THE DESIGN AND CONSTRUCTION OF A RADIO TELESCOPE

A Project Report

In partial fulfillment of the requirement for the degree

Bachelor of Science in Architectural Engineering

By

Avery Bunting

Kira Tolman

Advisor:

Craig V. Baltimore, Ph.D., S.E.

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1.0 Introduction

From Fall Quarter 2022 to Spring Quarter 2023, a group of three dedicated students was able to both design and fabricate a senior project that will continue to benefit at least one club, including Cal Poly Amateur Radio Club, for years to come. Student learning was also furthered in a way that will better the senior project group members as people and allow them to contribute more within their respective careers.

1.1 This Senior Project

The interdisciplinary senior project group consisted of Avery Bunting (Architectural Engineering), Kira Tolman (Architectural Engineering), and Jack McGuigan (Electrical Engineering). They are all part of Cal Poly Radio Astronomy (CPRA), which is a club created and run by Jack McGuigan. Radio Astronomy studies celestial objects at radio frequencies and is performed using a radio telescope. In order to provide CPRA with more potential learning opportunities and allow them to physically conduct radio astronomy, the design and fabrication of a radio telescope was undertaken as a senior project. Figure 1 shows the finished product.

Figure 1

1.1.1 Project Group

The team of three students met weekly with a faculty advisor, Craig Baltimore, Ph.D., S.E., during the Fall 2022 and Winter 2023 quarters to coordinate the design of the radio telescope. Help was received from many others throughout the process, though. This included a mechanical engineering and a civil engineering student, Gabriel Ahern and Brett Butler, respectively, as well as some members of CPRA. Dave Kempken and Tim Dieu from the CAED Support Shop also largely contributed to the fabrication process of the telescope through guidance and heavy machinery operation.

1.1.2 What Does This Specific Radio Telescope Do?

The dictionary definition of a radio telescope is "an instrument used to detect radio emissions from the sky, whether from natural celestial objects or from artificial satellites." They collect and amplify radio waves so that they may be analyzed.

The radio telescope for this project is specifically designed to conduct hydrogen line astronomy. This consists of collecting the photon emissions from hydrogen atoms when there is a spin flip of the 1s electron (Figure 2). This is a rare occurrence, but hydrogen is the most abundant element in the universe. Therefore, there are enough emissions to pick up a signal. These emissions (weak radio waves) are digitized and processed to form images. Figures 2-4 show a graphic representation of this process. Within these images, the color represents the relative velocity of the hydrogen, and the brightness represents the concentration.

An important feature that differentiates this radio telescope from others most used in the field is its unidirectional feed. The parabolic dish reflects the signal to a focal point – the feed (Figure 3). In most radio telescopes, the dish and feed can rotate together in all directions. In the case of this project, the spin of the earth is used for the East-West movement and the feed itself is on a track that moves in the North-South direction. This resulted in being able to map the entire galaxy after one 24-hour rotation of the earth. An example of this can be seen in Figure 4, and results from this project can be seen in Figures 32 and 33 of this report.

1.2 How This Project Will Progress the Learning of Future Students

The purpose of this radio telescope is two-fold, providing experience and understanding through the process of designing and building it, and providing learning opportunities to future students who will be tasked with the upkeep and operation of this equipment.

1.2.1 Technical Skills

Students will have the opportunity to gain and strengthen technical skills in areas such as electronics, computer programming, and data analysis.

1.2.2 Critical Thinking

Students will learn how to interpret the data gathered by the radio telescope and use it to draw conclusions and make predictions. Additionally, unexpected technical issues or data anomalies may arise while using the radio telescope, giving students experience identifying and solving problems that arise during the data collection process.

1.2.3 Collaboration

Students who work on a team to operate a radio telescope will learn how to collaborate, both within their own discipline and with students who possess different areas of expertise and research objectives. By working alongside their peers, students will learn to navigate challenges and develop effective communication strategies that allow them to work together efficiently and effectively.

1.2.4 Research Skills

Using a radio telescope is a form of scientific research. Students who work with the radio telescope will learn how to design experiments, analyze and organize data, and communicate their findings to others.

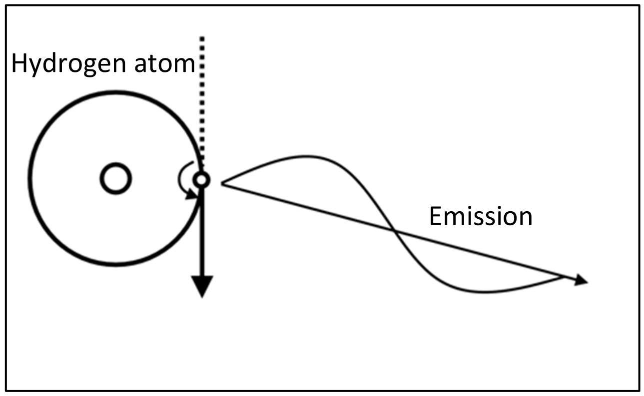

Figure 2: Spin flip of 1s electron releases energy in the form of a photon (hydrogen emission)

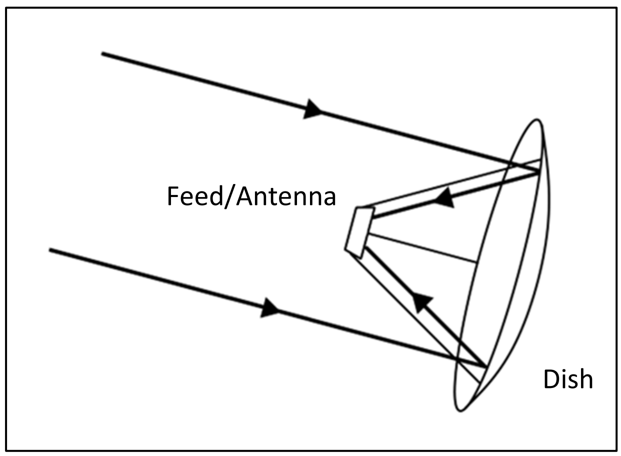

Figure 3: Dish focuses energy onto antenna where waves excite currents (collection)

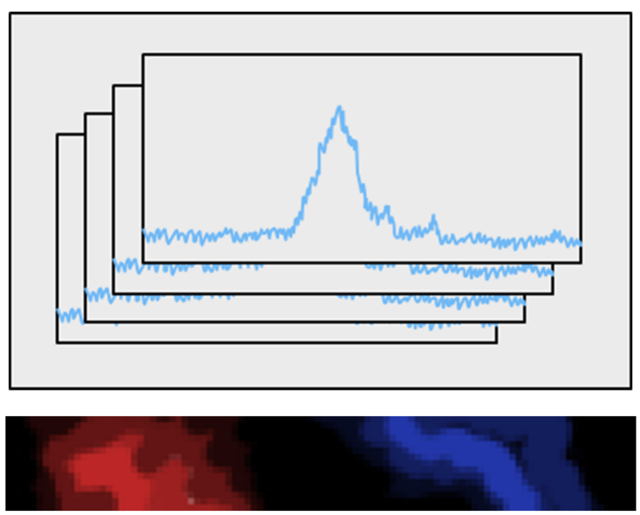

Figure 4: Radio waves are digitized and processed to form images (reception)

2.0 Interdisciplinary Work

Structural engineers collaborate with many disciplines to provide a holistic and functional building design for clients. As this interdisciplinary work is imperative in the field of structural engineering, it is extremely valuable to have the opportunity to practice interdisciplinary work in a relatively low-pressure environment where innovative ideas and even failures are encouraged.

2.1 The Team

As is previously discussed in 1.1.1, the team was interdisciplinary and included architectural engineering (ARCE) students and an electrical engineering (EE) student. This was an advantageous opportunity that capitalizes on the nature of the project to incorporate cross-discipline collaborative work with a non-typical discipline – electrical engineering.

2.1.1 Broadening Interdisciplinary Opportunities

The College of Architecture and Environmental Design (CAED) has provided opportunities to collaborate on design projects within the scope of the five majors housed in the college. These majors are:

- architecture (Arch)
- architectural engineering (ARCE)
- city and regional planning (CRP)
- construction management (CM)
- landscape architecture (LArch)

However, due to a lack of opportunities and the busy schedule of an ARCE student, it has been difficult to find opportunities to collaborate with students outside these five majors. This radio telescope senior project came about through a mutual club, CPRA, and proved to be a universally beneficial interdisciplinary collaboration, for the ARCE and electrical engineering students.

2.1.2 The Project by Discipline

The main function of the telescope is housed within the domain of electrical engineering, so consideration was first and foremost given to the design parameters dictated by the function of the telescope.

Once the design criteria were identified, the ARCE team was able to create an initial structural design and continue to iterate the model as communication with the electrical side of the project progressed.

In addition to the expertise of structural and electrical engineering from the group members, further input on the design of the feed mechanics was received from a mechanical engineering student. This increased the already critical need for clear and continuous communication in the design of the structure, as the success of the interface between the body of the telescope (structural scope) and the track of the feed (mechanical scope) were critical to the success of the project.

2.1.3 Benefits of Working with an Academically Diverse Team

This project began as a pet project of the electrical engineering student. After looking at the scope of the project, he decided to ask for input from a structural engineering student. Realizing this had the potential to be a senior project, the process was begun to undertake it as such. The transition of this team from a monodisciplinary team (EE only) to an interdisciplinary team (EE and ARCE) increased the complexity of the project, leading to a need for increased communication and scheduling in order to complete the project. Despite the challenges of increasing the team from one person to three, there were some marked benefits, including:

- allowing each person to meaningfully contribute to the project by playing to their unique strengths,
- optimizing the design by allowing different portions of the project to be completed simultaneously by team members who are trained in that field,
- allowing both ARCE and EE students to gain experience in working with disciplines that have different methods of approaching the same design challenge.

2.2 Collaborative Considerations

In the structural engineering profession, it is crucial to cooperate with architects, construction managers, MEP designers, civil engineers, and fellow structural engineers. Real-time cooperation from multiple disciplines who have the same overall objective, and yet different focuses, opens opportunities for holistic and cohesive designs. By applying different lenses of practice to a project, it’s possible to maximize efficiency, performance, and aesthetics of the structure. In this project, the electrical engineering portion of the project had a very specific parabolic curve shape and a deflection limit that were both necessary for the proper function of the radio telescope. The structural engineering students were able to be tailor their design to these requirements, resulting in a better final product than what may have been produced without such close collaboration between disciplines.

It’s important to become familiar with collaborative work while still in college where it is encouraged to experiment with approaches to workflow and communication. This project has provided an opportunity to do two important things in relation to collaborative design work:

1. Experience failures within a setting where they are not catastrophic. As a senior project, the purpose of this project was to allow for an iterative process of attempts and failures in the name of learning. Many of the lessons learned here about successes and failures in teamwork, design, budgeting, ordering, planning, and construction can be extrapolated and applied to situations that will be encountered in the outside industry.
2. Practice working with a diverse group of thinkers and designers before heading into the professional sphere. The team will take the lessons learned from this project into industry and positively contribute to collaborative projects competently and confidently.

2.3 Lessons Learned

Shortly after taking on this project, the realization was come to that communicating ideas across disciplines can be difficult, especially when one does not have a technical background in the topics another team member is attempting to explain. It became important to honestly communicate each team member's level of understanding of a subject to ensure comprehension of the important concepts being presented. It was imperative that the ARCE students understood the basics of radio astronomy to give context to the objectives of the EE student to ensure the function of the structure.

We learned the importance of carefully considering the needs of other disciplines to meet the needs of the entire team most effectively. We grasped the need to be flexible and willing to discuss to come to a consensus with other disciplines on a project, but we also came to understand the importance of strongly advocating for our own discipline's needs through clear explanation of concepts and concrete reasoning. Lastly, we came to understand that although there are many smaller moving parts of the project that require close attention, looking at the project in a wholistic manner advances all aspects of the project by creating a cohesive picture of the team's progress and next steps.

3.0 Design

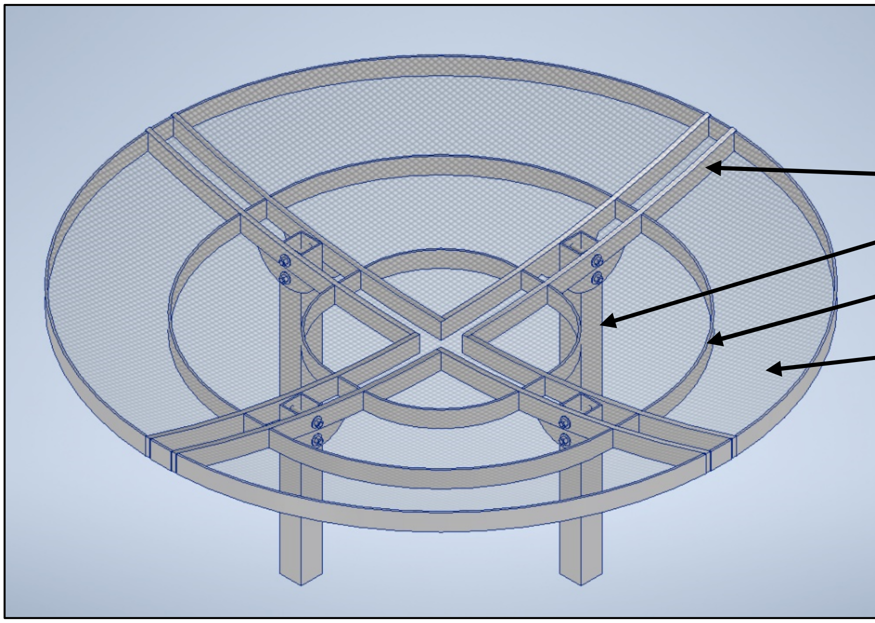

Figure 5: Finalized structural design done in Autodesk Inventor (no mechanical or electrical elements)

The parameters that affected the structural design the most were the deflection limits, constructability, and accuracy required in the shape of the parabolic reflector antenna (the mesh dish responsible for reflecting radio waves back to the feed). Electrical and mechanical aspects of the design also had to be incorporated into the structural design. This project differs from the typical buildings that Architectural Engineering majors are used to working on. This seems obvious since this structure is comparatively tiny and not intended for human live load, but some of the less intuitive differences occur in the design considerations. The final design can be seen in Figure 5 and consists of a two-meter in diameter mesh dish that is supported by four arms. These arms are bolted to the four legs that slide into the slot in the middle of each arm. There are also curved members connecting the arms that act as both lateral support and a surface to connect the mesh to. All these components are made of aluminum. More detail on the reason for material choice as well as the specific shapes and sizes of the members can be found in this section.

3.1 Deflection Limit

As stated in Table 1604.3 in the 2018 IBC (Appendix 8.1), typical deflection limits of building components range from L/240 to L/540. In the case of this project, it was necessary for the shape of the parabolic curve to be precise, so a deflection limit of L/1200 was chosen, which is used for elevator guide rails.

During the initial design phase, a 200-pound point load was applied at the end of one of the arms to account for the worst-case scenario of someone putting their entire weight on the edge of the dish. This is comparable to the design of a railing on a balcony or staircase, where said railing must be able to support a 200-pound point load according to ASCE 7-16 Section 4.5.1 (Appendix 8.2). The same thing is done in buildings, but with a 2000-pound point load.

Treating each arm as a cantilever, the equation $\Delta = PL^3 \div 3EI$ was used to estimate the deflection due to the 200-pound load. Since the deflection limit (Δ), Point Load (P), and Length (L) are constant throughout the equation, that left the modulus of elasticity (E) and moment of inertia (I) to be manipulated in order to meet the deflection limit. The modulus of elasticity corresponds to the material and the moment of inertia corresponds to the shape of the cross section. The method used here is linear elastic theory with small displacements and only considers bending, as the shear deformations are negligible.

3.1.1 Material

Aluminum and steel are common metals used in the construction of structures in developed nations, so they are the two that were most available in this situation. Therefore, they were the two that were considered and researched. Steel initially seemed the better choice because of its higher modulus of elasticity and strength, but after further research, aluminum was determined to be the superior option for this project. It has a natural resistance to rust and corrosion due to its outer layer of aluminum oxide that limits the material's exposure to air. Aluminum is also approximately one third the weight of steel. If this was a large job site with heavy machinery and an abundance of workers, weight would not be an issue, however the project team was comprised of only three students and had limited access to heavy machinery. Had the weight of the structure totaled more than its approximate 200 pounds, it would not have been feasible for a small group of students, such as this one, to manipulate or relocate it. After some preliminary calculations, it was found to be possible to design a reasonable cross section shape despite the smaller modulus of elasticity provided by aluminum as compared to steel.

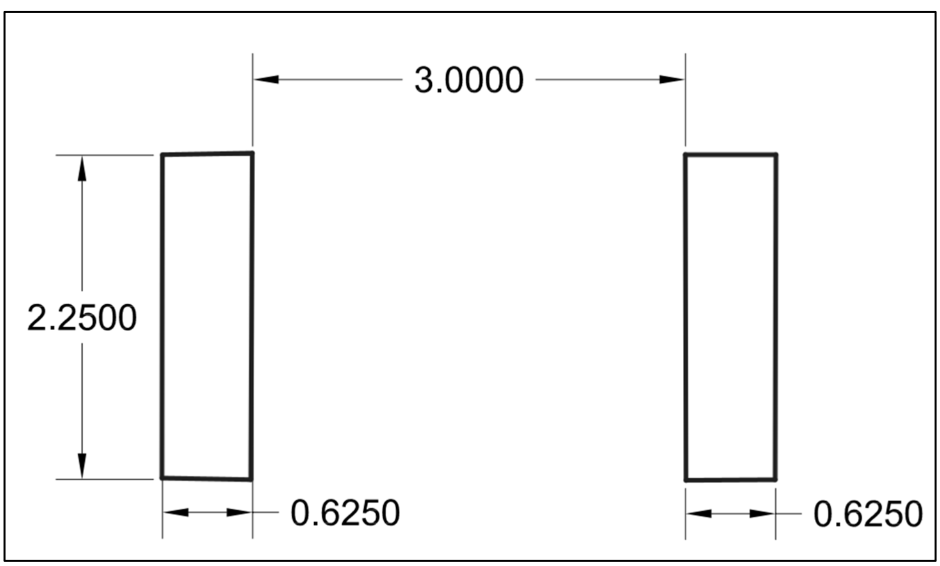

Figure 6: Cross Section of Arms (Dimensions in Inches)

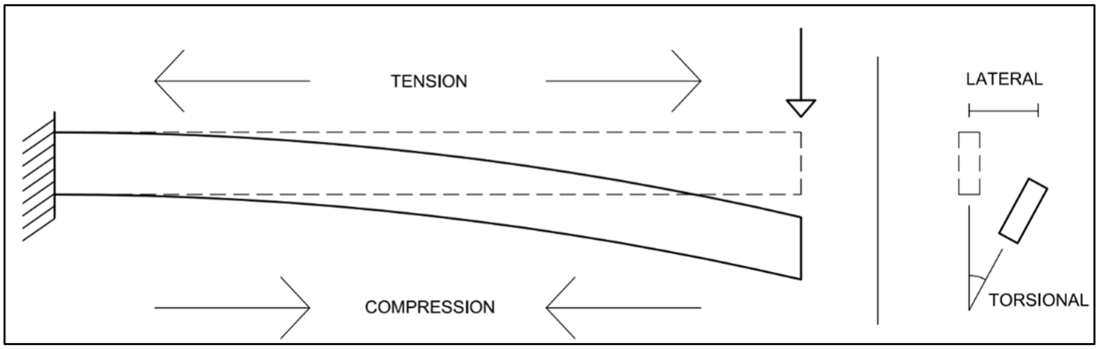

Figure 7: Lateral Torsional Buckling in a Cantilever (Elevation and Section Showing Displacement)

3.1.2 Cross Section Shape

Many aspects of this project were iterative, so instead of first deciding on a material and then selecting a shape for the cross section, alternation between the two occurred before landing on a design that was somewhat efficient. Aluminum may seem like the obvious answer based on the previous section, but without doing some iterative preliminary calculations, it was not certain whether the extra strength provided by steel would be required. The process was made much easier with the use of Excel. The final design based on the values from this Excel are shown in Appendix 8.3. Figure 5 provides an overview of what each part of the telescope is referred to throughout this report and will assist with the comprehension of the rest of this section.

The modulus of elasticity of aluminum is 10,000ksi which left a singular unknown in the deflection equation described in 3.1, the moment of inertia. This means that 6.14in^4 is the minimum required moment of inertia. Initially, the design for the arms consisted of two parallel 3/4in x 3in plates, two inches apart. From various materials classes, it was understood that the cross-sectional area could be decreased, but the moment of inertia could be kept the same by moving the material farther from the centroid of the cross section. Therefore, after further consideration for budget and constructability, the thickness and depth of the plates were decreased to 5/8in x 2 1/4in and they were spaced three inches apart (Figure 6). This design resulted in a factored demand to capacity ratio of 0.97, which is adequate since it is less than 1. This showed that the cross section would be adequate for bending about the strong axis, but weak axis bending still had to be analyzed. The mesh of the parabolic reflector antenna acts as lateral bracing along the top edge of the arm. This bracing occurs along the tension edge since the arm is a cantilever, leaving it susceptible to lateral torsional buckling (Figure 7). To prevent this from happening, intermediate lateral supports were included in the form of three sets of 3/16in thick rings around the underside of the mesh dish which can be seen in Figure 5. The calculations for lateral torsional buckling can be found in Appendix 8.4. These lateral supports also provided intermediate locations on which to secure the mesh. The 3in x 3in square tubes were used for the legs because they needed to fit between the arms that were designed to have a 3in gap. At this point, almost all the structure had been designed to get an acceptable cross section shape. This reinforces the idea that all parts of a structure work together and affect each other.

3.2 Constructability

As previously mentioned, material weight plays a large role in constructability, but that was not the only factor that needed to be considered. Other considerations included choosing between bolted and welded connections and designing members such that they are simple to assemble and don't leave too much room for error. This is yet another reason that the design was so iterative: constructability requires less number crunching and more visualization. Modeling software was helpful for evaluating constructability and was utilized throughout the design process of this project.

3.2.1 Connections

The two main types of connections in this structure are welds and bolts. Welds act as fixed connections and are typically stronger than the material itself but require skilled labor and can also result in residual stress. Bolted connections are easy to create but decrease the cross-sectional area of the bolted member, so it is not as strong.

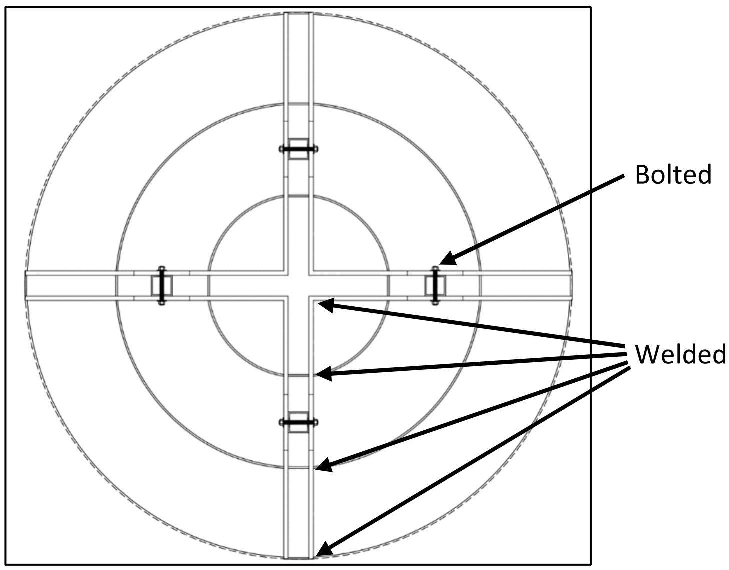

Figure 8: Planned connection types (Plan View)

Figure 8 shows all planned connections with the only bolts occurring at the connection between the arms and the legs. Just before the start of construction, new bolt holes were included in our water jet CAD file (Figure 9). These changes are not reflected in the final CAD or Inventor drawings because it was usure whether they would even be used. Section 4.2.1 goes more in depth on this choice to minimize the amount of welding by allowing the option of bolting instead of welding. These holes were drawn to be ¼" in diameter even though the expected bolt diameter was 5/16in. This choice allowed the team to either thread the holes using a tap and dye set or use a drill press to make them larger. Adding holes to the curved sections using CAD instead of hand measurements would prove to be beneficial later in construction due to small tolerances when getting bolt holes to line up.

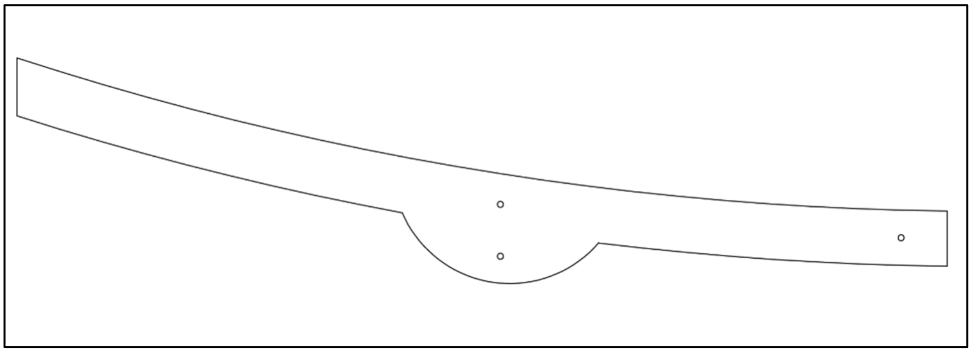

Figure 9: CAD file of Main Support Arm for Waterjet

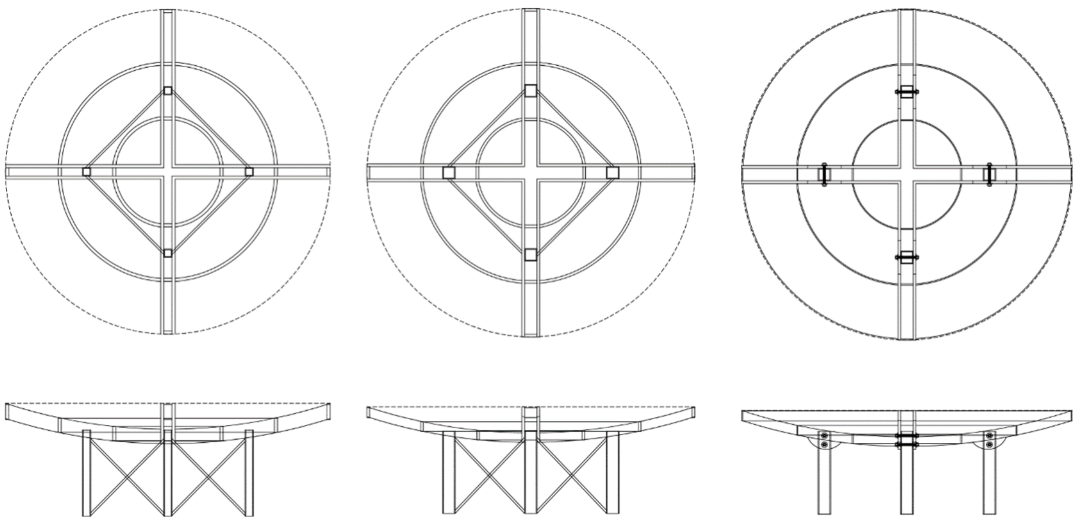

Figure 10: AutoCAD design iterations; 1st (Left), 2nd (Middle), 3rd (Right)

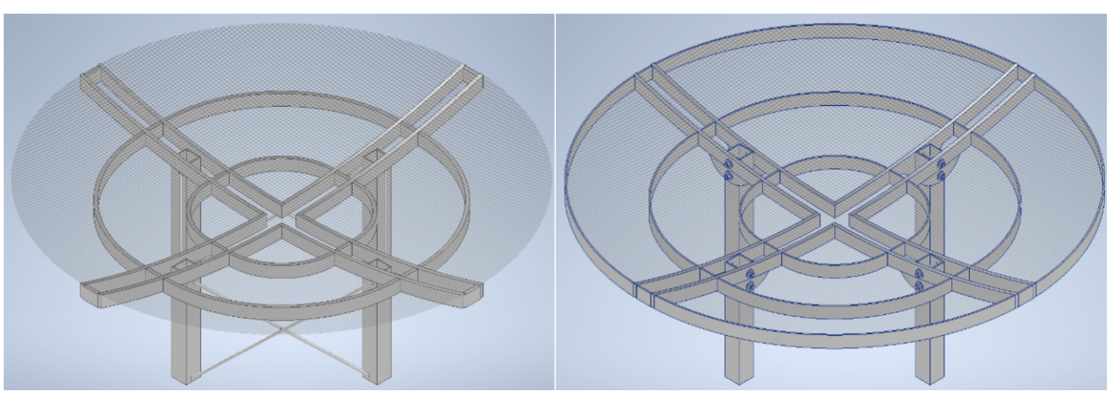

Figure 11: Inventor design iterations; 2nd (left) and 3rd (right)

3.2.2 Modeling

For the structural engineering side of this project, two different software programs were used for modeling. First, a plan and elevation view were created in AutoCAD. It is relatively easy to get exact dimensions in AutoCAD and the program acts as a precise drawing tool. After the initial AutoCAD drawing, changes were made including the cross-section changes described in section 3.1.2 that consisted of spacing the arms farther apart, making them thinner, and shallower. To better visualize the model in three dimensions, Autodesk Inventor was then used. This was a completely new program to the team and had somewhat of a learning curve, but after seeing the structure in 3D some things were discovered to be nearly impossible to construct with the precision required.

The only changes between the first and second iterations were the increase of spacing between the parallel arms and a subsequent reduction in their thickness. The arms were (and remain) curved which would prove challenging to weld on at the correct angle and there were diagonal rods used as lateral bracing for the legs which would also be difficult to cut and weld onto the legs. Thus, the third iteration was created. This iteration also included a third lateral support ring along the outer edge of the telescope to give the mesh an exterior boundary to connect to. Finally, the lateral supports were made thinner. The initial plan was to use the same metal thickness as the arms, but after seeing the cost of 5/8in thick aluminum, the lateral supports were downsized. Strength of these members was not an issue due to the main parameter being deflection of the arms. See Figures 10 and 11 above for the iterations.

3.3 Incorporating Other Disciplines

Although this report mainly focuses on the structural aspects of our radio telescope, electrical and mechanical considerations also had to be made throughout the design process. This is comparable to accounting for MEP in building design, which is often done in upper division ARCE design labs.

3.3.1 Electrical

The electrical requirements are what the entire structure is designed around, specifically the required curvature of the parabolic reflector dish. These calculations can be found in Appendix 8.5. Once the equation modeling the parabola was determined, the shape of the arms and therefore the rest of the structure, was able to be designed. The only other electrical components are the computers/code used to transform radio waves into images, but that had little to no impact on the design.

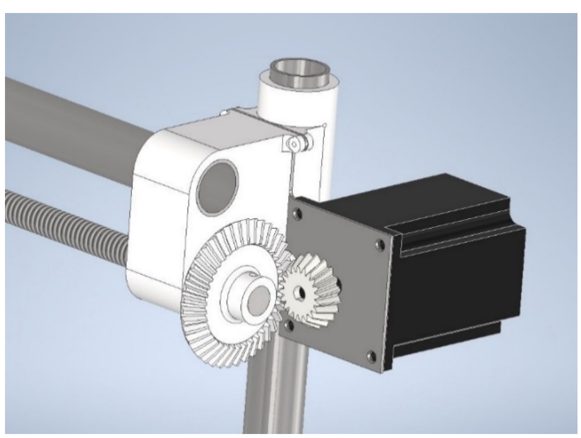

Figure 12: Feed design in Inventor

3.3.2 Mechanical

The main mechanical component on the telescope is the moveable feed. The design for this was not finalized until close to the end of fabrication, so a preliminary plan was made to work off throughout the design process. This plan consisted of attaching two vertical members to the telescope, one on each end. From there a threaded rod would connect these vertical members at the top and the feed would move along this rod. This would result in a relatively lightweight mechanical system that minimally impacted the structural design. The only action taken to incorporate the mechanical system was designing a flat face at the end of each arm for this mechanism to attach to. Figure 12 shows the final feed design that was presented to our structural team close to the end of the fabrication process.

4.0 Fabrication

The fabrication process included water jetting, drilling, and tapping the aluminum arms and legs; bending the intermediate stiffeners; bolting and welding the arms, legs, and stiffeners to attach them; attaching the mesh using pop rivets; and assembling and attaching the mechanical feed.

4.1 The Process in Pictures

1. Using a waterjet to cut out the arms.

Figure 13

1. Widening the holes at the midspan of the arms made by the waterjet.

Figure 14

2. Drilling holes in the legs for the bolts that connect them to the arms.

Figure 15

3. Threading the innermost holes in the arms.

Figure 16

4. Connecting the arms to each other using L brackets and to the legs using threaded rods cut to length.

Figure 17

5. Cutting 2 1/2in from the square tubes that make up the legs to be used as stiffeners at the ends of the arms and drilling holes in them for bolted connections.

Figure 18

6. Threading the holes in both the arms and stiffeners.

Figure 19

7. Labeling the faces of the arms and stiffeners.

Figure 20

8. Cutting the bars that would be used as lateral supports to their respective lengths.

Figure 21

9. Bending the bars to the proper radius using a manual slip roller.

Figure 22

10. TIG welding the lateral supports to the arms.

Figure 23

11. Marking and drilling holes for the feed support.

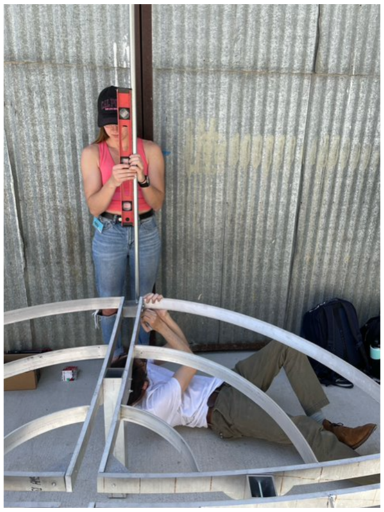

Figure 24

12. Placing the brackets to support the feed mechanism.

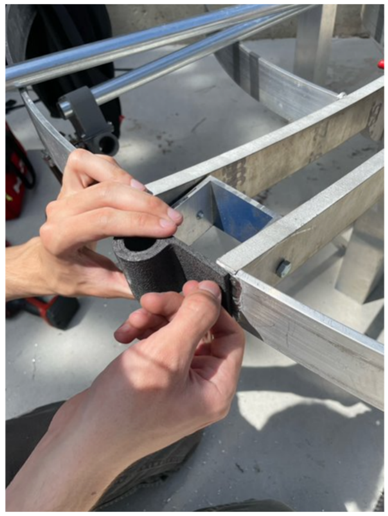

Figure 25

13. Installing the threaded rod and motor to the feed system. Once again, 200lbs is proven a reasonable value for design.

Figure 26

14. Drilling holes to attach the mesh.

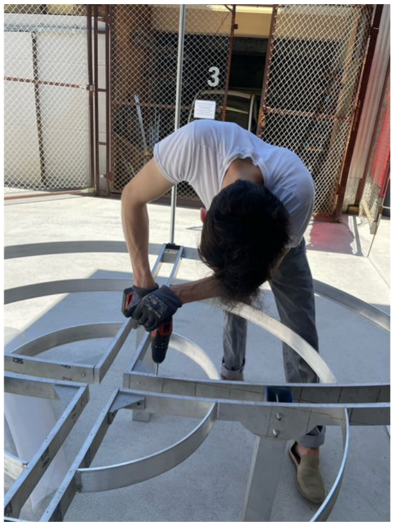

Figure 27

15. Pop riveting the mesh dish onto the arms.

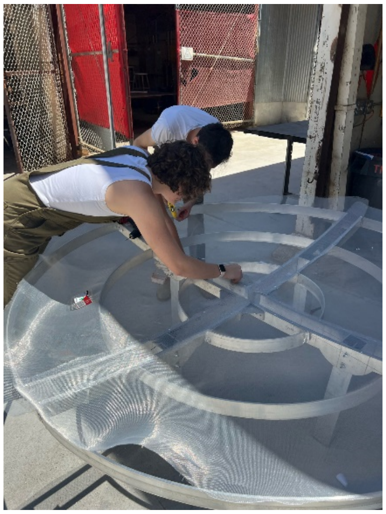

Figure 28

The fabrication of this structure involved even more than the steps listed above. Purchasing the materials was a very involved process that utilized our construction management skills. Throughout the process, there were multiple unforeseen issues that required design changes, mostly for constructability reasons.

4.2 Purchasing Materials

To even begin the described fabrication process, materials needed to be acquired. This was more complicated than anticipated. The amount of each material section needed had to be calculated. The team needed to clearly specify the exact amount of material that needed to be ordered for the ARCE department to properly place the order. Suppliers had to be found, delivery logistics communicated, and the budget had to be established and carefully monitored.

Figure 29

4.2.1 Estimating Amount

To most accurately estimate the amount of material to order, a spreadsheet was created (Appendix 8.7). Within this spreadsheet, the most unintuitive thing that had to be accounted for was the layout of the curved arms on a singular rectangular sheet of aluminum that would be cut out with the waterjet (Figure 29).

4.2.2 Communicating Delivery

One of the most stressful aspects of the project was obtaining the aluminum. No one on the team had ever ordered materials from an outside company, and coordinating delivery proved to be more difficult than expected due to Winter Break. Everyone was gone during this time, and it was unsure whether the materials would be delivered when no one was on campus to receive them. The materials were delivered at the end of January to the specified location – the concrete yard behind the Support Shop – and the materials were stored in High Bay Lab until they were needed.

4.2.3 Budget Management

When ordering materials, funding for the project had not yet been acquired, so the Architectural Engineering Department covered the cost of the shipment of aluminum parts. It became imperative that funding be secured from somewhere outside the department to reimburse them. Funding was secured from The Alliance[1], however, the lag in receiving the check due to administrative issues resulted in the use of both department funds and personal funds for longer than expected.

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[1] Address: P.O. Box 388 Cardiff, CA 92007 Email: info@thealliance.foundation Website: thealliance.foundation

4.3 Overcoming Construction Issues

Going into this project, the team was unsure of the challenges ahead, but was confident that whatever came up could be overcome and the project would be a success. Lack of skills and some specialized tools turned out to be a hurdle to the progress of the construction, but these challenges were overcome through guidance by Support Shop staff and the use of Industrial Technology and Packaging's water jet.

4.3.1 Lacking Skills

The team's lack of expertise in TIG welding aluminum necessitated outsourcing the task to a skilled civil engineering student who successfully welded all intermediate rings within two days. Additionally, due to the lack of welding capabilities within the immediate team, connections that were initially designed as welds were redesigned as bolted connections. A tap and dye set was used to thread all the holes, except the ones where the legs connected to the arms, which were the only set of holes in the original design. The welded connections were replaced with bolted connections where the arms connected to one another in the middle and where the brackets are at the outermost end of every arm. The reason the holes on the legs were not threaded and a rod was instead put all the way through both sides of the arm is because it is a difficult area of the structure to access, so we wanted to minimize the number of bolts there. These alterations yielded two-fold advantages: a reduction in the amount of welding required and the capability of disassembling the dish into quarters in the future, facilitating its transportation.

The changed connections include the brackets at the center of the dish where the arms connect to one another, and the square tube pieces bolted to the end of the arms which support the feed structure. The transition from mostly welded connections to mostly bolted connects and the continued need for tight, rigid connections meant that it was necessary to learn how to tap holes in the aluminum to receive threaded bolts. This process was much easier and less labor and material intensive than welding, and therefore, resulted in a smoother construction process. Ultimately, the inability to weld all connections engendered a valuable learning experience and resulted in a final product that is better suited to the needs of its end-users.

4.3.2 Lacking Tools

The CAED support shop boasts a comprehensive assortment of tools that can effectively address the needs of most student projects. Nonetheless, the radio telescope presented a unique set of challenges. Specifically, the intermediate rings of the telescope are 1/4-inch aluminum. Staff at the shop were unsure of the feasibility of rolling these pieces, especially the shortest ones that measure 1.35 feet in length, into the necessary curved shapes. A trial was run through the sheet metal roller which established that curving these pieces was indeed feasible. However, determining the optimal settings of the roller to generate the appropriate radius of curvature for each intermediate support circle remained uncertain. An iterative approach of trial and error was utilized until the correct curvature was achieved and the three other pieces of the same curvature were sent through the machine to ensure uniformity. When using the trial-and-error method, it was not uncommon for this process to result in overly curved pieces that necessitated manual adjustments involving gravitational and ground forces. A need for a specific shape on a certain piece of material led to a process of creative problem-solving and ingenuity that would not have been required had the limitations of tools available not been a factor in this construction process.

Due to the thickness of the aluminum sheet used for the radio telescope arms and the concern over degradation of the metal's strength due to the use of heat to cut the material, it was decided that a waterjet would be used to cut out the members. This posed a new challenge, as no one on the team had used the waterjet before. It was necessary to inquire as to the filetype requirements, schedule a time with an Industrial Technology and Packaging shop assistant, and be present for the set-up of the machine. As this machine was not in the CAED shop, but in an adjacent one, the communication and scheduling process was more arduous than anticipated and required perseverance and adaptability. In addition to this, the waterjet required 30 minutes to cut out each of the eight arms, totaling four hours of operation. In the middle of the process, the machine broke, and it took multiple shop technicians several days to troubleshoot the issue and perform a repair of the system.

Figure 30: Transporting the 5/8in thick aluminum plate to the waterjet via forklift.

Figure 31: Transporting from Mustang 60 shop back to CAED shop after welding.

4.3.3 Construction Scheduling and Manpower Inefficiencies

The process of scheduling construction of the radio telescope posed a significant challenge due to the full courseloads of all three team members throughout the Winter 2022 and Spring 2023 quarters. Fortunately, there were weekly windows of time that all members were able to attend and assist with the project, which proved immensely beneficial. The collaborative efforts of all team members facilitated decision-making and expedited the construction process.

A difficulty that was encountered during construction, specifically, was the inability to split up during this time to do multiple tasks at once. The nature of the construction process demanded that each task be done sequentially and with great precision, so tasks were not divided up and done simultaneously. This resulted in crew resource management inefficiencies, as usually only two people were able to be actively involved in the process at any given time. Despite this, the presence of all three team members resulted in a collaborative and efficient problem-solving that was integral to the success of the project.

Even though aluminum was used instead of steel, it was still much too heavy to be transported by hand in some cases. The radio telescope is approximately 6ft in diameter and 2ft tall, resulting in a heavy structure. Figure 30 shows the plate that would eventually be cut into the arms being transported by forklift. Even with all three team members, it was impossible to carry it due to its weight and awkward shape. Another example of alternative transportation appears in Figure 31. The telescope had to be welded in the Mustang 60 Shop across campus. With only two people available to carry it such a long distance, some improvisation had to occur.

4.3.4 Issues During Construction

Hurdles during construction are common, especially when a project is the first design build project in one's portfolio. Therefore, it was not a surprise when the team encountered issues such as not considering the kerf of the waterjet and struggling with the exact placement of hand-drilled holes due to measurement and marking errors.

It was planned that the waterjet would cut out holes that would them be drilled out further and tapped to accommodate bolts, however, the kerf of the water jet was not considered, and the holes ended up being slightly larger than what the tap for a 5/16" bolt called for. This resulted in threads that were not as deep as intended, but still functioned sufficiently.

The holes at the ends of the arms for the brackets were not initially planned (see 4.3 for further details), and therefore, the holes were drilled by hand, leading to inconsistent placement. This resulted in some of the holes in the arms and brackets being misaligned. This was an issue because the holes in the brackets were tapped, requiring the bolt to fit into the hole perpendicular to the threads to fit fully in the connection. This human error led to the need to drill out the hole in the arm to accommodate the bolt. In subsequent attempts, a more accurate method of marking and drilling holes was used, which resulted in the bolts fitting into the holes without further alteration.

Due to the small human error in drilling and tapping holes, the L-brackets that are located at the intersections of the arms in the center of the dish do not sit entirely flat with each arm. This is due to each of the arms coming into the center at what is not exactly perfect right angles. Despite this, the telescope's function is not affected.

4.4 Design Changes During Construction

Holes had been initially drilled into the arms at other connection points when they were cut by the water jet, but not at the ends where the arms connect to the brackets as the design for this connection was an addition made during the construction process. To ensure the best possible fit of these joints that were previously designed to be welded, a system was devised to keep track of where each arm was in relation to the others and to the square tube pieces located at the end of each arm. Holes were drilled in each of the arms and these holes were used to mark the necessary location of each hole in the square tubing piece acting as a bracket. These holes needed to be precise in their location because the process of tapping the holes required the bolts to be properly aligned in both the arms and the bracket. To address this, a letter and number metal stamping set was employed to mark each member with unique combinations such as A1, A2, B1, B2, and so on after the hole in the bracket was marked (Figure 20). This method allowed for clear identification of each arm and the corresponding face of the bracket signifying which side the arms would bolt to. This marking system was crucial in facilitating the proper alignment of the joints and promoting a more seamless construction process.

5.0 Data Collection

5.1 Physical Testing Setup

Permission was received from University Facilities to place the radio telescope on Dexter Lawn next to Building 21 between 7:00 a.m. on May 21, 2023, and 12:00 a.m. on May 23, 2023. This location gave an opportunity to best capture the galaxy without interruption. Not only this, it gave this project a large amount of visibility, with people walking up to it all day to read the project description and watch it work.

To safely place it on Dexter Lawn, cones were set up at all four corners, caution tape was wrapped around the perimeter, and the sprinklers were turned off to preserve the electrical equipment.

5.2 Results

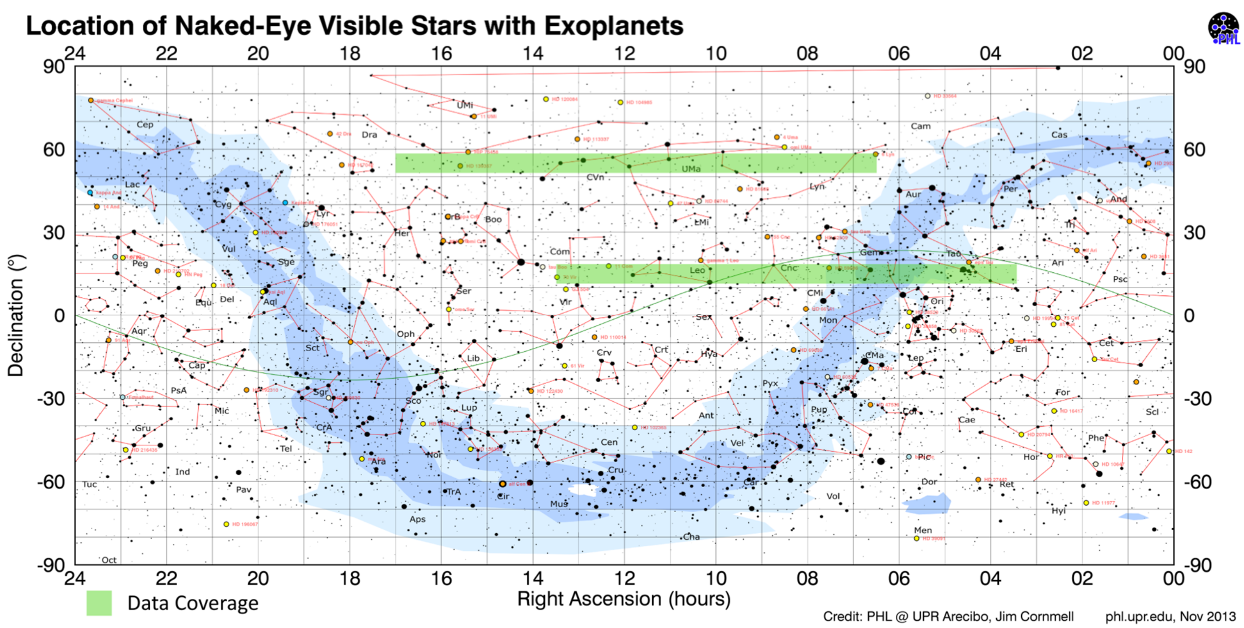


Figure 32

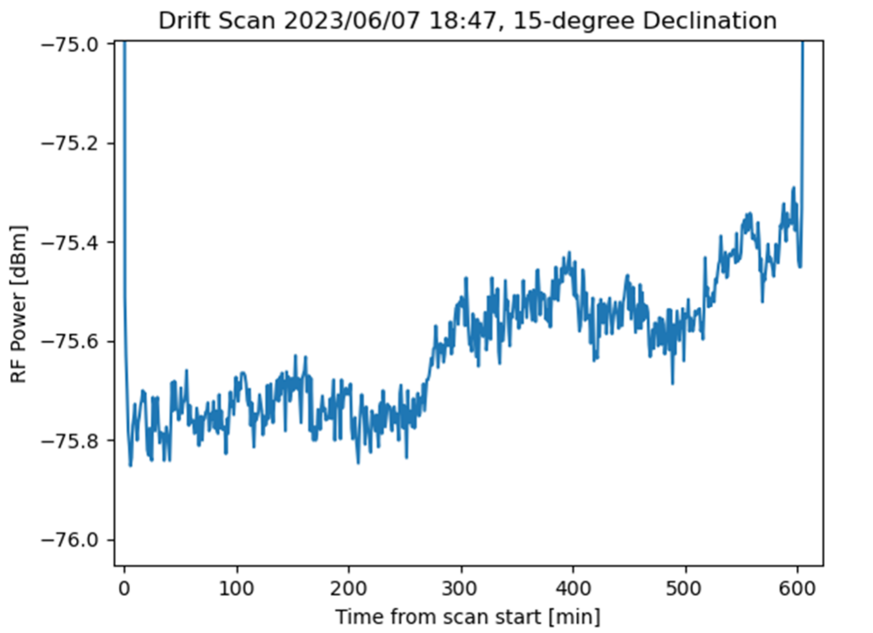


Figure 33

Multiple observational passes were conducted to collect data in different regions of the sky, with the goal of capturing a portion the Milky Way Galaxy. The two green stripes in Figure 32 represent the distinct areas selected for data acquisition, the upper stripe being the first attempt and the lower stripe being the second attempt. This second attempt captured a portion of the Milky Way – denoted in blue. The drift scan in Figure 33 shows the emissions from the hydrogen emitted from the bodies in the Milky Way. The power fluctuation (increase of emissions from the hydrogen) in the middle of the chart corresponds with the Milky Way entering the field of vision of the radio telescope.

It's important to note that data collection from this radio telescope is an ongoing process and is therefore not complete. The images presented in Figures 32 and 33 represent the initial findings attained during a two-week data collection period, which regrettably was shortened due to the necessary redesign and construction of the analog power detector. It was not feasible to complete this, collect and analyze the data, and write a report all within the span of two weeks. For this reason, the images in Figures 32 and 33 are preliminary visual depictions of the results, preceding the implementation of more complex visual representations derived from the data.

6.0 Writing the Report and Funding Application

Writing this report has been an incremental process and iterative learning experience. As the project has progressed, we've added increasing amounts of information to reflect the progress that's been made off paper. Meetings were had with the faculty advisor to receive feedback and allow improvements to be made to the report before the final version was submitted.

6.1 Working with an Advisor

As this was a senior project, we also had a faculty advisor to guide and educate us through the duration of the project – Craig Baltimore, Ph.D., S.E. Working with a seasoned professional added experience that can be seen as analogous to that of working under a project manager at a firm. We attended twice-weekly meetings with our advisor, one on Monday to plan and one on Thursday to assess progress. We provided status updates, asked questions about structural design requirements, and presented accurate and relevant information in the interest of holding a productive and concise meeting.

6.2 Funding Application

Our advisor directed us to apply for funding from the Alliance for Interdisciplinary Learning. Filling out the application required us to think critically, early on, about the purpose and scope of our project. Additionally, it was asked that we present a PowerPoint presentation detailing what we would like to accomplish with our project and the funding necessary. Making this report in the pursuit of funding gave us a great head start on our final presentation as well as this report, and it encouraged us to learn more about radio astronomy and the mechanisms designed by the EE student.

7.0 Thank You

We would like to acknowledge that this project would not have been completed without the help of many people. Listed below are each of these entities and their contribution to this project:

The Alliance Foundation for Interdisciplinary Learning – The Alliance provided our team with a scholarship that facilitated the purchase of all necessary materials for this project. They also gave us opportunities to practice public speaking, sharing about our project, and network with industry professionals and fellow students at quarterly roundtables.

Dave Kempken – Dave is the shops manager with decades of experience who assisted with finding any necessary parts and tools we were looking for and advising on best practices for construction. Dave was an invaluable source of support whenever we were working in the shop.

Tim Dieu – Tim is a support shop technician who lent his expertise to advising us on best construction practices. Tim helped us find ways to achieve the results we were looking for on very specific pieces using the tools in the support shop.

Allen Estes – Al is the Head of the ARCE Department and was the first person, aside from our advisor, to encourage and support us in the pursuit of this project. He promised us funds from the Learn by Doing Fund while we were searching for funding from The Alliance.

Parents' Learn by Doing Fund – The Learn by Doing Fund is one of the largest reasons we were able to complete this project this year. Without the donation contributions from parents and friends of the department, we would have been forced to pay for the materials out of pocket while waiting to secure funding from the Alliance, something that was not possible for us. Thank you to everyone who has donated to that fund.

Sydney Anthoni – Sydney was an office temp in the ARCE department's office. She was extremely helpful in working with us to order the aluminum parts, coordinate the delivery location, and keep us updated on the status of the order.

Jamie O'Kane – Jamie is the ARCE departments' administrative coordinator. She has been a great source of knowledge about the financial aspects of reimbursing the ARCE department after receiving our funding. She is the backbone of this department, and we would all be lost without her. Thank you, Jamie!

Brett Butler – Brett is a civil engineering major who has experience in TIG welding. He spent over 8 hours of his free time to weld the lateral supports of our radio telescope to the arms. Brett saved us a lot of time and effort with his expertise.

Cal Poly University Facilities Management & Development – Facilities provided us a space to collect data on Dexter Lawn and even turned off the sprinklers to protect our project. A specific thank you to Cesar Galvez for scheduling our time on Dexter.

Our sincerest thank you, again, to everyone listed above for assisting with such a massive undertaking and providing our team with the support to complete this radio telescope.

8.0 Appendix

8.1 Deflection Limits Table

TABLE 1604.3 DEFLECTION LIMITS[a, b, c, h, i]

CONSTRUCTION	L or L_r	S or W^f	$D + L^{d,g}$
Roof members:[e]			
Supporting plaster or stucco ceiling	$l/360$	$l/360$	$l/240$
Supporting nonplaster ceiling	$l/240$	$l/240$	$l/180$
Not supporting ceiling	$l/180$	$l/180$	$l/120$
Floor members	$l/360$	—	$l/240$
Exterior walls:			
With plaster or stucco finishes	—	$l/360$	—
With other brittle finishes	—	$l/240$	—
With flexible finishes	—	$l/120$	—
Interior partitions:[b]			
With plaster or stucco finishes	$l/360$	—	—
With other brittle finishes	$l/240$	—	—
With flexible finishes	$l/120$	—	—
Farm buildings	—	—	$l/180$
Greenhouses	—	—	$l/120$

8.2 Design Requirement for a Handrail

4.5 LOADS ON HANDRAIL, GUARDRAIL, GRAB BAR, AND VEHICLE BARRIER SYSTEMS, AND ON FIXED LADDERS

4.5.1 Handrail and Guardrail Systems. Handrail and guardrail systems shall be designed to resist a single concentrated load of 200 lb (0.89 kN) applied in any direction at any point on the handrail or top rail to produce the maximum load effect on the element being considered and to transfer this load through the supports to the structure.

8.3 Moment of Inertia of Radio Telescope Arms

Supporting Calcs for Finalized Design

Arms

$I_{req} = (PL^3)/(3E\Delta_{allow}) = 6.139 in^4$

$P = 200\#$ $L = 1m = 39.37 in$ $E = 10100 ksi$ $\Delta_{allow} = \frac{L}{1200} = 0.066 in$

Sheet metal $A_{req} = 16(d_{req}) + 16\sqrt{39.37/.159} = 1623.648 in^2$

$d_{req} = \sqrt{(I_{req} - 2t(.5t + .5S_{cL})^2)/(2t/12)} = 2.178 in$

$t = 5/8 in$ $S_{cL} = S_{int} + t = 3 + 0.625 = 3.625''$

Tubes

$S_{ext} = 3''$ $L_{total} = h \times 4 = .5m \times 3.3 ft/m \times 4 = 6.6 ft$

Rods BUT did not end up using rods

$L_{each} = \sqrt{h^2 + w^2} = 3.668 ft$

$h = .5m = 1.65 ft$ $w = 1m = 3.3 ft$

Check $\Delta L = PL_{each}/EA = 0.0044 in$

$A = \pi r^2 = \pi(.25)^2 = 0.196 in^2$ $P = 200\#$ $E = 10100 ksi$

Lateral Bracing

Sheet metal $A_{req} = 4d(L_{B1} + L_{B2} + L_{B3})$ BUT used bars instead

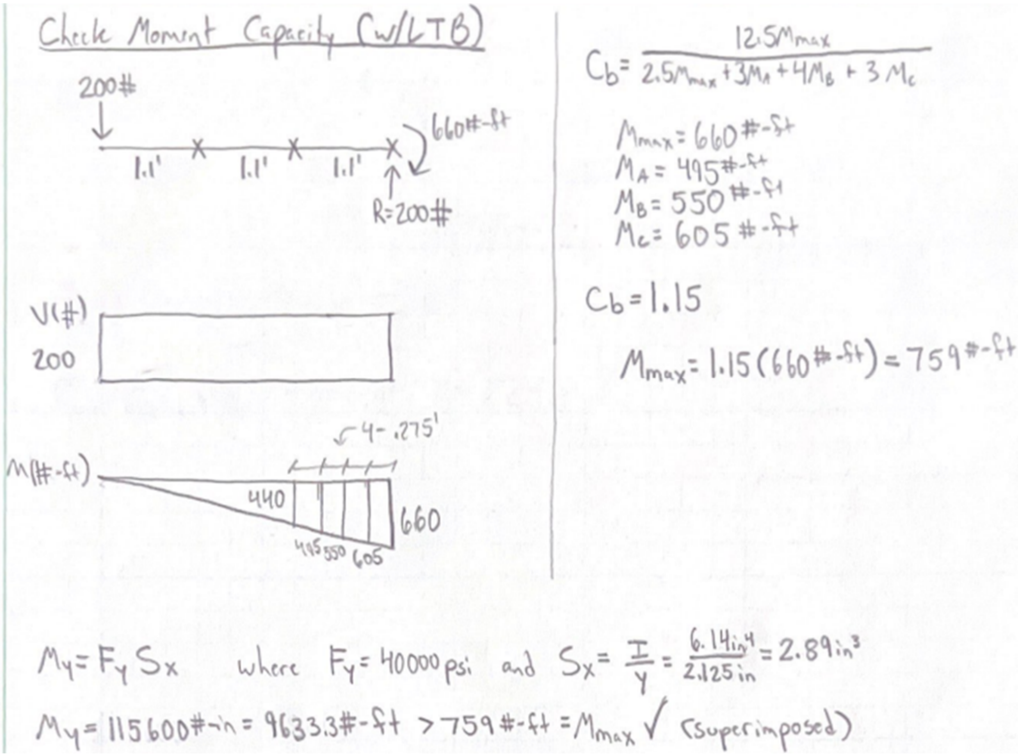
$r_{B1} = .333m$ $r_{B2} = .667m$ $r_{B3} = 1m$ $d = 2.25 in$

$L_{B1} = \frac{2\pi r_{B1}}{4} - S_{int} = 17.59 in$

$L_{B2} = \frac{2\pi r_{B2}}{4} - S_{int} = 38.25 in$

$L_{B3} = \frac{2\pi r_{B3}}{4} - S_{int} = 58.84 in$

8.4 Lateral Torsional Buckling Check



8.5 Equation for the Curve of the Parabolic Dish

Shape of Parabolic Reflector

$y = x^2/4f$ where $f/d = .785$ and $d = 2m$

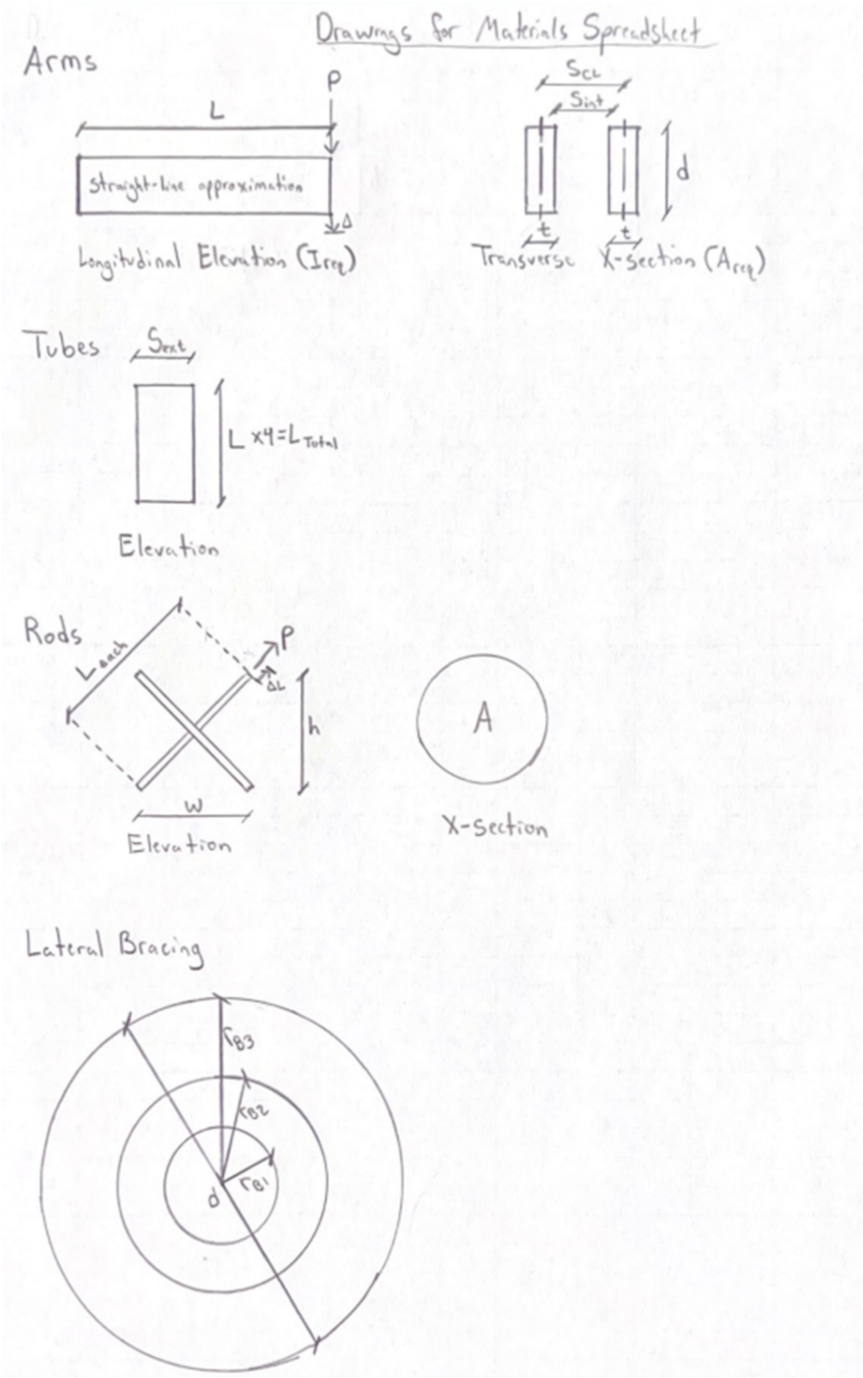
$f = .785d = .785(2) = 1.57$

$y = x^2/4(1.57) = \boxed{.159x^2 = y}$

Significant points to help w/CAD: @x=1 y=.159m

@x=.5 y=.03975m

8.6 Radio Telescope Material Dimensions



8.7 Material Order Calculation

ARMS				
I_{req}	**6.139**	**in^4**		
P	200	lb		
L	1	m		
E	10100	ksi		
Δ_{allow}	0.066	in		
Sheet Metal A_{req}	**1623.648**	**in^2**	**L_{min}=**	**3.3 ft**
s_{int}	3	in	**W=**	**3.42 ft**
s_{CL}	3.625	in		
t	0.625	in		
d_{req}	2.178	in		

TUBES				
S_{ext}	**3**	**in**		
L_{total}	**6.6**	**ft**		

RODS				
L_{each}	**3.668**	**ft**		
h	0.5	m		
w	1	m		
Check ΔL	**0.0044**	**in**		
A	0.196	in^2	when D=	0.5 in
P	200	lb		
E	10100	ksi		

LATERAL BRACING				
Sheet Metal A_{req}	**873.818514**	**in^2**	**L_{min}=**	**3.2 ft**
r_{B1}	0.333	m	**W=**	**1.9 ft**
r_{B2}	0.667	m		
r_{B3}	1	m		
d	2.25	in		
L_{B1}	17.5934523	in		
L_{B2}	38.2487468	in		
L_{B3}	58.8421992	in		

8.8 Euler Buckling Check

Buckling Check (legs)

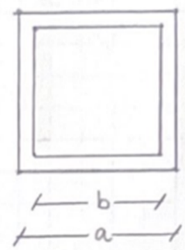
Euler Buckling: $P_{cr} = \frac{\pi^2 EI}{(kL)^2}$

$E = 10000^{ksi}$ $L = 19.69in$ assume $k=1$ (conservative)

$I = (a^4 - b^4)/12 = (3^4 - 2.625^4)/12 = 2.79 in^4$

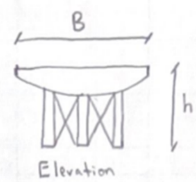
$P_{cr} = \pi^2 (10000)(2.79)/19.69^2 = 717^k$

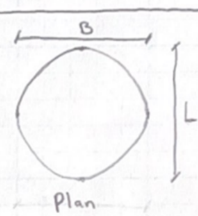
$P_{max} = P_{applied} + P_{self} = .2^k + .3^k = .5^k << 717^k$ ✓



8.9 Wind Loading Calculation

References	Wind Loading
ASCE7-16	• Building 5, h: 28', Exposure B
29.4.1	$F_h = q_h (GC_r) A_f$ (lb) (eqn. 29.4-2)
	$A_f = Bh = 6.56'(2.13') = 13.97 ft^2$
	$(GC_r) = 1.0$ since $A_f = Bh$
26.10.2	$q_h = q_z = .00256 K_z K_{zt} K_d K_e V^2$ (psf) (eqn. 26.10-1)
26.10.1	$K_z = .7$
26.8.2	$K_{zt} = (1 + K_1 K_2 K_3)^2 = 1$
26.6	$K_d = .85$
26.9	$K_e = 1$ since ~250' above sea level
26.5	$V = 92$ mph (Risk Cat. II)
	$q_h = .00256(.7)(1)(.85)(1)(92)^2 = 12.89 psf$
	$F_h = 12.89 psf (1)(13.97 ft^2) =$ **180.07 lb** ← F_h (wind)
29.4.1	$F_v = q_h (GC_r) A_r$ (lb) (eqn. 29.4-3)
	$A_r = BL = (6.56')^2 = 43.06 ft^2$
	$(GC_r) = 1.0$ since $A_r = BL$
	$q_h = 12.89 psf$
	$F_v = 12.89 psf (1.0)(43.06 ft^2) =$ **555.04 lb** ← F_v (wind)

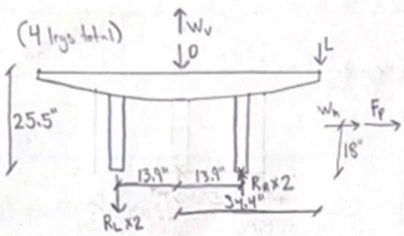




8.10 Roof Connection Forces

References

Roof Connection Loading (Overturning)



D = 200 lb
L = 200 lb
Wv = 555 lb
Wh = 180 lb
Fp = 83 lb

ASCE 7-16 Check Required Connection Capacity by $+\uparrow \Sigma F_y$ and $\circlearrowleft \Sigma M_x$:

2.3.1 Load Combo 1: 1.4D

0 = 4(R) − 1.4(200 lb) ⇝ $R_L = R_R$ = 70 lb (C)

Load Combo 2: 1.2D + 1.6L + .5 (Lr or S or R)

0 = 27.8"(2)R_L + 1.2(13.9")(200 lb) − 1.6(20.5")(200 lb) ⇝ R_L = 58 lb (T)

0 = −2(58 lb) − 1.2(200 lb) − 1.6(200 lb) + 2R_R ⇝ R_R = 338 lb (C) *

Load Combo 3: 1.2D + 1.6(Lr or S or R) + (L or .5W)

0 = 27.8"(2)R_L + 1.2(13.9")(200 lb) − 20.5"(200 lb) ⇝ R_L = 14 lb (T)

0 = −2(14 lb) − 1.2(200 lb) − 200 lb + 2R_R ⇝ R_R = 234 lb (C)

Load Combo 4: 1.2D + 1.0W + L + .5(Lr or S or R)

0 = 27.8"(2)R_L + 1.2(13.9")(200 lb) − 13.9"(555 lb) − 18"(180 lb) − 20.5"(200 lb)

↳ R_L = 211 lb (T) *

0 = −2(211 lb) − 1.2(200 lb) + 555 lb − 200 lb + 2R_R ⇝ R_R = 154 lb (C)

Load Combo 5: .9D + 1.0W

0 = 27.8"(2)R_L + .9(13.9")(200 lb) − 13.9"(555 lb) − 18"(180 lb) ⇝ R_L = 152 lb (T)

0 = −2(152 lb) − .9(200 lb) + 555 lb + 2R_R ⇝ R_R = 36 lb (T)

2.3.6
12.4.2.1
12.4.2.2

Load Combo 6: 1.2D + Ev + Eh + L + .2S ⇝ $(\underbrace{1.2 + .2S_{DS}}_{1.37})$D + Fp + L where S_{DS} = .862

0 = 27.8"(2)R_L + 1.37(13.9")(200 lb) − 18"(83 lb) − 20.5"(200 lb) ⇝ R_L = 32 lb (T)

0 = −2(32 lb) − 1.37(200 lb) + 2R_R − 200 lb ⇝ R_R = 269 lb (C)

Load Combo 7: .9D − Ev + Eh ⇝ $(\underbrace{.9 - .2S_{DS}}_{.728})$D + Fp

0 = 27.8"(2)R_L + .728(13.9")(200 lb) − 18"(83 lb) ⇝ R_L = 10 lb (C)

0 = +2(10 lb) − .728(200 lb) + 2R_R ⇝ R_R = 63 lb (C)

Max Connection Loading: C = 338 lb, T = 211 lb ← Connection Loading @ feet

8.11 Sample Meeting Minutes

Monday Planning Meeting

Date: November 28, 2022 **Time**: 11:00 am – 12:00 pm
Location: Office 108-B, Building 21, Engineering West, Cal Poly San Luis Obispo
Project Name: Radio Telescope
Attendees:

Name	Position	Email
Dr. Craig Baltimore (CVB)	Advisor	cbaltimo@calpoly.edu
Avery Bunting (AEB)	Undergraduate Student	aebuntin@calpoly.edu
Kira Tolman (KHT)	Undergraduate Student	ktolman@calpoly.edu
Jack McGuigan (JEM)	Undergraduate Student	jmcguiga@calpoly.edu

Meeting Notes
Discussion

1. Stiffeners are used for stress concentrations and lateral torsional buckling
   a. To get the entire setup to act more as one, put stiffeners between the lateral braces and at the end of the arms
   b. Attach plates at the end of the arms to screw on the supports for the feed
2. Use narrow thread pitch to reduce the slop in the bolted connection between the legs and the arms
3. Ordering parts
   a. EE parts - low-loss copper clapboard substrate, low noise amplifier, band pass filter
   b. Attempt to order parts ASAP to avoid delay due to potential for train strike
4. Talking to Al Estes
   a. Speak to him about where the funding will be coming from to reimburse the department

Deliverables

Item	Description	RP	Due
1	Inquire with James Mwangi about possibility of locating telescope on the roof of Building 5	AEB, KHT	12/1
2	Create templates for cutting of members	AEB, KHT	12/5
3	Construction drawings (details, isometrics, notes)	AEB, KHT	12/5
4	Finish the 1-sheet	KHT, AEB, JEM	Ongoing
5	Update senior project report	AEB, KHT, JEM	Ongoing
6	Create Gantt chart	KHT	12/5
7	Set up meeting with Al Estes	AEB, KHT	12/1
8	Meet with Dave and Tim to look at Support Shop schedule for delivery	AEB, KHT	12/1
9	Talk to Mustang 60 and Industrial Technologies to see about water jet	AEB, KHT	12/1

Next Meeting
Monday, January 9th, 11:00am, at Dr. Baltimore's office