coded Plastic Shim Stock
Not only lightweight and economical, this extruded shim stock is rustproof, impervious to oil, and comes in several colors for quick and easy size identification.

#### Sheets
- **Thickness:** 0.00005" to 0.006" thick are carboarded for shipping. 6" Wd.x50" Lg. for maximum temperature. Sheets may be gray, black, or white. Width and length tolerances are ±1/16. Sold in packages of 6.

### Precision Shim Bushing Stock
The tight tolerances on these smooth, low-friction materials allow you to increase or decrease a shaft or rod diameter size by simply slipping the bushing over the shaft or rod. They also fit inside each other to increase more than one wall thickness. Use carbide blades to cut to a specific length for a bushing, spacer, shim, or sleeve bearing. Length is 6".

**Delrin:**
- **Hardness:** Rockwell C60-65. Temper is annealed with a hardened surface. Tested cold finished. Meets ASTM A513, except 1 1/2 OD meets ASTM A519. OD tolerance is ±0.035. ID tolerance is ±0.025. Length tolerance is ±0.025. Steel is 1 1/2 OD is harder than steel bushing stock.
- **Steel (Alloy 4130):**
  - **Hardness:** Rockwell C65-68. Temper is annealed with a hardened surface. Tested cold finished. Meets ASTM A513, except 1 1/2 OD meets ASTM A519. OD tolerance is ±0.025. ID tolerance is ±0.015. Length tolerance is ±0.015. Stainless steel is 1 1/2 OD is harder than steel bushing stock.

#### OD/ID/Each

<table>
<thead>
<tr>
<th>OD</th>
<th>ID</th>
<th>Each</th>
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</thead>
<tbody>
<tr>
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<td>0.156&quot;</td>
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<td>0.075&quot;</td>
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### McMaster-Carr

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<td>Precision Shim Bushing Stock</td>
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**(PLEASE NOTE: Additional information is available upon request.**
**Thrust Bearings**

**Part Number: 5909K31**

<table>
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<th>Type</th>
<th>Needle-Roller Bearings</th>
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<tr>
<td>Bearing Material</td>
<td>Steel</td>
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<tr>
<td>For Shaft Diameter (Inside Diameter)</td>
<td>1/2&quot;</td>
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<tr>
<td>Outside Diameter</td>
<td>15/16&quot;</td>
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<tr>
<td>Cage Assembly Thickness</td>
<td>5/64&quot;</td>
</tr>
<tr>
<td>Dynamic Thrust Load Capacity, lbs.</td>
<td>1,920</td>
</tr>
<tr>
<td>Maximum rpm</td>
<td>13,000</td>
</tr>
<tr>
<td>Specifications Met</td>
<td>Not Rated</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-40° to +248° F</td>
</tr>
<tr>
<td>Compatible Washer</td>
<td>For a complete bearing you'll need one cage assembly and two washers (each washer sold separately). Order 5909K44 for .032&quot; thick washer. For a lower profile, the cage assembly can be used without washers, but only on material that is hardened to Rockwell C58-C64.</td>
</tr>
</tbody>
</table>

**Note**

---

![Thrust Bearing Diagram](image-url)
Appendix H. Vendor Supplied Component Specifications and Data Sheets
1.0 PRODUCT AND COMPANY IDENTIFICATION

PMX Industries, Inc.
5300 Willow Creek Drive SW
Cedar Rapids, Iowa 52404-4303

Emergency: 319-368-7700

TELEPHONE: 319-368-7700
FAX: 319-368-7701

PRODUCT NAMES:  

<table>
<thead>
<tr>
<th>ALLOY #</th>
<th>COMMON NAME</th>
<th>UNS #/CDA #</th>
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<tbody>
<tr>
<td>510</td>
<td>Phosphor Bronze 5%</td>
<td>C51000</td>
</tr>
<tr>
<td>511</td>
<td>Phosphor Bronze 4%</td>
<td>C51100</td>
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<td>519</td>
<td>Phosphor Bronze 6%</td>
<td>C51900</td>
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<tr>
<td>521</td>
<td>Phosphor Bronze 8%</td>
<td>C52100</td>
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CHEMICAL FAMILY: Copper Alloy

ISSUE DATE: December 15, 2004
SUPERSEDES DATE: May 13, 1999

2.0 HAZARDS IDENTIFICATION

EMERGENCY OVERVIEW:
Copper alloy products in the natural state do not present a hazard for emergency response personnel.

POTENTIAL HEALTH EFFECTS:
Copper alloy products in the natural state do not present an inhalation, ingestion, or contact hazard. However, operations such as burning, welding, sawing, brazing, or grinding may release fumes and/or dusts which may present health hazards if occupational exposure limits are exceeded.

LIKELY ROUTES OF EXPOSURE: Inhalation, Eye Contact, Skin Contact

INHALATION: Short-term exposure to fumes/dust may produce irritation of the respiratory system. Exposure to high concentrations of oxide fumes of copper or tin may cause metal fume fever.

EYE: Short-term exposure to fumes/dust may produce irritation.

SKIN: Repeated or prolonged exposure to copper dusts or mists may cause irritant or allergic contact dermatitis.

INGESTION: Abdominal pain, nausea, vomiting.

MEDICAL CONDITIONS AGGRAVATED BY EXPOSURE:
Exposure to fumes or dust may aggravate existing respiratory disease or dermatitis.

December 15, 2004
TARGET ORGANS: Upper respiratory tract, eyes, skin

SIGNS AND SYMPTOMS:
Metal fume fever – metallic taste in mouth, dryness, and irritation of the throat, and influenza-like symptoms. The effects may be delayed.

CARCINOGENICITY:

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>ACGIH</th>
<th>IARC</th>
<th>NTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper (fume, dusts &amp; mists)</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Tin (metal/oxide)</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

See Toxicological Information (Section #11)

POTENTIAL ENVIRONMENTAL EFFECTS:
None known. Product has not been tested for environmental properties.

3.0 CHEMICAL COMPONENTS

NOTE: This MSDS applies to a range of alloys. For actual compositions refer to material test report or specific alloy specification. All percentages are by weight.

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>CAS #</th>
<th>%</th>
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</thead>
<tbody>
<tr>
<td>Copper</td>
<td>7440-50-8</td>
<td>91.9 – 95.9</td>
</tr>
<tr>
<td>Tin</td>
<td>7440-31-5</td>
<td>4 – 8</td>
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</tbody>
</table>

4.0 FIRST AID MEASURES

INHALATION: If exposed to excessive levels of metal fumes, remove to fresh air. Seek medical attention.
EYE: Flush with water for at least 15 minutes.
SKIN: Wash with soap and water.

5.0 FIRE FIGHTING MEASURES

SUITABLE EXTINGUISHING MEDIA: Use extinguishing media appropriate to the surrounding material.
SPECIAL FIREFIGHTING INSTRUCTIONS: Copper alloy products in the solid state present no fire or explosion hazard, but may react with strong acids, bases, or oxidizing agents.

6.0 ACCIDENTAL RELEASE MEASURES

STEPS TO BE TAKEN IN THE EVENT OF SPILLS, LEAKS, OR RELEASES: Not applicable

December 15, 2004
7.0 HANDLING AND STORAGE

HANDLING: In welding, precautions should be taken for airborne contaminants that may originate from components of the welding rod.

8.0 EXPOSURE CONTROLS/PERSONAL PROTECTION

EXPOSURE GUIDELINES

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>OSHA PEL TWA</th>
<th>ACGIH® TLV® TWA</th>
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</thead>
<tbody>
<tr>
<td>Copper dust, mist</td>
<td>1.0 mg/m³</td>
<td>1.0 mg/m³</td>
</tr>
<tr>
<td>Copper fume</td>
<td>0.1 mg/m³</td>
<td>0.2 mg/m³</td>
</tr>
<tr>
<td>Tin metal/oxide</td>
<td>2.0 mg/m³</td>
<td>2.0 mg/m³</td>
</tr>
</tbody>
</table>

ENGINEERING CONTROLS: Local exhaust ventilation should be utilized when welding, burning, sawing, brazing, grinding, or machining when exposure exceeds occupational exposure limits.

EYE PROTECTION: Safety glasses or goggles should be utilized as required by exposure. Other protective equipment should be utilized as required by welding standards.

SKIN PROTECTION: Wear appropriate personal protective clothing to prevent skin contact with copper dusts and mists.

RESPIRATORY PROTECTION: NIOSH-approved dust or fume respirator should be used to avoid excessive inhalation of particulates when exposure exceeds occupational exposure limits.

OTHER PREVENTIVE MEASURES: Do not eat, drink, or smoke during work. Wash hands before eating or smoking.

9.0 PHYSICAL AND CHEMICAL PROPERTIES

APPEARANCE: Salmon-colored, lustrous metal

ODOR: None

PH: Not applicable

VAPOR DENSITY (AIR = 1) Not applicable

EVAPORATION RATE: Not applicable

SOLUBILITY IN WATER: Not applicable

MELTING POINT: 1,880 – 1,945 °F

FLASH POINT: Not applicable

AUTOIGNITION TEMPERATURE: Not applicable

PHYSICAL STATE: Solid

VAPOR PRESSURE: Not applicable

PERCENT VOLATILE: Not applicable

SPECIFIC GRAVITY: 8.8 – 8.9

DENSITY, LB/IN³: 0.32

LOWER EXPLOSIVE LIMIT (%): None

UPPER EXPLOSIVE LIMIT (%): None

December 15, 2004
10.0 STABILITY AND REACTIVITY

CHEMICAL STABILITY: Stable

CONDITIONS TO AVOID: None

INCOMPATIBLE MATERIALS: Mercury, ammonia, acetylene acids. Contact with strong acids, bases, or oxidizing agents

HAZARDOUS DECOMPOSITION PRODUCTS: Metallic dust or fumes may be produced during welding, burning, grinding, and machining.

POSSIBILITY OF HAZARDOUS REACTIONS: Will not occur

11.0 TOXICOLOGY INFORMATION

ACUTE TOXICITY DATA FOR COMPONENTS

Copper TDL₀: 120 μg/kg (human, oral—gastrointestinal effects)
LD₅₀: 0.07 mg/kg (mouse, intraperitoneal)

Tin TDL₀: 250 mg/kg (human, oral—gastrointestinal effects)

CHRONIC EFFECTS:
Repeated or prolonged overexposure to copper fume may cause the skin and hair to change color.
Repeated or prolonged overexposure to tin dusts or fumes may cause stannosis.

12.0 ECOLOGICAL INFORMATION

Not applicable

13.0 DISPOSAL CONSIDERATIONS

WASTE DISPOSAL METHODS:
According to local, state, and federal regulations.

14.0 TRANSPORT INFORMATION

Not applicable

15.0 REGULATORY INFORMATION

GLOBAL INVENTORIES

TSCA: United States Included Included
DSL: Canada Included Included
EINECS: European Union Included Included

December 15, 2004
SARA TITLE III SECTION 302 EXTREMELY HAZARDOUS SUBSTANCES (40 CFR 355):
These alloys are not regulated under Section 302 of SARA and 40 CFR 355.

SARA TITLE III SECTION 311/312 HAZARDOUS CATEGORIZATION (40 CFR 370):
OSHA defines these alloys as hazardous under 29 CFR 1910.1200(d).

SARA TITLE III SECTION 313 TOXIC CHEMICALS (40 CFR 372):
These alloys may contain the following toxic chemical(s) subject to reporting requirements under this section of SARA and of 40 CFR 372:

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>CAS #</th>
<th>% BY WEIGHT</th>
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<tbody>
<tr>
<td>Copper</td>
<td>7440-50-8</td>
<td>87.5 – 88.5</td>
</tr>
</tbody>
</table>

OTHER LISTS

<table>
<thead>
<tr>
<th>Chemical Name</th>
<th>CA Prop 65 Chemical</th>
<th>MA Toxic Substance List</th>
<th>MI Critical Materials Register</th>
<th>NJ Hazardous Substances List</th>
<th>PA Right-to-Know List</th>
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</thead>
<tbody>
<tr>
<td>Copper</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Tin</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

16.0 OTHER INFORMATION

REFERENCES
ACGIH® Threshold Limit Values (TLV®) (2004)
Agency for Toxic Substances and Disease Registry (ATSDR):
   Toxicological Profile for Copper, September 2002
   Draft Toxicological Profile for Tin, September 2003
International Agency for Research on Cancer (IARC) Monographs
National Library of Medicine (NLM) Databases:
   ChemID
   Integrated Risk Information (IRIS)
   International Toxicity Estimates for Risk (ITER)
   Chemical Carcinogenesis Risk Information System (CCRIS)
   Hazardous Substances Data Bank (HSDB)
National Toxicology Program (NTP) Reports
NIOSH/OSHA Occupational Health Guideline for Copper Fume
NIOSH/OSHA Occupational Health Guideline for Copper Dusts and Mists

December 15, 2004
NIOSH/OSHA Occupational Health Guideline for Inorganic Tin Compounds (as Tin)
OSHA General Industry Standards (29 CFR 1910)
Registry of Toxic Effects of Chemical Substances (RTECS®)

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PREPARATION INFORMATION

Prepared by: Cindy Baldwin, CIH

Terracon
5855 Willow Creek Drive SW
Cedar Rapids, Iowa 52404

December 15, 2004
Appendix I. Gantt Chart
<table>
<thead>
<tr>
<th>ID</th>
<th>Task Mode</th>
<th>Task Name</th>
<th>Duration</th>
<th>Start</th>
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<tbody>
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<td>Fall Quarter</td>
<td>30 days</td>
<td>Mon 11/1/10</td>
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<td>Mon 11/1/10</td>
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<td>5 days</td>
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<td>Fri 11/19/10</td>
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<td>Fri 12/3/10</td>
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<td>Fri 3/18/11</td>
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Project: Gantt Chart
Date: Thu 2/3/11
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<th>Task Name</th>
<th>Duration</th>
<th>Start</th>
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<td>33</td>
<td>Mode</td>
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<td>Sun 3/27/11</td>
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<td>34</td>
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<td>40</td>
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Project: Gantt Chart  
Date: Thu 2/3/11
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**Project: Gantt Chart**

**Date:** Thu 2/3/11
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<td>4/3</td>
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<td>5/22</td>
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<td>6/12</td>
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**Project: Gantt Chart**
Date: Thu 2/3/11
Appendix J. Specification Verification Checklist
<table>
<thead>
<tr>
<th>Item No</th>
<th>Specification or Clause Reference</th>
<th>Test Description</th>
<th>Acceptance Criteria</th>
<th>Test Stage</th>
<th>Sample Quantity</th>
<th>Start date</th>
<th>Finish date</th>
<th>Test Result</th>
<th>Quantity Pass</th>
<th>Quantity Fail</th>
<th>Notes</th>
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<tbody>
<tr>
<td>1</td>
<td>3.1.1</td>
<td>Measure deployed boom length with reliable measuring tool</td>
<td>&gt; 0.8 meters passes</td>
<td>DF</td>
<td>CV</td>
<td>1</td>
<td>A</td>
<td></td>
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<tr>
<td>2</td>
<td>3.1.2</td>
<td>Weigh sensor package with bracket and extra mass with calibrated 1 kg scale</td>
<td>100 ± 20 grams</td>
<td>JC</td>
<td>DV</td>
<td>1</td>
<td>B</td>
<td></td>
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<tr>
<td>3</td>
<td>3.1.3.a</td>
<td>Use the HyperCube CAD model and the BOOMSTIC deployer CAD model to affix the deployer to the HyperCube in all possible configurations</td>
<td>Deployer readily affixes to X and Y internal faces of the HyperCube structure with no interference of parts</td>
<td>MB</td>
<td>CV</td>
<td>1</td>
<td>A</td>
<td></td>
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<tr>
<td>4</td>
<td>3.1.3.b</td>
<td>Use the HyperCube CAD model and the BOOMSTIC deployer CAD model to orient the boom in every possible orientation</td>
<td>Boom can be directed longitudinally out of any one of the four sides of the X and Y axes at 90° ± 10° degrees to the cube surface</td>
<td>AJ</td>
<td>CV</td>
<td>1</td>
<td>A</td>
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<tr>
<td>5</td>
<td>3.1.3.c</td>
<td>Verify, using the HyperCube CAD model and the BOOMSTIC deployer CAD model, that the boom can be directed through any of the X or Y faces by mating the assemblies together in the configurations of interest</td>
<td>Boom can be directed out of any one of the four sides of the X and Y axes</td>
<td>DF</td>
<td>CV</td>
<td>1</td>
<td>A</td>
<td></td>
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</tr>
<tr>
<td>6</td>
<td>3.1.3.d</td>
<td>Visually verify using CAD model assembly</td>
<td>&gt; 3/4 of affected side panel will still be usable for solar cells using a HyperCube structure</td>
<td>JC</td>
<td>CV</td>
<td>1</td>
<td>A</td>
<td></td>
<td></td>
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<tr>
<td>7</td>
<td>3.1.5.a</td>
<td>Visually verify using CAD model assembly</td>
<td>≥ 1/2 interior space of HyperCube is left available for additional payload</td>
<td>MB</td>
<td>CV</td>
<td>1</td>
<td>A</td>
<td></td>
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<tr>
<td>8</td>
<td>3.1.5.b</td>
<td>Measure any and all protrusions from the stowed BOOMSTIC system that protrude past the exterior of the HyperCube frame</td>
<td>No part of the stowed boom or boom deployer system will extend more than 6.5 mm past the exterior edge of the HyperCube rails</td>
<td>AJ</td>
<td>DV</td>
<td>1</td>
<td>B</td>
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<tr>
<td>9</td>
<td>3.1.6</td>
<td>Pack boom into storage/pre-deployment configuration and let sit indoors (climate controlled area) for predetermined time, then deploy boom by releasing burn wire</td>
<td>The boom will deploy after storage time of ≥ 6 mo.</td>
<td>DF</td>
<td>DV</td>
<td>1</td>
<td>B</td>
<td></td>
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<tr>
<td>10</td>
<td>3.2.1</td>
<td>Visual inspection of antenna components and configuration</td>
<td>Antenna must be Turn Style or Dipole type</td>
<td>JC</td>
<td>DV</td>
<td>1</td>
<td>B</td>
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<tr>
<td>11</td>
<td>3.2.1.b</td>
<td>Measure the lateral displacement of points on the antenna relative to the tangent line of the longitudinal axis at one designated point</td>
<td>&lt; 8 cm deviation from centerline</td>
<td>MB</td>
<td>DV</td>
<td>1</td>
<td>B</td>
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<tr>
<td>Item No</td>
<td>Specification or Clause Reference</td>
<td>Test Description</td>
<td>Acceptance Criteria</td>
<td>Test Responsibilities</td>
<td>Test Stage</td>
<td>SAMPLES</td>
<td>TIMING</td>
<td>TEST RESULTS</td>
<td>NOTES</td>
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<tr>
<td>12</td>
<td>3.2.2</td>
<td>Measure longitudinal length of antenna arms</td>
<td>Appropriate for 437 MHz Band</td>
<td>AJ</td>
<td>DV</td>
<td>1</td>
<td>B</td>
<td></td>
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<tr>
<td>13</td>
<td>3.2.3.a</td>
<td>Visually verify the location of the antenna on the CAD model</td>
<td>The antenna will be located in or on the Top-Hat</td>
<td>DF</td>
<td>CV</td>
<td>1</td>
<td>A</td>
<td></td>
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<tr>
<td>14</td>
<td>3.2.3.b</td>
<td>Measure angle between deployed arms and face of CubeSat</td>
<td>Within 10% of optimized value</td>
<td>JC</td>
<td>DV</td>
<td>1</td>
<td>B</td>
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<tr>
<td>15</td>
<td>3.2.4</td>
<td>Pack antenna into storage/pre-deployment configuration and let sit indoors</td>
<td>The antenna will deploy after storage time of ≥ 6 mo.</td>
<td>MB</td>
<td>DV</td>
<td>1</td>
<td>B</td>
<td></td>
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<tr>
<td>16</td>
<td>3.3.1.a</td>
<td>Pack antenna into storage/pre-deployment configuration, then deploy antenna and</td>
<td>Full antenna length and boom length will deploy</td>
<td>AJ</td>
<td>DV</td>
<td>1</td>
<td>B</td>
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<tr>
<td>17</td>
<td>3.3.1.b</td>
<td>During deployment test (3.3.1.a) time the deployment of antenna and boom from</td>
<td>&lt; 2 minutes</td>
<td>DF</td>
<td>DV</td>
<td>1</td>
<td>B</td>
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<tr>
<td>18</td>
<td>3.3.1.c</td>
<td>Pack antenna into storage/pre-deployment configuration, then deploy antenna and</td>
<td>Boom and antenna deploy upon severing the burn wire</td>
<td>JC</td>
<td>DV</td>
<td>1</td>
<td>B</td>
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<tr>
<td>19</td>
<td>3.3.2</td>
<td>Analyze the forces the torquers will have to overcome to orient the CubeSat and</td>
<td>Not to exceed battery or solar cell limits</td>
<td>MB</td>
<td>CV</td>
<td>1</td>
<td>A</td>
<td></td>
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<tr>
<td>20</td>
<td>3.3.3</td>
<td>Analyze using generated MATLAB code</td>
<td>Settle within 3 mo.</td>
<td>AJ</td>
<td>CV</td>
<td>1</td>
<td>A</td>
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<tr>
<td>21</td>
<td>3.4.1</td>
<td>Using Cal Poly facilities, integrate the HyperCube/BOOMSTIC assembly into a test</td>
<td>No failures at NASA GEVS (≥ 3 dB) levels</td>
<td>DF</td>
<td>DV</td>
<td>1</td>
<td>B</td>
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<tr>
<td>22</td>
<td>3.4.2</td>
<td>Place deployed boom in vertical position with the tip mass end and pivot about</td>
<td>≤ 10 degrees from vertical, no buckling</td>
<td>JC</td>
<td>DV</td>
<td>1</td>
<td>B</td>
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<tr>
<td>23</td>
<td>3.5.2</td>
<td>Verify, while in deployed configuration no moving or active components</td>
<td></td>
<td>MB</td>
<td>DV</td>
<td>1</td>
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<tr>
<td>24</td>
<td>3.6.1.a</td>
<td>Analysis of boom and antenna material to determine likelihood of magnetic</td>
<td>No expected magnetic properties will develop within a 5 year life span</td>
<td>AJ</td>
<td>CV</td>
<td>1</td>
<td>A</td>
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<tr>
<td>25</td>
<td>3.6.1.b</td>
<td>Analysis of boom material to determine ability of material to adhere to thermal</td>
<td>Coatable</td>
<td>DF</td>
<td>CV</td>
<td>1</td>
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<td>26</td>
<td>3.6.2.a</td>
<td>Analysis of antenna material to determine material conductivity Conductivity ≥</td>
<td></td>
<td>MB</td>
<td>CV</td>
<td>1</td>
<td>A</td>
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<tr>
<td>27</td>
<td>3.6.2.b</td>
<td>Test conductivity between the boom and the HyperCube structure, if the Boom</td>
<td></td>
<td>AJ</td>
<td>DV</td>
<td>1</td>
<td>B</td>
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### BOOMSTIC DESIGN VERIFICATION PLAN AND REPORT

**TEST PLAN**

<table>
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<tr>
<th>Item No</th>
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<th>Test Description</th>
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<th>SAMPLES</th>
<th>TIMING</th>
<th>TEST RESULTS</th>
<th>NOTES</th>
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<tr>
<td>28</td>
<td>3.8.2</td>
<td>Visually observe deployment test (3.3.1.a) using highspeed camera to verify deployment safety to CubeSat</td>
<td>No impact of deployables onto each other or the satellite</td>
<td>DF</td>
<td>DV</td>
<td>1</td>
<td>B</td>
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Appendix K. Part Drawings
NOTE: BREAK ALL SHARP EDGES. MASK ALL HOLES BEFORE ANODIZING.
NOTE: BREAK ALL SHARP EDGES,
MASK ALL HOLES BEFORE ANODIZING.
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