DYNAMIC AFFORDABLE RADIO TELESCOPE (DART)

An Undergraduate Research Scholars Thesis

by

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This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

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ABSTRACT

Dynamic Affordable Radio Telescope (DART)

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Substantial discoveries and achievements in space are waiting to be made. Even though increasing public and private investment has considerably decreased the barrier to entry, many significant advancements require expensive and specialized equipment – particularly in the electromagnetic spectrum. The Dynamic Affordable Radio Telescope (DART) design is a class of quick deployment and low-cost radio telescopes for single or multi-band use from parts obtainable at a local hardware store. The DART design provided in this thesis is a single band receiver purpose built for hydrogen line observations and serves as a model for cost, implementation and construction. Once complete, it will function as an educational tool for Texas A&M University.

Previous research has shown DART like radio telescopes in operation however, these stressed parabolic dish designs are complex and require high tolerances. The DART is not an optimal design, opting to satisfy the role as an instrument for the masses, focused on affordability and ease of implementation. Instead of requiring high precision tools and high tolerance construction techniques, DARTs focus on flexibility. For a fraction of the cost, DARTs can be built using low precision construction techniques while still achieving similar gains and beamwidths as professionally fabricated dishes. After construction, if gain is lacking or additional frequencies need to be observed an existing implementation can be easily modified and optimized.

This research focuses on best practices and implementation strategies for constructing DARTs. The methods used are those in theory and experimentation. Theoretical elements such as literature and numeric computations are quick and set a direction however, theory does not directly translate into results. Experimentation, built on theory's foundation, establishes the physical design limits due to unaccounted and complex variables in environment, material and tool availability. Various graphs, explanations, photographs, and a program are prepared to support implementation throughout the design process as well as expression of personal design decisions and challenges.

DARTs are designed to be the lowest entry point for organizations and individuals into the electromagnetic spectrum. Unlike traditional telescopes which are purely passive in design, DARTs may be used for passive and active applications such as observations of natural and artificial electromagnetic phenomena. The DART design is the complete package for rapid development and deployment including features such as a motorized mount and programs for both antenna control and construction aid. A high schooler with no experience should be able to afford in both time and money the implementation, control, and maintenance of a DART. The most significant impact of a low barrier to entry radio telescope is providing accessibility to study and interact with the cosmos to the masses.

As of March 31, 2023, only the antenna has been constructed. Moving forward antenna testing will be completed and supporting systems will be implemented.

DEDICATION

To my loving parents, Brandi and Andy Cox, and to my loving fiancée Anh Nguyen, for their consistent understanding, patience, and encouragement.

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NOMENCLATURE

DART	Dynamic Affordable Radio Telescope
VHF	Very High Frequency (30MHz-300MHz)
UHF	Ultra High Frequency (300MHz-3GHz)
SHF	Super High Frequency (3GHz-30GHz)
EME	Earth-Moon-Earth Communication
SDR	Software Defined Radio
SCORE	Signal Communication by Orbiting RElay
ARRL	American Radio Relay League
PWM	Pulse Width Modulation
RF	Radio Frequency
SMA	SubMiniture version A (semi-precision RF coaxial cable)
RMS	Root Mean Square (used as a way to model the "average" voltage for sine waves)
IC	Integrated Circuit

1. INTRODUCTION

DART style radio telescopes provide a low barrier of entry into cosmic radio observations. As parabolic reflectors, they can also be used outside of their intended purpose, as a radio telescope, and perform active communication with satellites and ham radio operators. DARTs focus on distant observations and communication in space. While the prospect of affordable satellite launches and construction are still reserved for those with large backing, peeking into the signal activities in space have been accessible to individuals for decades. DART's design and creation techniques only require access to a local hardware store and basic fabrication skills. The DART radio telescope is a simple front-feed parabolic dish reflector. This instance will utilize SDR for receiving signals on the 21cm line however, other radio transmitters and receivers can be used. Some common observations in a noisy, terrestrial environment include: hydrogen, hydroxyl, satellite data, and SETI observations searching for unnatural patterns.

1.1 Purpose

Early astronomical radio observations arose from the telecommunications industry, which has long been in the intersection of astrophysics and electrical engineering. In 1933, while working at Bell Laboratories, Karl Jansky discovered the first radio waves radiating from what he first believed was the Sun but, was actually the Milky Way [1]. Radio observations are important in modern astronomy since they provide astrophysicists the ability to trace the cold universe, as opposed to optical astronomy, which relies on the light generated from hot stars. The most prominent spectral feature of cosmic radio waves is the hydrogen or 21cm line, arising from atomic gas in galaxies throughout the universe including the Milky Way. This line is detectable by low-cost modern electronics. Currently Texas A&M University has no facilities available to demonstrate this in education or outreach settings. The DART designed in this thesis is for hydrogen line observations, since the hydrogen line is one of the brightest cosmic radiation sources that can be observed on Earth's surface. Once complete this DART will serve as a model for implementation, a demonstration to the public, and as a demonstration in undergraduate and graduate level astronomy courses at Texas A&M University. The goal is to implement this design for $400 or less, with the most expensive components being the stepper motors and miscellaneous hardware and electronic components. As a goal, the antenna design itself should be less than $100. This design should be good for UHF frequencies however, stressed parabolic dishes can also be designed for VHF and SHF frequencies as well, though they may require much higher precision in their construction or physically larger sizes.

1.2 Literature Review

In the literature I have reviewed, most amateur radio telescope implementations use a horn antenna and some stationary mount. The issue with these designs is horn antennas lack of scalability and that stationary mounts cannot track celestial objects. The second most popular radio telescope for amateurs are parabolic dishes however, the count is considerably lower than that of horn antenna types. I primarily reference amateur radio publications by Paul Wade, ARRL, QST Magazine, and Ham Radio Magazine since they share practical considerations in radio antenna development. I rely on academic texts to cross reference equations used in the amateur articles since they may not be entirely accurate. In particular while writing the program for DISHCALC the *Antenna Engineering Handbook, Fourth Edition* was vital in understanding TM01 and TE11 modes, intricacies of parabolic dish geometry, and providing zeros for relevant Bessel Functions [2]. Some armature articles will include formula constants with no explanation or provide low precision tables, while academic texts cover these details in depth. The academic texts can be too abstract relying on ideal circumstances, complex math, and expensive software simulations in their works. I conducted a delicate cross referencing of both academic and amateur works to ensure that both theory and implementation of DART telescopes is sound. The most significant similarity between both amateur and academic works is that parabolic dish design is complex.

1.3 Previous Research

The University of Hawaii designed a 21cm horn antenna [3]. They used a SDR and readily available parts from their local hardware store in their design. In their paper, they provide antenna performance, construction details, and how to calibrate the antenna. Harvard University also has designs for a "horn-antenna radio telescope for education and outreach" and The implementation of this telescope is very similar to the University of Hawaii's [4]. There are examples of functional amateur helical antennas for hydrogen line observations [5] however, the amateur designs lack easily reproducible design elements. Where components used in this amateur antenna design are not appropriately tuned for its intended application of observing the 21cm line. Finally, an article by Allen Katz on EME and stressed parabolic dishes caught my attention [6]. While many of the featured designs are professional and used high tolerance construction techniques, it provided the initial inspiration for DART radio telescopes.

In my research, I first chose to implement a helical style antenna. Constructing a conductive helix with high directivity was attractive and simple [7]. Issues in implementation quickly arose due to the physical size needed for the required gain. It was not practical since the antenna gain is dependent on the length and number of turns in the helical antenna, thus leading to a significantly large antenna. The initial design planned was expensive and required multiple meters of copper coil. Even though a helical antenna can be broken up from one large helix into multiple smaller helices and formed into an antenna array, the size would still be significant and networking multiple helix antennae together correctly is a high precision task. To do this, one would have to ensure that all electrical impedances and phases for each helix is correct. The primary issue with horn style antennae is that they are impractical to scale due to being physically large, since they are simply a wave guide and all the incoming electromagnetic radiation across all frequencies will be collected. The radio amateur parabolic dish designs are complex to produce correctly and while professional parabolic dishes can be purchased, they come at a high price. This is the niche that DART radio telescopes fulfill, something that has all the features for a fraction of the price, with reasonable performance.

I studied these four antenna designs and determined that a stressed parabolic dish design would be best, since it can be easily constructed. Instead of requiring high precision and accurate construction techniques this design will rely on adjust-ability to account for non-ideal construction methods and materials. A computer can aim and compile data collected by the DART. I see this being a standard design for hobbyists and institutions interested in educational outreach for space. The impacts are not just limited to those just in academia; uses exist for satellite communication and listening to cosmic and terrestrial radio waves. As of March 31, 2023, much of the conceptual work has been performed however, much of the physical implementation is yet to be realized. Post COVID-19 inflation has significantly impacted the price of materials. The stressed parabolic dish antenna and all of its components can be constructed over a five-day period by one person. This was not an enjoyable experience and I would highly recommend forming a team which can easily halve or quarter the construction time. As of 2 April 2023, the mount, software, and motor control are yet to be physically produced. The mount and control software still need to be conceptually designed. I will provide information regarding these subsystems' theoretical implementations.

2. METHODS

Both numerical computation and experimentation were used in the DART's design process. While software models provide behavior details for ideal parabolic dishes, the low tolerance design of the DART will not behave ideally. Direct experimentation with different models and methods is best since software cannot account for real world performance. The anatomy section provides an overview of the structure of a DART. The numerical computations are done by a program I have written in FORTRAN called DISHCALC and is designed to generate ball-park performance and construction data. Antenna design and DISHCALC are covered in-depth due to being the only actualized systems. Important terminology, know that frequency f, wavelength λ, and the speed of light c are related as seen in equation 1. In this thesis beamwidth refers to half-powered beamwidth.

$$c = f\lambda \tag{1}$$

2.1 Anatomy

A complete DART radio telescope has an antenna, mount, motor control, receiver or transmitter, computer and required software. The antenna is constructed to provide the necessary gain and directivity for a target wavelength to observe. As stated earlier, stressed parabolic dish antennas are used due to their ease of construction. The anatomy the stressed parabolic dish antenna constructed in this thesis is provided below in detail.

2.1.1 Mount

The mount must be lightweight, mobile, and support the weight of the antenna as well as motor control components and logic circuitry. Unlike the antenna design which can be scaled up or down to meet the user's requirements the mount architecture changes considerably depending on the supported load. Many parabolic dish mounts are stationary and the "mobile mounts" are very complex and are typically made of metal. In the time allotted, I was unable to construct a mobile mount. This area must be expanded on, especially since the mount design changes with load, even a simple non-motor-controlled mount can be quite complex to construct. Further research is necessary to complete this system however, a potential option is a powered azimuth-elevation mount [8].

2.1.2 Electronic Controls

There are many methods to actuate a parabolic dish, typically two motors are required. Two stepper motors must be used for directional control, one for X, Y and another for Z axis movement. I suggest using bipolar stepper motors of a standard NEMA size with a step size of 1.8 degree or less, appropriate holding torque for the worst case load, and be driven by an H-Bridge. The initial schematics for a software/hardware agnostic controller are provided in the appendix. This controller converts PWM audio signals from the left and right channels of a standard 3.5mm stero jack to velocity instructions for each motor. The PWM signal will control the motors' direction and speed, to halt the motor no PWM (a speed of zero) will be applied. The faster the PWM signal the faster the stepper motors step. While the controller is incomplete, this will provide insight into how it could be implemented. The control circuitry is designed for battery powered applications, a 12V lawnmower battery would be a good starting point for most applications. The largest current draw will be from the stepper motors, ensure that the evaluated battery can provide a constant power for the required amount of time to collect data from observations. If a single battery cannot provide enough current, multiple batteries of the same kind can be placed in parallel, this will ensure that the voltage remains the same while adding current, and therefore increasing the power capacity of the overall battery system. A voltage regulator may be required to ensure power regulation for the op-amp and logic ICs. The op-amp's responsibility is to filter the signal and provide gain to step up the line level voltage, which can vary from 0.316 to 1.228 VRMS, to be converted into logic high and low pulses by the voltage comparators. The voltage comparators are biased to either output logic low or high based on their respective input voltage. The output of the comparators feed into a larger network of CMOS CD4000 series logic chips which control the velocity of each motor. The CD4000 CMOS logic controls the MOSFET H-bridges which power the motors step by step. It is important to use logic level MOSFETS, ideally HEXFET MOSFETS from International Rectifier.

The circuit I provide in the appendix does not have a particular H-Bridge design or stepper motors. The reason being is first an appropriate motor must be determined, then an appropriate H-Bridge must be constructed for that motor and many H-Bridge designs can be pulled from the internet. The general logic and signal controls are complete. In some applications sine waves maybe used instead of PWM if the PWM signal is too degraded. A simple script can graphically interface the user with the computer audio output to control where the antenna aims, this has yet to be designed. Further research is necessary to complete this system.

2.1.3 Data Processing & Receiver Considerations

The simplest instrument for data processing is called a Software Defined Radio (SDR). SDRs are affordable and effective in converting the analog information gathered from the probe into data that can be digitally processed. Some SDRs are specifically built for common wavelengths such as the hydrogen line. SDRs utilized in ham radio applications provide more flexibility since they can be tuned to specific frequencies. Thus if a DART is designed to observe the 18cm hydroxyl line and the 21cm hydrogen line one SDR can tune into both frequencies simultaneously. Another laboratory instrument that can be used is a spectrum analyzer if one is interested in more robust frequency information measurements of the signal. In this research the AirSpy R2 SDR is used. The University of Hawaii's radio telescope utilizes an older AirSpy SDR and provides detailed explanations in its operation and software [3]. The AirSpy R2 may have software and driver issues when operating with modern computers, in particular those that do not have native USB 2.0 ports and require USB 2.0 expansion. Notice that inputs on most RF equipment are SMA. Impedance matching and noise considerations from all elements in the signal chain including the cable, probe, and device input is required. To prevent noise and signal degradation a bauln or transformer may be necessary to resolve these issues. The probe inserted into the waveguide will most likely have to be constructed by hand, while this is simple, account for this during the antenna design phase. Also, ensure that the computer directing the DART and compiling data from the DART has a platform capable of executing all of the necessary software to execute these tasks.

Know that the DART will need to be calibrated before collecting data. The most common method observes two targets of known brightness or temperature. To calibrate, point the DART at a blank patch of sky, which would have a temperature of 3K, the temperature of the cosmic microwave background. Then stick a piece of foam in front of the waveguide that has been cooled with liquid nitrogen–LN_2– -77K. Having recorded the DART performance with both signals, one can calibrate the response of the telescope when pointing at other objects. Provided below is a listing of possible noise and gain loss sources:

1. Error in matching waveguide to focus
2. Feedline losses
3. Imperfect or crumpled surface
4. Waveguide blockage
5. Waveguide sidelobes
6. Supporting structure blockage
7. Noise/interference
8. Spillover
9. Improper calibration

2.1.4 Antenna

The three most important aspects of the antenna is its gain, directivity, and f/d ratio. The hydrogen line signals from space are extremely weak and need to be amplified. The gain of a parabolic dish antenna is proportional to its diameter. While other factors are important, its diameter is a major contributor to the antenna's gain characteristics. When observing the radiation plot of an antenna, the length and width of the largest most narrow lobe establishes the directivity of the antenna. If modeled in the optical realm, if one was to peer through a telescope, directivity would determine the width of the observable area and its ability to resolve far-away entities. The f/d ratio stands for focal length to diameter ratio. In theory, the f/d ratio is somewhat unimportant since the theoretical design is isolated and everything behaves ideally, however in practice, this ratio is incredibly important since it impacts the direct physical design of the dish and the materials that can be used. Below is the anatomy of a fully constructed DART stressed parabolic dish antenna.

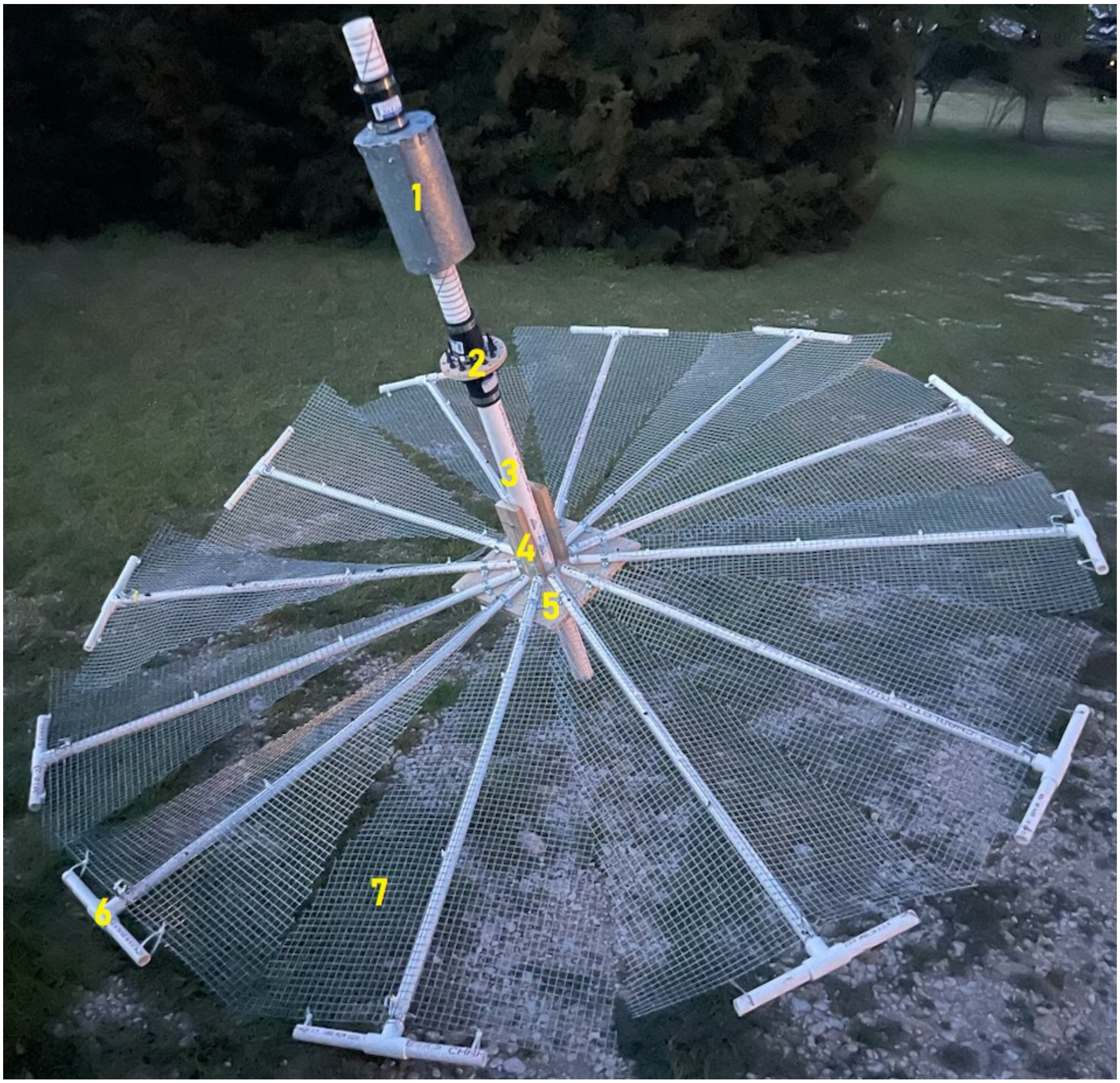

Figure 1: The Texas A&M University's DART antenna. Note that the dish is not parabolic since it is not stressed.

More details are provided in the *Results* section regarding specific details and construction methods. The main sections for DART style parabolic dish are listed below:

1. Waveguide – Responsible for capturing all of the directed energy from the parabolic dish's focus where a conductive probe will convert this energy into voltage.
2. Collar – Responsible for setting an anchor point for the stress wires.
3. Center Pole – The central mounting point; serves as the mount for the waveguide, collar, base, and antenna to mobile mount.
4. Center Pole Supports – Two wooden planks used to support the center pole and two bolts are fed through these and the center pole to stabilize the center pole.
5. Base – The central platform used to mount the center pole and spokes.
6. Spokes – Used as a frame to support the petals and provide handles.
7. Petals – Used to collect and reflect electromagnetic energy into a central focus when stressed.
8. Stress Wires (not seen) – Apply stress on the spokes and petals to form a parabolic dish.

2.2 Antenna Considerations

This section is a compilation of theoretical considerations while designing the DART. Selecting the appropriate f/d ratio is critical for the DART's performance. The f/d ratio does not favor one wavelength more than another, but it has considerable impact on physical design considerations. Materials used for spokes are placed under intense strain, notice that shallower dishes lighten the strain on the spokes and allow for lighter stress wire and more variety in affordable material options. I highly recommended reading Ham Radio's February and March 1986 article for parabolic antenna and feed designs [9][10].

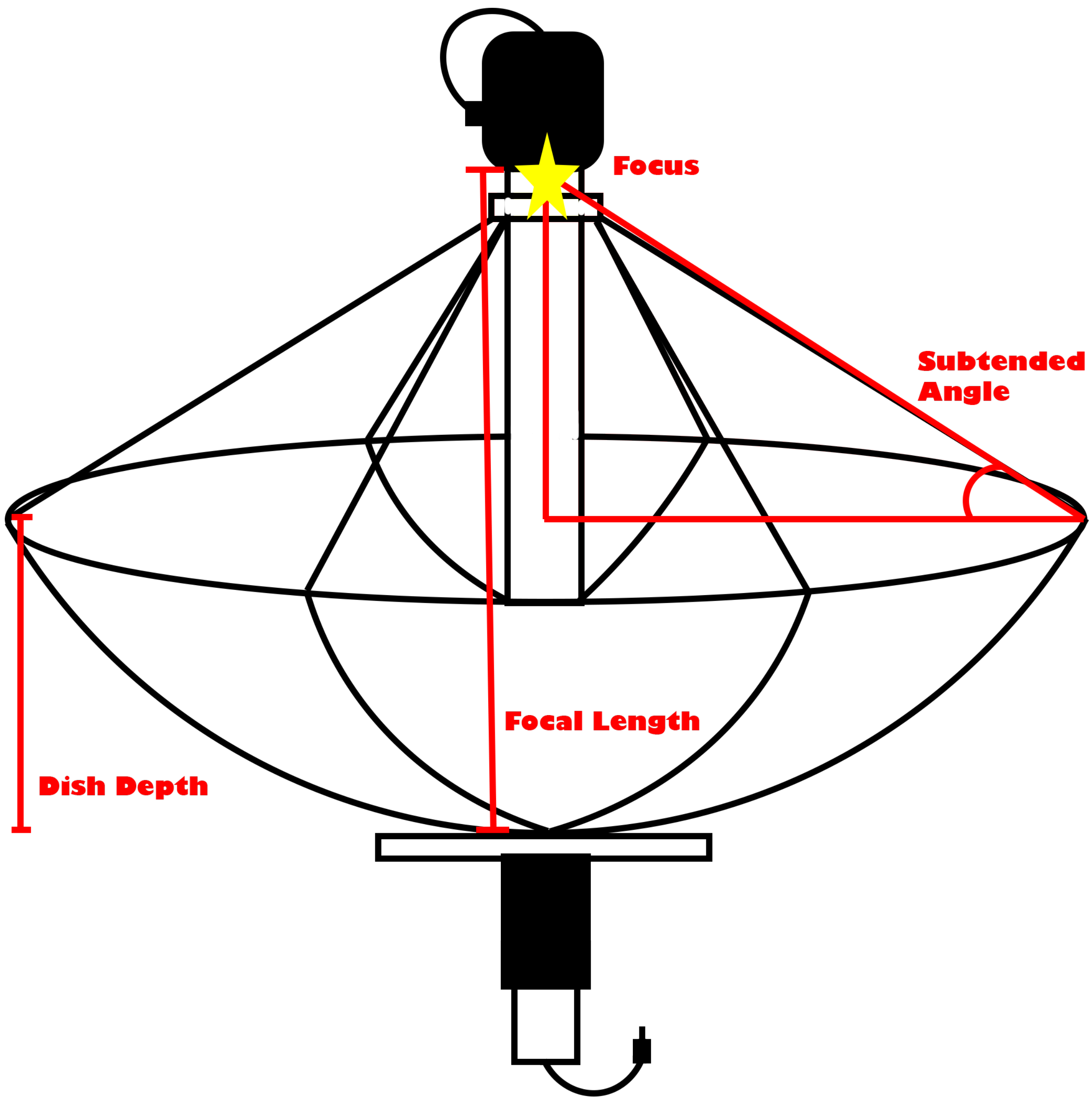

Figure 2: Parabolic dish terminology visualized.

2.2.1 Antenna Design

When constructing a parabolic dish antenna without the aid of DISHCALC or to verify DISHCALC results use the equations in the *Equations* section of the appendix for dish design. Notice that the listed equations using the *selector* variable are used in DISHCALC and should not be used in hand dish design. There are various ways to begin designing a parabolic dish. Below were my design steps:

1. Set the maximum budget
2. Set wavelength(s) to observe
    - (a) Where do they come from?
    - (b) How strong are they after entering Earth's atmosphere?
    - (c) Are there any known entities that use this frequency other than what you are trying to observe?
3. Antenna Design
    - (a) Set the desired gain
    - (b) Set the desired beamwidth – Keep in mind to favor "breadth of visible area" or ability to resolve
    - (c) Determine the dish diameter – Keep in mind operational gain and beamwidth features
    - (d) Set the f/d ratio
    - (e) Compute the focal length
    - (f) Compute dish depth
    - (g) Determine stress wire length – This is easily performed experimentally
    - (h) Determine the amount of petals – DISHCALC is programmed for parabolic dishes constructed with 12 petals

4. Petal Design

    (a) Compute maximum mesh size

    (b) Compute total area of mesh needed

    (c) Determine central angle for each petal – This sets the percentage of overlap necessary for each petal, for 12 petal designs the minimum is 30 degrees

5. Construct the waveguide

    (a) Compute aperture radius

    (b) Compute TE11 Cut off wavelength

    (c) Compute guide wavelength

    (d) Compute probe to wall distance

    (e) Compute probe height

    (f) Determine probe connection (recommend SMA style)

6. Construct the antenna

7. Construct the petals

8. Determine recording instrument, software, and computer to use (recommend SDR style recording instrument)

9. Testing

    (a) Determine significant noise sources

    (b) Determine an ideal location

    (c) Calibrate

    (d) Test

    (e) If performance is not ideal, keep in mind potential antenna gain losses

2.2.2 *f/d Ratio Considerations*

The f/d ratio is a unitless ratio based off of the focal length and dish diameter. The focal length, subtended angle, and depth of the dish are dependent on this value, which is crucial for design. There are two popular ranges for f/d ratios spanning between 0.25 and 0.4 for deeper dish designs and spanning between 0.5 to 0.6 for shallower dish designs [9]. Any f/d ratio between zero and one is valid, but may not be possible to physically implement or it may not perform ideally in a real world environment. Deep dishes are common in commercial applications, since they have short focal lengths, they are susceptible to less noise [9]. The two primary disadvantages for deep dishes are maintaining and constructing the dish curvature and constructing a waveguide to accommodate the wider subtended angle [9]. Shallower dishes have less curvature and therefore are easier to construct. The waveguide and mechanical supports of shallower dishes are under less strain and the waveguide can be constructed for a smaller subtended angle [9]. However, since the f/d ratio is higher the focal length will be further away from the waveguide it will be more more noisy and harder to tune [9].

2.2.3 *Petal Considerations*

Petals are what bend and reflect electromagnetic energy into the focus of the parabolic dish. Their design is important, I recommend and DISHCALC has pre-programmed a petal count of 12. This was determined subjectively as a circular "enough" shape for the dish while having a low spoke count and therefore reduced material and labor costs. Petal counts less than 12 can become unwieldy to construct due to the size of the sheets of mesh used to construct each petal. Keep in mind that the longest part, the arc length of the petal, and this is limited by the width of the material. Most material at home improvement stores for meshes are sold in 2ft wide rolls. Larger petals are not impossible to create, but would require extra geometry and work to combine sheets of mesh that is smaller than the petals arc length. Having more than 12 spokes begins to step into the territory of higher precision construction techniques. 12 petals can be placed together to form a regular-dodecagon where each segment has a central angle of 30 degrees. Central angles less than 30 degrees are more sensitive to variation when cutting the mesh by hand.

Petals can be designed to use material strategically and there are two petal geometries. One geometry is triangular and the other is sector like, where the sector like is based off of segments of a circle. The sector like geometry is harder to physically construct since an arc must be cut into the material by hand. Triangular geometry is much simpler to construct at the cost of a parabolic dish that would have the shape of a polygon rather than a perfect circle. If implementing the DART with triangular petals, the more spokes, the more circular the dish will be. I used the triangular geometry since it was the easiest to construct and the results were circular enough for me. If the base of a triangular petal is the width of a rectangular segment of material then it forms an isosceles triangle. What makes this special is that the two leftover sides from the extra material can be combined to form another petal if bound from longest leg to longest leg as seen in the figure below.

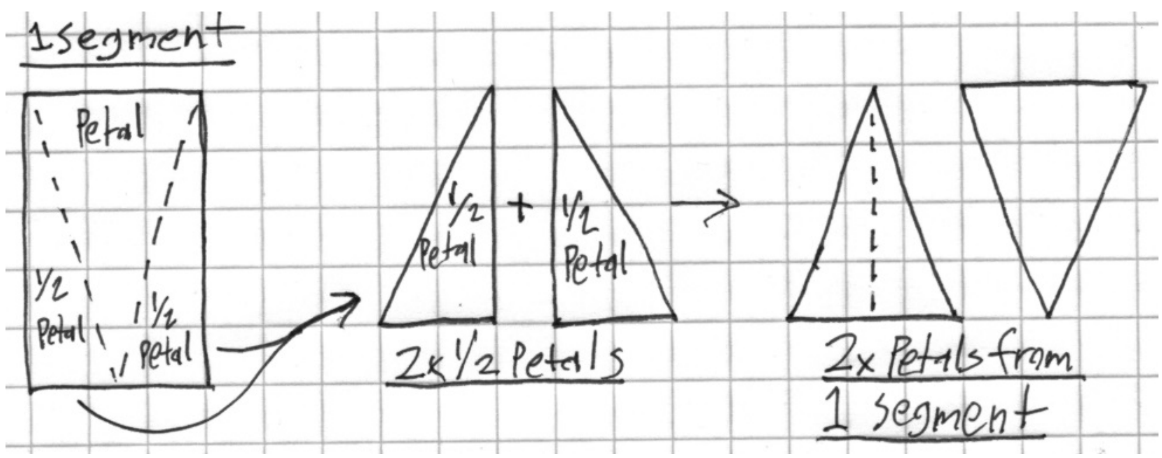

Figure 3: Two petals from one material segment.

Petals must not deform when moving from one stress position to another while adjusting the dish and they must withstand environmental factors. One of the most significant environmental factors is the load force of wind on a parabolic dish, to mitigate this, wire mesh is used to allow the wind to pass through the dish. There are many choices for metal mesh, the two most popular are chicken wire and steel hardware cloth. Chicken wire is thin enough to where it will deform, strategically placed layers of steel hardware cloth mesh is ideal. First number each spoke, then place down a layer of six of the sturdiest petals on all of the odd spokes, finally place the remaining six petals on all of the even spokes. Ensure that the petals are a size where they slightly overlap. When the petals are strained the odd numbered petals will structurally support the parabolic dish shape since they will be supporting the even numbered petals. It maybe useful to have the odd numbered petals stress wires be slightly longer than the even numbered petals, so they move after the even petals move. Note that the maximum mesh size is 1/12 of the observed wavelength. If a mesh with a wider hole spacing is used the electromagnetic radiation, just like the wind, will simply pass through the mesh. Each petal has a handle and each handle serves three purposes:

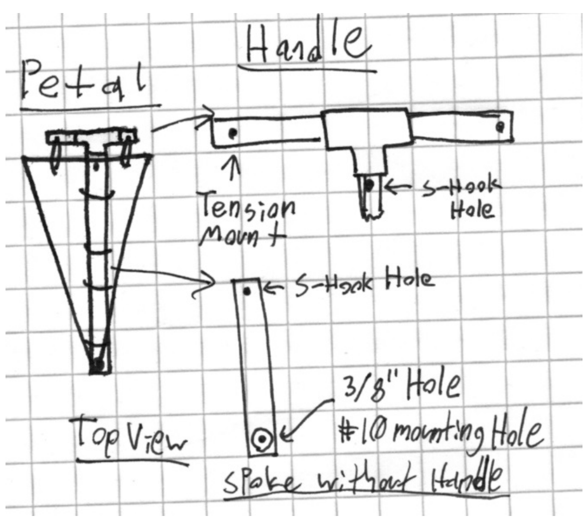

Figure 4: Handle and petal configuration.

1. To add tension to the end of the petal to keep them from wanting to deform.

2. To have a point where people can hold onto when moving the antenna.

3. To independently swivel each petal to the side when turned and turned back so that the center pole can be accessed so the DART can be adjusted in the field.

2.2.4 Material Consideration

Use metals and UV resistant plastics as much as possible. Nylon is an excellent option for the stress wire and plastic zip-ties make quick work of securing the petals and their handles and spokes. However, while baling wire would take significantly more time than a zip-tie it has superior durability. I would recommend constructing the dish with zip-ties and as the dish needs maintained and zip-ties are replaced, replace the zip-ties with baling wire. Baling wire is a soft flexible metal wire that can be tied and maintain its place under stressful loads. Avoid the use of wood and if wood is used ensure that it is painted as to protect it from the elements.

2.3 Wave Guide Design

The are many kinds of waveguides, all of which are made of a material that can reflect electromagnetic radiation from some input and channel it to some output. In this case, the input is radiation to be captured is at the focus of a parabolic dish and collected by an internal probe for data processing. DART style radio telescopes utilize circular waveguides. Circular waveguides are one of the simplest waveguides to construct taking on the shape of a coffee can [7]. A piece of rectangular sheet metal can be formed into a cylinder and then capped with a circle on one end leaving the other end open. While this seems simple it can be quite complex to execute this by hand with limited tools. Construction methods such as riveting and tack-welding can be used to bind the metal pieces together. The key attributes for a circular waveguide are waveguide length, probe height, and probe distance from the back wall [7]. Circular waveguides operate in the TM01 and TE11 modes [2]. These modes of operation represent the interference patterns of the E and H planes. Electromagnetic radiation comes in two parts, the E plane serves as the electric field vector and the H plane serves as the magnetic field vector. Electromagnetic energy is constructed from both the E and H planes which are 90 degrees in phase of each other. The guide wavelength is dependent on the observed wavelength since the geometry of the waveguide must be optimized to minimize destructive interference the E and H planes as they are channeled in and read by the probe. In parabolic dish designs, the waveguide can support multiple probes for different frequencies. To do this, construct the waveguide for the largest frequency and place the probes in their respective positions for the lesser frequencies and ensure that TM01 and TE11 modes for all frequencies are being respected. Notice that for circular apertures, hence circular waveguides, the beamwidth formula constant is 70. Some other beamwidth formulas are not designed for circular waveguides and thus, have constants other than 70 [7]. I have seen this referred to as the *k* factor in some online resources.

2.3.1 E and H Planes

E and H plane interference can be described as waves crashing onto the shore. Imagine a beach adjacent to the ocean with a shipping channel that provides boats access to the ocean from a river. From a distance as the waves crash onto the shore they all crash in a straight line parallel to the shore line however, as the water reaches the mouth of the channel it collides with the walls of the channel. This channel is shaped like a "V" and funnels in the water from a wider point to a more narrow point. As this water travels into the channel the waves begin to interfere with each other causing both constructive and destructive interference, causing some waves to grow while others are eliminated.

Note that E and H plane interference is three dimensional. Circular waveguides behave like high-pass filters and their ideal behavior is where TE11 is asymptotically less than and TM01 is infinitely greater than the observed wavelength. DISHCALC provides multiple waveguide options, since practically, an approximate aperture radius maybe more convenient to construct than the actual ideal aperture. In constructing a waveguide the aperture radius must be fall within bounds, $a_{TE11} < a < a_{TM01}$, where *a* is the aperture radius [2]. All referenced formulas are in the appendix *Equation* section. A good rule of thumb suggests that an ideal aperture radius exists at 76% of the observed wavelength while acceptable limits are within 66%-76% of the observed wavelength for circular waveguides [7]. TE11 cut off wavelength must be computed before computing the guide wavelength.

2.3.2 Probe

The probe is strategically sized and placed to capture and convert the electromagnetic energy into voltage that can later be processed into data by a computer. Most likely, the probe will have to be custom built. Probes are constructed from electrically conductive material and are connected to coax cables, ideally SMA style, to transmit this voltage down the signal chain. The place and size of a probe depends on the guide wavelength and wavelength of the observed frequency. SMA coaxial cable is chosen due to its affordability, wide availability, and good quality coaxial cables have built in shielding to ensure a purer signal. Input impedance from the probe, cable, and device input must match to prevent signal degradation, a bauln or impedance matching circuit may be required. Once constructed, if the environment is too noisy, an optional disc like choke can be placed on the waveguide with a diameter up to 2λ to reduce noise [10] [7].

2.3.3 Subtended Angle Considerations

The subtended angle of the waveguide is more of an art rather than an exact science. The use of computer-generated models is almost necessary for this application. The waveguide's subtended angle is important. The more adventurous user may opt to add a conical flange at the end of the cylindrical waveguide to shape the waveguide's lobes into a more optimal shape. If the subtended angle into the waveguide is too small then the dish will only be partially illuminated and potential signal and gain will be lost. If the subtended angle for the waveguide is too large noise sources behind the dish may leak into the data recordings. An ideal subtended angle would match that of the parabolic dish however, in practice, it is best to have the subtended angle be slightly less than the subtended angle of the parabolic dish to prevent noise from leaking into the signal path and corrupting the data recordings.

2.4 DISHCALC

DISHCALC is a FORTRAN program used to quicken the creation process by computing design considerations. DISHCALC provides the user a layer of abstraction from the deeper knowledge required to construct a DART. While it is useful to know basic mechanical and electrical engineering principles, waveguide and parabolic dish design can become tedious and users may not have a strong background in these topics. DISHCALC is written in Intel FORTRAN for Microsoft Windows. DISHCALC has not been tested on any other system or compiler however, the program is designed to be cross-compiler and cross-system friendly. DISHCALC is written in free form FORTRAN, which does not have a column limit for source code, some FORTRAN compilers may need to be adjusted to account for this. DISHCALC uses a terminal to interface with the user. In the future, a scripting language such as Python can be used to process DISHCALC's output as well as provide users a graphical user interface to interact with DISHCALC. DISHCALC expects an input of five floating point numbers that are piped or typed into the program. This list of input variables are provided in table 1.

Table 1: DISHCALC input variables.

Variable	Purpose	Units	Interval
λ	Observed Wavelength	Meters	$(0, \infty)$
b	Beamwidth	Degrees	$(0, 360)$
g	Gain	Decibels	$(0, \infty)$
s	Selection	Unitless	$[0, 1]$
e	Aperture Efficiency	Unitless	$[0, 1]$

The user will enter their wavelength to observe, aperture efficiency (typically 50%-60%) [7], selector value, and most importantly an ideal beamwidth and gain for their antenna. Since not all antenna configurations are supported, the selector variable is used to bias the dish diameter to a value that can be actualized. While this would not retain the original configuration parameters, the user will be able to set which parameter they favor more. Selector variable numbers closer to one favor gain while numbers near zero favor beamwidth, as seen in equation 2.

$$DishDiameter = s\frac{\sqrt{\frac{10^{\frac{g}{10}}\lambda^2}{e}}}{\pi} + (1-s)\frac{70\lambda}{b} \tag{2}$$

After the dish diameter is determined, other constants are computed, and two other algorithms perform computations for petal sizes and various dish designs as a function of the f/d ratio. Finally, waveguide attributes are computed independently from dish diameter, since they are only dependent on wavelength. All DISHCALC output is categorized in table 2. Note that FORTRAN internally stores matrices in column-major format, the table below provides dimensions as the typical row-major order. The *Data Matrix* column provides each matrix as they are printed out to the terminal and all matrix elements in DISHCALC are FORTRAN real types (floating point). All formulas utilized for DISCALC and antenna design can be found both in the source code, *Equations* section and journal entries found in the appendix.

Table 2: DISHCALC output data.

Data Matrix	Dimension	Column 1	Column 2	Column 3	Column 4	Column 5
User Conformation Data	1×5	Observed Wavelength	Desired Gain	Desired Beamwidth	Selector	Aperture Efficiency
f/d Designs	100×4	f/d	Subtended Angle	Dish Depth	Focal Length	N/A
Petals	31×4	Central Angle	Area	Arc Length	Total Area	N/A
Waveguide	10×5	Aperture Radius	TE11 Cut Off Wavelength	Minimum Guide Wavelength	Probe to Back Wall Distance	Probe Height
Dish Constants	1×5	Dish Diameter	Area	Gain	Beamwidth	Maximum Mesh Size

DISHCALC is pre-programmed to account for a 12 segment dish constructed using circular segments. The output data can be piped into a text file which a script or spreadsheet software can be used to extract the relevant data. DISHCALC will always write to and read from standard I/O, therefore, data can be piped into DISHCALC (recommended) or typed if the user is unfamiliar with terminal commands.

3. RESULTS

Since the antenna has yet to collect data, construction techniques, parts, and design decisions will be described in best possible detail. All of the parts for the antenna were purchased from Lowe's or Home Depot in Waco, Texas in March 2023. For further information, the original journal pages 21-30 are included in the appendix for waveguide and petal design. Table 4 provides a part and cost listing for the Texas A&M University DART. Without tax the DART costs \$211.73, and with tax (8.25%) costs \$229.20 in total, the antenna budget overshot the \$100 goal by 129.2%. While the operational specifications are still unknown, the theoretical specifications are provided in table 3. The dish efficiency is assumed to be 50% the same as lower-end of amateur dishes. The diameter of the dish is known and is $(40" - 3") + (40" - 3") + 12" = 86"$ or 2.1844 meters since each spoke is 40", the base is a 1ft square, and 3" of each spoke overlaps the base. The diameter must be recorded in high precision since it is vital to computing other dish attributes which maybe sensitive to changes in diameter. Notice that the numbers in table 3 maybe slightly different than those in the journal, the reason being is the use of a higher precision diameter than what the journal in the appendix uses. The tool count is very low, this DART was built using:

1. Cordless Electric Drill
   (a) Drill bit for #10 machine screw – Size depends on desired fit: 3/16" to 13/64".
   (b) Drill bit for 1/4" machine screw – Size depends on desired fit: 1/4" to 17/64".
   (c) 3/8" Drill bit for PVC spoke inlet hole.
   (d) 1/8" Drill bit for waveguide pop rivets.
   (e) 2-1/8" hole bit for center pole and base.
2. Pop riveter for 1/8" rivets – Used for binding the tin for the waveguide.
3. Fence Wire Cutters – Something that can cut at least 19 gauge wire.
4. Hammer – For beating the steel roll into shape for the waveguide.

5. Tin snips – Used to cut the tin for the waveguide.
6. Hacksaw with fine teeth for cutting PVC.
7. 7/16" nut driver and wrench for 1/4" nuts.
8. 5/16" nut driver and wrench for #10 nuts.
9. Screwdriver for #10 screw.
10. Speed square.
11. Tape measure.
12. Yard stick or ruler.
13. Protractor.

Table 3: Texas A&M University DART Specifications.

Parameter	Value
Diameter (m)	2.1844
f/d Ratio	0.5
Observed Wavelength (m)	0.21
Beamwidth (deg)	6.7295
Gain (dB)	27.2750
Focal Length (m)	1.0922
Dish Depth (m)	0.2731
Subtended Angle (deg)	53.1301
Guide Wavelength (m)	0.2273
Guide Aperture Radius (m)	0.07

Table 4: Cost of parts from Waco, Texas Lowe's as of 1 April 2023.

Part	Price	Count	Total Cost	Antenna Section	Comment
24-Pack #10 Zinc-Plated Flat Washer	$1.38	2	$2.76	Base	36x Used on back end of bolt for spoke mounting
1/2" x 2ft Birch Sanded Plywood	$12.98	1	$12.98	Base and Collar	Bolt, DO NOT screw into plywood
1-1/2" x 5ft Schedule 40 PVC Pipe	$10.86	1	$10.86	Center Pole	OD should be 1.9" by Schedule 40 specifications
1-1/2" Plastic PVC Pipe Coupling	$5.21	4	$20.84	Center Pole	2x for collar and 2x for waveguide mounting
1/2" x 4" x 2ft Square Edge Poplar Board	$4.98	1	$4.98	Center Pole Support	Must be solid wood for screws
4-Pack 2" x 5/8" x 2" Zinc-Plated Steel Corner Brace w/ screws	$3.98	1	$3.98	Center Pole Support	2x per poplar support to base
3-1/2" Coarse Thread Hex Bolt	$0.38	2	$0.76	Center Pole Support	Used to mount the center pole and base
1/4" Nut	$0.10	2	$0.20	Center Pole Support	Used to mount the nut to the center pole
25-Pack 1/4" Zinc-Plated Flat Washer	$3.28	1	$3.28	Collar and Center Pole Support	12x for collar and to fit for center pole support
5/16" x 3-1/4" Black Phosphate Coarse Thread eye Bolt	$1.78	12	$21.36	Collar	Standard steel eyebolts can be used
25ft x 2ft Steel Hardware Cloth Fencing Mesh 1/2" x 1/2"	$37.48	1	$37.48	Petals	Used to create the petals
100-Pack 8" Nylon Zip Ties	$9.98	1	$9.98	Petals	UV resistant (use baling wire)
1/2" x 10ft Schedule 40 PVC Pipe	$4.71	5	$23.55	Spokes	12x40" spokes + 24x5" handles = 50ft total
1/2" Schedule 40 PVC Tee	$0.79	12	$9.48	Spokes	Mounted at end of each spoke for handles
8-Pack #10-24 1" Phillips/Slotted Machine Screws w/ nuts	$1.38	5	$6.90	Spokes	36x Used for spoke mounting
4-Pack 1/2" Zinc-Plated Steel Two-hole strap Conduit Fitting	$1.20	3	$3.60	Spokes	Used to mount spokes
3-Pack 1-1/2" S-Hooks	$1.48	4	$5.92	Spokes	Used as tie down point for stress wires
1/8" x 48ft Braided Nylon Rope	$6.58	1	$6.58	Spokes	Stress wires: rot, UV, abrasion, and chemical resistant
JB Weld WaterWeld PVC Putty	$7.48	1	$7.48	Spokes and Center Pole	Used to repair damage in PVC
10" x 10ft Steel Roll Flashing	$12.28	1	$12.28	Waveguide	Used to construct waveguide material
Package of 1/8" Steel Rivets	$6.48	1	$6.48	Waveguide	Used to rivet together waveguide

3.1 Antenna Construction

The DART constructed for Texas A&M University is designed for hydrogen line observations. Much of the first DART design was determined by intuition, knowing that everything can be easily adjusted, if issues arise. PVC can be purchased and welded onto each other by the use of PVC glue, or attached together using PVC couplings and other binding methods. Initially, a beamwidth of 10 degrees and a gain above 20dB was selected since this instrument will be used for scientific outreach and educational purposes. This was deemed worthy after confirming with Dr. Spilker and comparing to examples on the internet.

The base of the parabolic dish is a 1ft square and each of the spokes is 40" in length braced to the base by 3". Thus the radius of the dish is 43" resulting in a diameter of 86" or 2.1844 meters. The value of 43" is computed from 6" from half the distance of the base plus 40" of spoke minus 3" for bracing the spoke onto the base. The center pole is 5ft in length with a 1-1/2" inner diameter and 1.9" outer diameter. About 3ft of the center pole is usable for waveguide adjustments while the other 2ft is behind the base to serve as a future mounting point to some mobile mount. The antenna is the only system to be fully constructed at this time and has yet to be tested.

3.1.1 Material and Technical Wisdom

Below is a listing of material and technical considerations when fabricating the DART.

1. **DO NOT** screw anything into plywood and only bolt to plywood. Plywood is made of layers of thin sheets of wood glued together, the forces from a screw would tear these apart overtime.

2. **AVOID** pressing in creases into the waveguide's sheet metal. It is incredibly difficult to remove creases from sheet metal.

3. Avoid the use of wood as much as possible and if it is used paint it. Wood will rot if exposed to the elements.

4. Know that it is better to have extra material that can be cut off later than have too little material in the initial cut.

5. When drawing lines on PVC pipe or cylindrical material, find something with a 90 degree edge such as a concrete step or plywood edge to hold it.
6. Keep the inside of the waveguide as smooth as possible, the way the rivets hold it together matters.
7. This DART was constructed in a little over a week in total, including design, by one person. The creation of a DART with more than one person would significantly decrease production time.
8. Anything handmade will have deformities, plan for this.
9. Once the petals are placed they may need to have a small hole cut in them so that the S-Hooks can be fit into the spoke.
10. When cutting the steel roll or hardware cloth keep in mind that when cutting segments form these rolls the segment edges will be sharp and have tendency to roll up themselves. I highly recommend wearing protective gloves to protect your hands from the sharp cuts.
11. No screw or bolt should have contact with wood. A washer should be placed between any point that the screw or bolt would otherwise contact wood.

3.1.2 PVC

The plastic PVC pipe couplings will not initially fit onto the center pole. Since each coupling has two sets of hose clamps, first remove the hose clamps. The couplings should be somewhat rubbery and soft, use tin snips to cut the couplings in half. Finally, the couplings will fit onto the center pole, place the hose clamps back onto them and tighten. Each device, except for the base, must be secured using a pair of PVC pipe couplings to prevent the devices from sliding. If the hole for the device is too big and the device has depth, take the wooden collar for instance, rubber window stripping can be used to fill in the gap. I do not recommend using foam weather stripping or weather stripping applied by adhesive, these will deteriorate quickly. The weather stripping should be secured by strategically placed tacks in the device's inner diameter. When purchasing PVC pipe keep in mind the outside diameter and inside diameter sizes. My experience with 1/2" x 40" PVC pipe showed that an 0.5 is an ideal f/d ratio due to the PVC pipe flexibility characteristics. Use JB Weld WaterWeld to repair unwanted holes and other damage on PVC pipes. Schedule 40 PVC is used since it can be drilled, has standard sizes and specifications, and is structurally sound. Smaller segments of PVC do not bend as well as longer segments of PVC. Only glue PVC if necessary since gluing PVC together forms a permanent bond. To extend the length of smaller PVC segments additional PVC segments may be glued to them.

3.1.3 Drawing Circles

Drawing large and small circles can be challenging without the correct tools. I used a piece of thin cardboard and nailed on end to the center of the circle I wanted to draw then created a hole at the other end of the cardboard strip for a hole for a pen. The first nail secured the cardboard strip to the center and any lateral force applied to the pen will begin drawing the circle. To find the center of the circle, first draw a circumscribed squared. A circumscribed square has the circle inside of it. Then find the center of the square by drawing two lines that form a perpendicular intersection in the middle, I drew two lines from the midpoint of two adjacent sides. Finally, the center of the circle will also be the center of the square. These steps are shown in the *Collar* construction subsection.

3.2 Dish Construction

The DART design relies on the stressed parabolic dish structure. As stated in *Methods*, the components of a DART are as follows: support pole, base, stress wires, spokes, waveguide, collar, and petals. The base and center pole are fundamental to the structure of the DART. The spokes are structural support for the petals and when under stress a parabolic dish is formed. The geometry of this stressed parabolic dish is modeled after a flower.

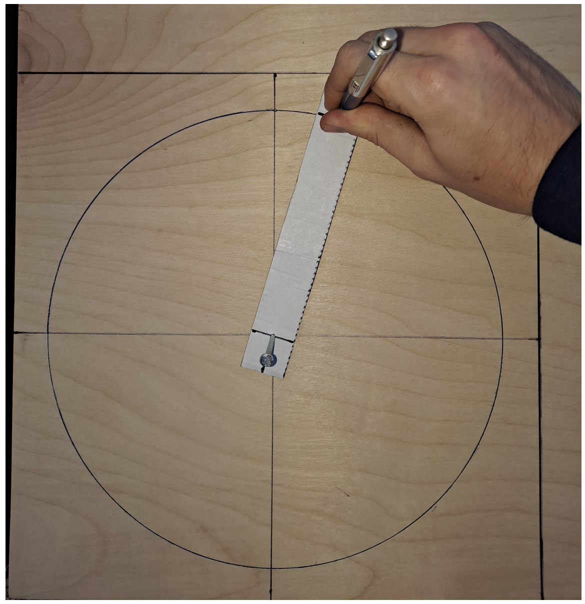

Figure 5: Drawing a circle using cardboard.

3.2.1 *Base*

The base supports the support pole and spokes. It is constructed from a 1ft plank of 1/2" plywood and two 8" tall wood boards 3" in length and 1/2" wide. The plywood serves as a mount for all of the required hardware. There is a 2-1/8" hole in the middle to allow the support pole to slide through the base. On one side of the plywood the two 8 inch boards have two holes drilled out 3" apart and are placed on either side of the center hole and they serve as a mount of the support pole. The plywood also has 12 mounting points for all 12 spokes. Each mounting point has a two holes for the 1/2" brace and one hole to mount the PVC directly to the base. It is important to know that plywood does not take screws due to its construction. Plywood is made from layered pieces of wood laminate which is then held together by glue and cannot withstand vertical strains, since vertical strains will cause the plywood to tear apart and delaminate. The only method to mount to plywood is machined screws, nuts, and washers. #10 screws, washers, and nuts are used to mount material to the base.

Figure 6: Aligned spoke braces and drilled mounting holes

3.2.2 Center Pole and Center Pole Supports

The center pole has an inner diameter of 1-1/2", an outer diameter of 1.9" per Schedule 40 specifications, and a length of 5ft. The mounting collar, waveguide, coaxial cable, stress wires, spokes and petals are dependent on it being sturdy and secure. The support pole must be able to support itself and the structures straining on it. While the collar and waveguide are mounted by plastic PVC couplings, two holes for 1/4" hex bolts are drilled into the center pole, and its supports, to anchor the center pole to the base. The fit must be as tight as possible to ensure that the center pole has no play. Extra 1/4" washers are placed in between the center pole supports and center pole to ensure a tight fit and prevent any play or slippage.

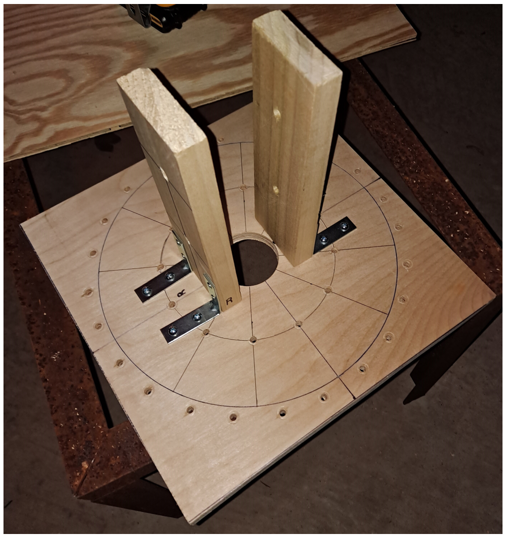


Figure 7: Base with center pole support.

3.2.3 Collar

The collar is a 5" x 1/2" disc of plywood with a 2-1/8" hole in the center so that it may freely slide along the center pole. The collar is an anchor for the stress wires and must not pull apart while holding the stress of 12 spokes and petals. The position of the collar determines the length of the stress wires and their angle of termination with the collar. The collar is held into position by two plastic PVC couplings. While it remains untested, the current collar design has 12 steel eyebolts. It is unknown how the metal eyebolts will impact the signal performance, I theorize it will be negligible since the collar will ideally be placed below the focus. If issues arise, an alternative may be to get rid of the collar entirely and use one PVC coupling. This coupling will anchor extra lengths of stress wire. Metal eyebolts were used since I could not find plastic ones that were sufficient.

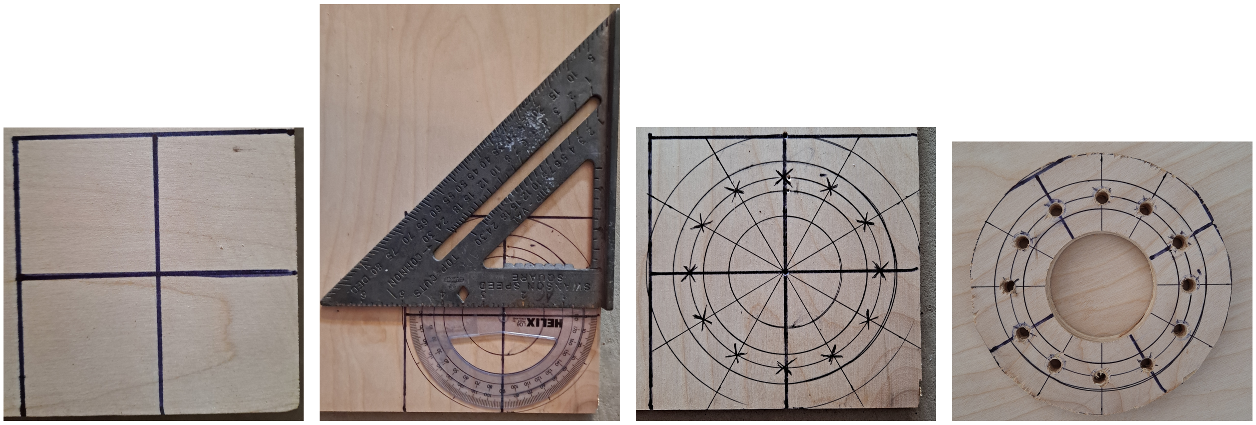

Figure 8: Collar creation.

3.2.4 Stress wires

The stress wires connect from the petals by S-Hooks to the collar's eyebolts and apply a force that shapes the petals into a parabola. The stress wire must be made of a material that can withstand high strain and not grow or become less elastic under long term strain. It must support the resistance force of the petal being pulled from rest and it must not rot. I have opted to use nylon chord since it was affordable and has a high pound force. Nylon can be melted together with a lighter so that knots can remain permanent. A light gauge steel wire, like baling wire, may be twisted together to form a durable bond. A potential issue could be that since steel is magnetic it may impact signal quality however, since the wire's diameter is s small, the impact will most likely be negligible.

3.2.5 Spokes

The spokes are made of 1/2" diameter schedule 40 PVC pipe and are mounted to the base at three points. Each spoke is mounted to the base by one electrical conduit clamp and one machine screw directly through one of the ends of the PVC. The other end of the spoke also has a hole for the S-Hooks. The electrical conduit clamp is a hemispherical brace with two screw holes and are positioned closest to the edge of the base.v A singular screw hole is positioned closest to the center pole hole on the base. I determined that for 40" of 1/2" PVC, 3" of pipe should be used to mount the spoke to the base. The singular screw hole was placed a little before the 3" mark from the edge and two more screw holes were placed a little before the edge of the base for the brace. It is important not to drill too close to the edge on either the base or PVC pipe since this could cause the material to split. The S-Hook and singular screw hole must be placed on the same line. A good rule of thumb is that the holes are drilled approximately 1" away from either end of the PVC pipe to prevent splitting of the PVC pipe, for wood this can be up to 3/4". The singular screw side should have a tight fitting hole drilled through both sides of the pipe for #10 screws and a singlular hole drilled on the other end for the S-Hook. The side with the S-Hook hole will be considered the top of the spoke. On the same side as the S-Hook hole, the hole that would be used to mount the spoke to the base, and only that hole, will be drilled to 3/8". This is to ensure that the machine screw for the singular screw hole can fit through and connect through to the bottom of the pipe to mount the spoke. If damage occurs JB Weld WaterWeld can be used to patch and repair the PVC pipe and can be drilled and sanded once dry. The spokes must support the petals and maintain a parabolic curve for extended periods of time. The strain caused by the stress wire will bend the spoke and cause a curve.

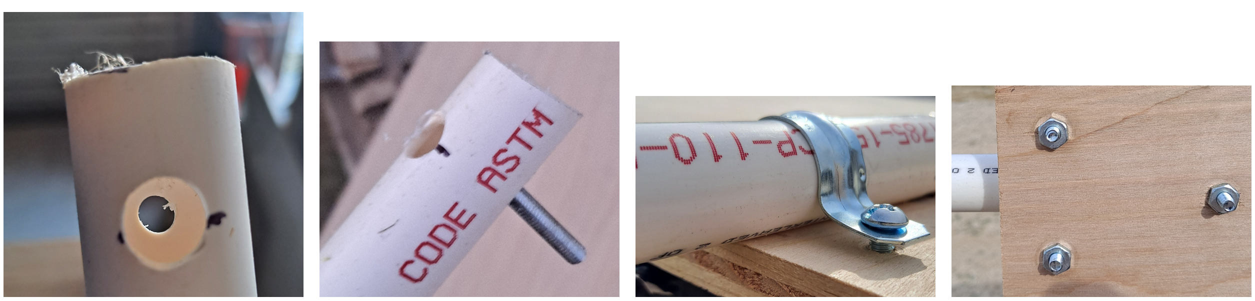

Figure 9: Spoke mounting.

3.2.6 *Petals*

The petals are made of a lightweight material that can reflect electromagnetic radiation, be bent, and can hold its original shape when at rest. I have opted to use 1/2" hardware cloth mesh. Using wire mesh has advantages in being light weight, easy to form, and can resist strong wind since the wind will pass through, unlike in a solid dish. One caveat is that in using a mesh, the holes must be at maximum the size of 1/12 of the observed wavelength. The mesh is shaped into 12 sectors which slightly overlap each other at rest as explained in *Methods*. It maybe advantageous to cut the nylon cord for the odd and even petals at different lengths, so that the even number petals are lifted first followed by the odd numbered support petals. In constructing the petals a segment of the metal roll must be cut to size, keep in mind once the final cut is performed the segment and the main roll will curl. For this DART, triangular petal segments were used instead of circular sectors since they were easier to construct. I made a simple device using two weights, three light gauge nails, nylon cord, and spare plywood to serve as a trace for the petals as seen in figure 10. I then cut a triangle from the mesh segment. I used these procedures to design the petals (pulled from appendix journal page 22):

1. Determine the base width – In this case it was the width of the roll 2ft.
2. Determine the height – I used 1" less than the length of the spoke, however I would recommend 1.5" to 2" less than spoke length.
3. Determine the central angle – I set this to 34 degrees to ensure some slight overlap of the petals.
4. Compute all other attributes of the triangle and determine if they are acceptable.

Keep in mind that the center pole must be easily accessible after final construction so adjustments can be made in the field. Since the handle is not glued to the spoke, it can turn freely, since the petal will be tightly bound to the handle, it will also turn with the handle. Turning the petals can be performed when no stress wire is applied and provides a large enough gap for someone to access the center pole. Note that in the handle and petal configuration, the petal is held to

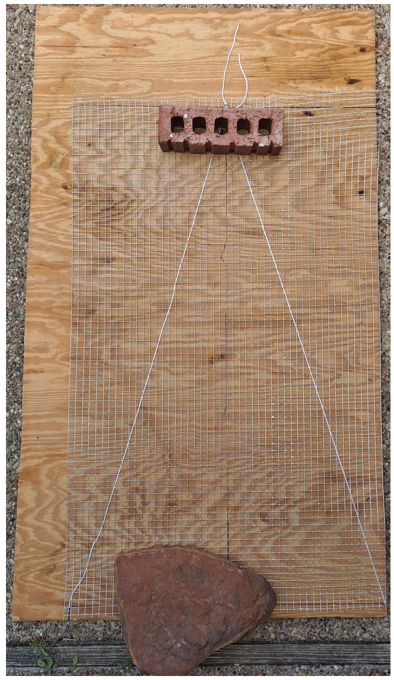

Figure 10: Petal cut out guide.

the spoke and handle by either zip-ties or baling wire, tight enough to keep them in place, but not tight enough to prevent them from moving when the spoke moves. The handles are created from a 1/2" PVC tee and two 5" segments of PVC pipe with holes at either end of the handle for zip-ties or baling wire to apply tension on the petals. The holes drilled into the handles are 1" away from either end and are wide enough to have zip-ties and baling wire pass through them.

Figure 11: Handle close up.

3.3 Waveguide Construction

Tin is used as a common colloquial term, modern day tin is actually steel sheet metal. The sheet metal may have a tendency to roll and not stay flat, weights may need to be placed to ensure a flat strip of sheet metal can be cut. The waveguide will require a circular end cap and a rectangle to be rolled into a cylinder. The end cap and cylinder are combined by riveting or welding and held in place to the center pole by a pair of plastic PVC couplings on both ends of the end cap. Leave extra space on the width of the rectangular segment, I have found only one way to form sheet metal into an actual cylinder requires the ends to be delicately folded into each other. Ensure that the inside of the cylinder is as smooth as possible and to drill holes for the probe. The design procedure I used for constructing the circular waveguide is as follows:

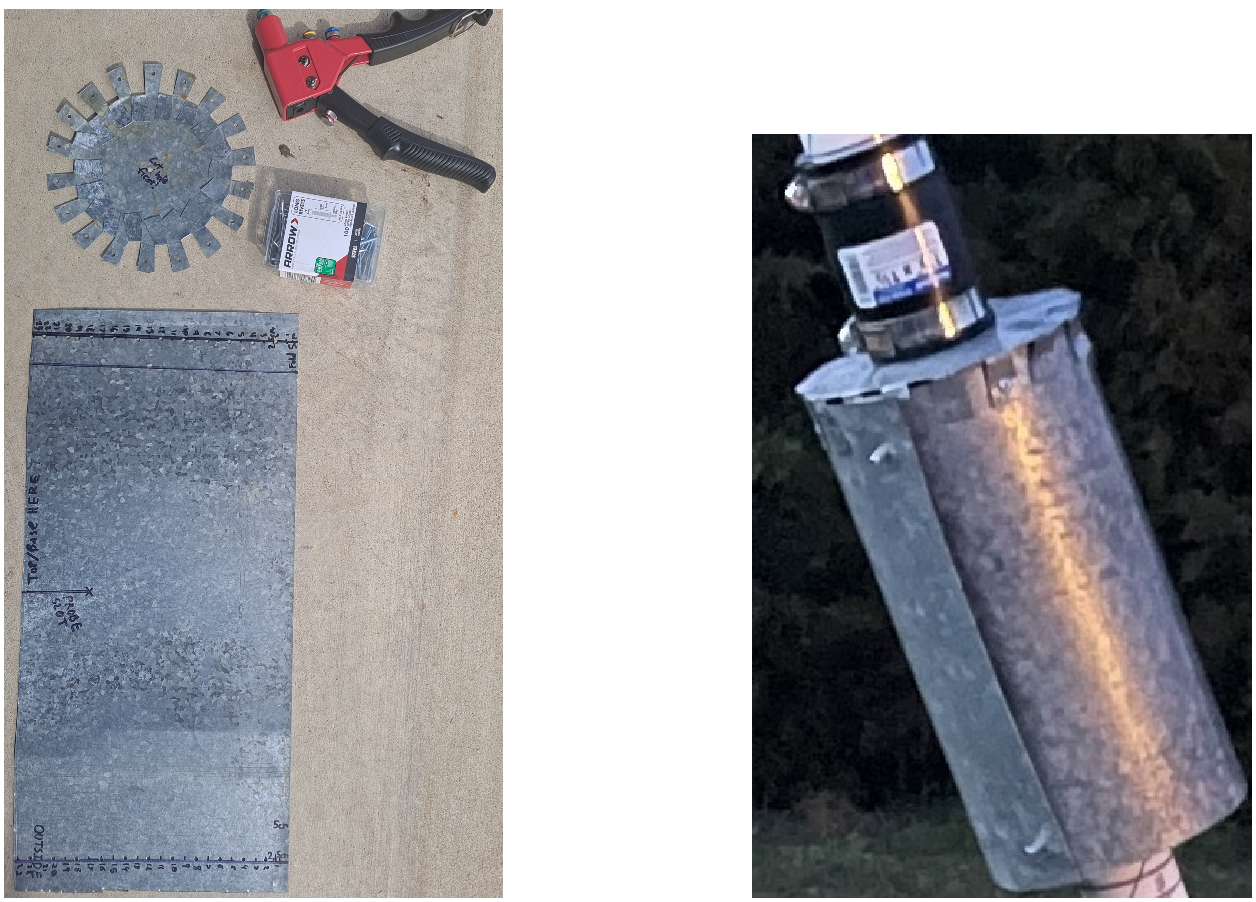

Figure 12: Parts to assemble waveguide and final waveguide.

3.3.1 *Cylinder Creation*

The construction procedure for the cylinder is as follows:

1. Compute the size of the rectangular sheet.
   (a) One side will be at least the length of the circumference of the base – ensure to leave around 1"-1-1/2" of extra material on each side. This extra material is called the margin.
   (b) The other side will be the length of the guide wavelength.
   (c) In my design for Texas A&M University, I did not include enough margin which shrunk the diameter of the waveguide by 1cm. However, this was still within the boundary for acceptable limits toeing the line with the absolute minimum.
2. Fold one margin 90 degrees.
3. Fold the other margin 90 degrees in the opposite direction of the first margin.
4. Lightly fold the two ends together where one margin overlaps the other margin.
5. Use a hammer and a solid surface to fold the margins over each other.
6. Repeat the previous step of folding the margins into each other until the cylinder strongly holds its shape.
7. Drill 1/8" holes for the 1/8" rivets.
8. Rivet the cylinder together.

3.3.2 *Cylinder Base*

The construction procedure for the base/end cap is as follows:

1. Compute the aperture size which will be the size of the base.
2. Compute the side length for a circumscribed square and add 1" to the final side length.
3. Cut out this square from the sheet metal.

4. Draw the circle using the radius of the aperture.

5. Draw another the circle using the radius of the aperture plus 1".

6. Draw lines that go through both circles every 10 degrees from the center.

7. Drill the center hole 2-1/8".

8. Cut to the outermost circle.

9. Cut each 10 degree line a little before the innermost circle.

10. Drill 1/8" holes for the 1/8" rivets.

11. Fold each tab, alternate between folding a tab completely inwards or removing it and folding a tab 90 degrees.

Finally, rivet the base to the cylinder to form the waveguide. The probe will have to be constructed by hand so ensure to have a soldering iron, solder, and copper wire whose gauge will fit the probe. The probe placement and height equations are provided in the *Equations* section in the appendix. The figure below is the probe installed into the waveguide. The black nylon washer was not included since it was unnecessary to isolate the probe socket from the waveguide's metal construction. The internal probe wire is electrically isolated from the outside of the SMA socket and is made from 2" of unsheathed 18 AWG solid hookup wire.

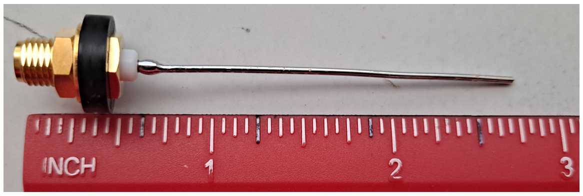

Figure 13: Waveguide probe.

4. CONCLUSION

In studying the cosmos, the optical spectrum is readily accessible by optical telescopes however, visible light is a small piece of the electromagnetic spectrum. Research in DARTs explore the possibility of affordable and simple to construct radio telescopes. While The University of Hawaii and Harvard have designed horn radio telescopes for educational outreach, horn radio telescopes do not scale well. Professional radio telescopes are a costly and use specialized equipment. This DART implementation is designed for educational purposes at Texas A&M University and will perform hydrogen line observations in the Milky Way. DART style radio telescopes are the complete package promising a mobile motor-controlled mount and an easily re-configurable antenna. At this time only the antenna is constructed and will be tested later. DART research is multifaceted, utilizing expertise from material science, astrophysics, mechanical engineering, electrical engineering, and software engineering. Future research is necessary, focusing on implementing the remaining subsystems and improving on the current design, material specifications, construction techniques, and use of computer-generated models.

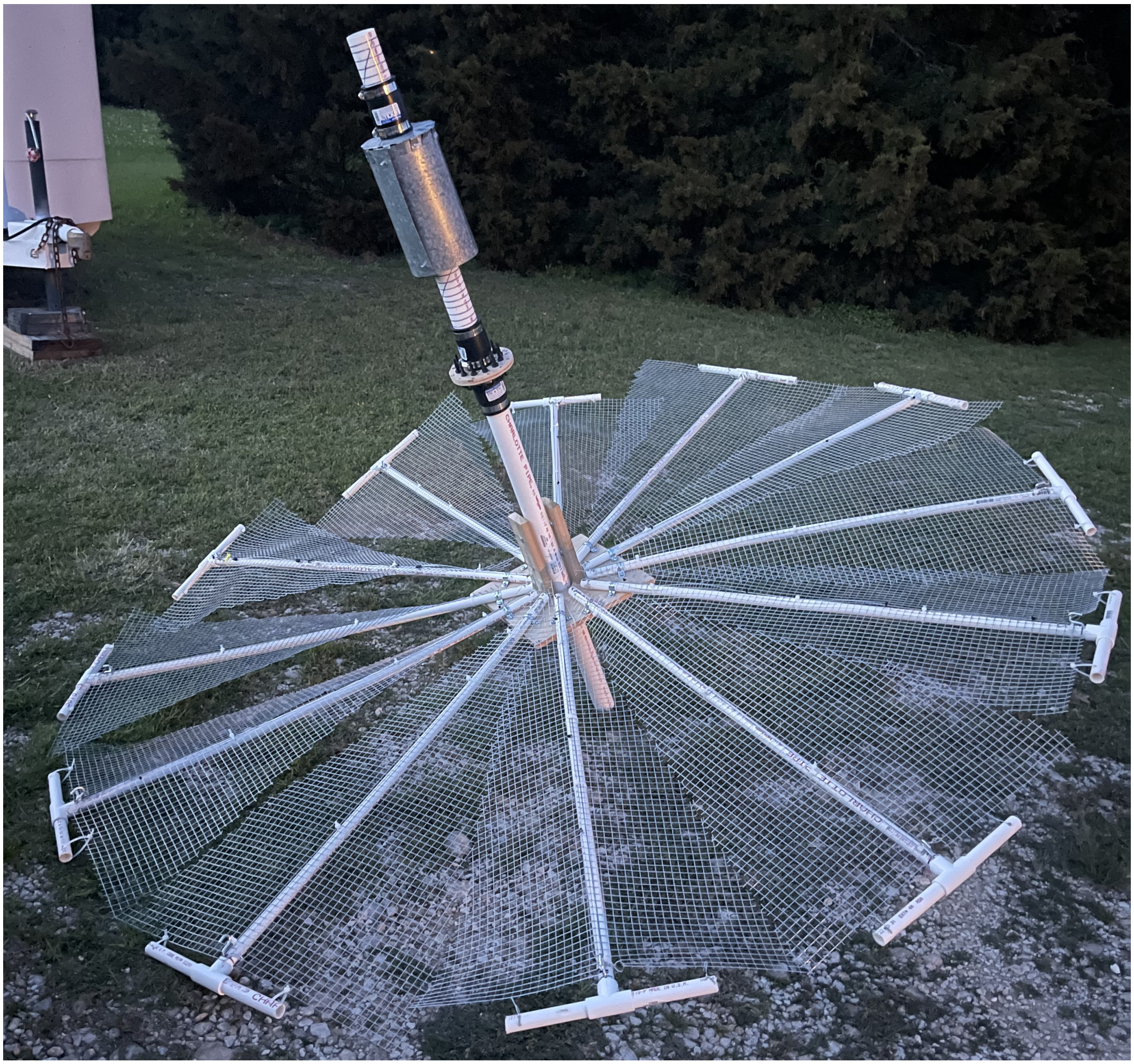

Figure 14: Hi-resolution image of the Texas A&M University DART without stress wires.

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APPENDIX A: EQUATIONS

1. Parabolic Dish Design Equations: 1-7
2. Petal Design Equations: 8-13
   (a) General: 8
   (b) Sector Based: 9-10
   (c) Triangle Based Petal Design Equations: 11-13
3. Waveguide Design Equations: 14-20

Table A.1: Equation variables.

Variable	Description	Units
e	Dish Efficiency (typically 50%-60%)	Unitless
d	Dish Diameter	Meters
λ	Observed Wavelength	Meters
λ_g	Guide Wavelength	Meters
ϕ	f/d Ratio	Unitless
θ	Central Angle	Degrees
h	Triangle Height	Meters
a	Triangle Side	Meters
b	Triangle Base	Meters
c	Triangle Hypotenuse	Meters

$$Y^2 = 4AX \tag{A.1}$$

Equation A.1: Parabola Formula: Y = Radius, X = Dish depth, A = Focal length [9].

$$Gain = 10log_{10}(e(\frac{d\pi}{\lambda})^2) \tag{A.2}$$

Equation A.2: Parabolic Dish Gain (dB).

$$Beamwidth = \frac{70\lambda}{d} \tag{A.3}$$

Equation A.3: Beamwidth (deg) for parabolic dishes with circular waveguides.

$$SubtendedAngle = \frac{360}{\pi}arccot(4\phi) \tag{A.4}$$

Equation A.4: Subtended Angle (deg).

$$FocalLength = d\phi \tag{A.5}$$

Equation A.5: Focal Length (m).

$$Depth = \frac{d}{16\phi} \tag{A.6}$$

Equation A.6: Dish Depth (m).

$$Area = \frac{d^2\pi}{2} \tag{A.7}$$

Equation A.7: Dish Area (m^2).

$$MaximumMeshSize = \frac{\lambda}{12} \tag{A.8}$$

Equation A.8: Maximum Mesh Size (m).

$$Area = \frac{d^2\theta}{2} \tag{A.9}$$

Equation A.9: Area (m^2) of a petal modeled as a sector.

$$Area = \frac{d\theta}{2} \tag{A.10}$$

Equation A.10: Arc Length (m) of a petal modeled as a sector.

$$h = \sqrt{a^2 - \frac{b^2}{4}} \tag{A.11}$$

Equation A.11: Height (m) of a petal modeled as a triangle.

$$Area = \frac{bh}{2} \tag{A.12}$$

Equation A.12: Area (m^2) of a petal modeled as a triangle.

$$c^2 = a^2 + b^2 \tag{A.13}$$

Equation A.13: Pythagorean Theorem (property of right triangles).

$$a_{TE11} = \frac{1.8412\lambda}{2\pi} \tag{A.14}$$

Equation A.14: Waveguide Aperture Radius for given TE11 = $J'_{1,1} = 1.8412$ mode propagation (m).

$$a_{TM01} = \frac{2.4048\lambda}{2\pi} \tag{A.15}$$

Equation A.15: Waveguide Aperture Radius (m) for given TM01 = $J_{0,1} = 2.4048$ mode propagation (m).

$$TE11Cut = \frac{2a_{TM01}\pi}{1.8412} \tag{A.16}$$

Equation A.16: TE11 Cut off frequency (m).

$$\lambda_g = \frac{\lambda}{1 - (\frac{\lambda}{TE11Cut})^2} = 1.08246\lambda \tag{A.17}$$

Equation A.17: Minimum Guide Wavelength (m): final simplification for all circular waveguides is right most linear equation.

$$ProbeWallDistance = \frac{\lambda_g}{4} \tag{A.18}$$

Equation A.18: Probe Distance to Wall (m).

$$ProbeHeight = \frac{\lambda}{4} \tag{A.19}$$

Equation A.19: Probe Height (m).

APPENDIX B: SCHEMATICS

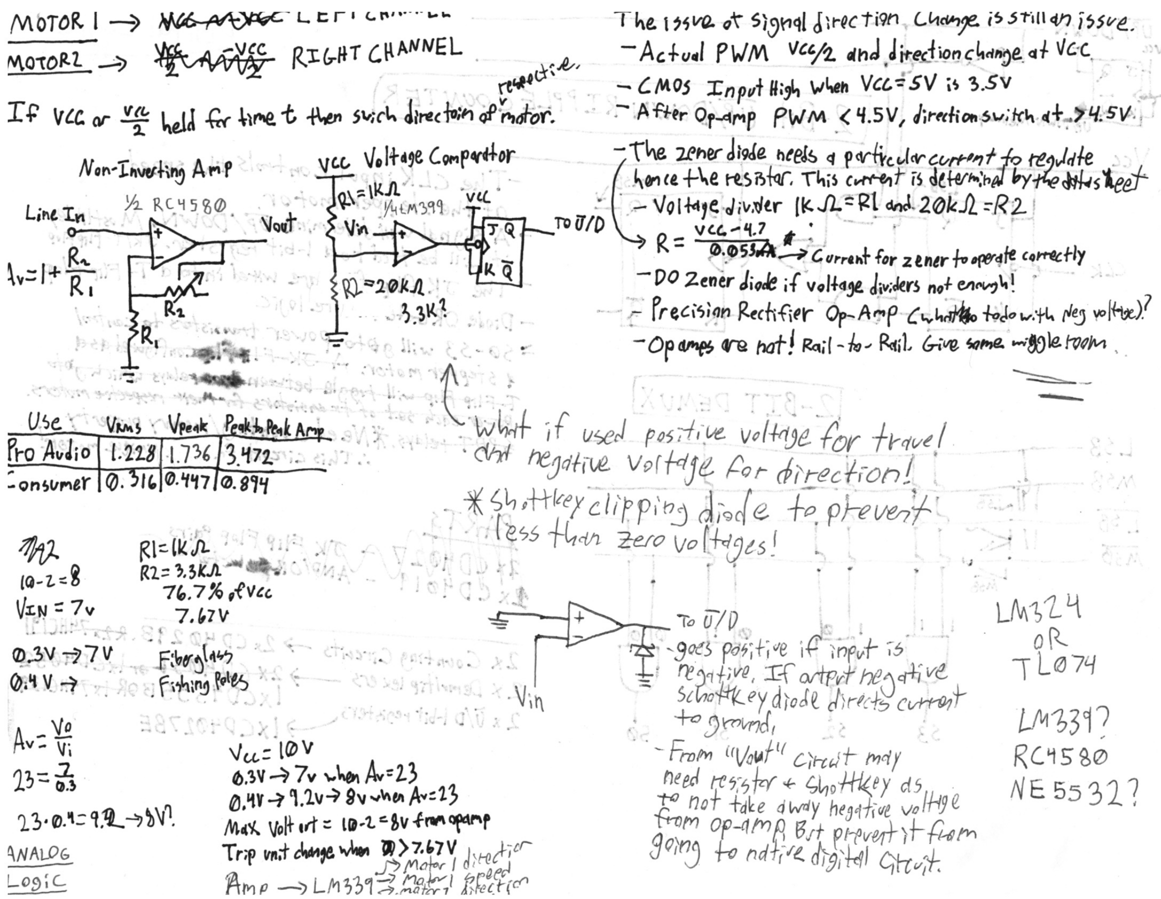


Figure B.1: Analog electric motor control circuitry.

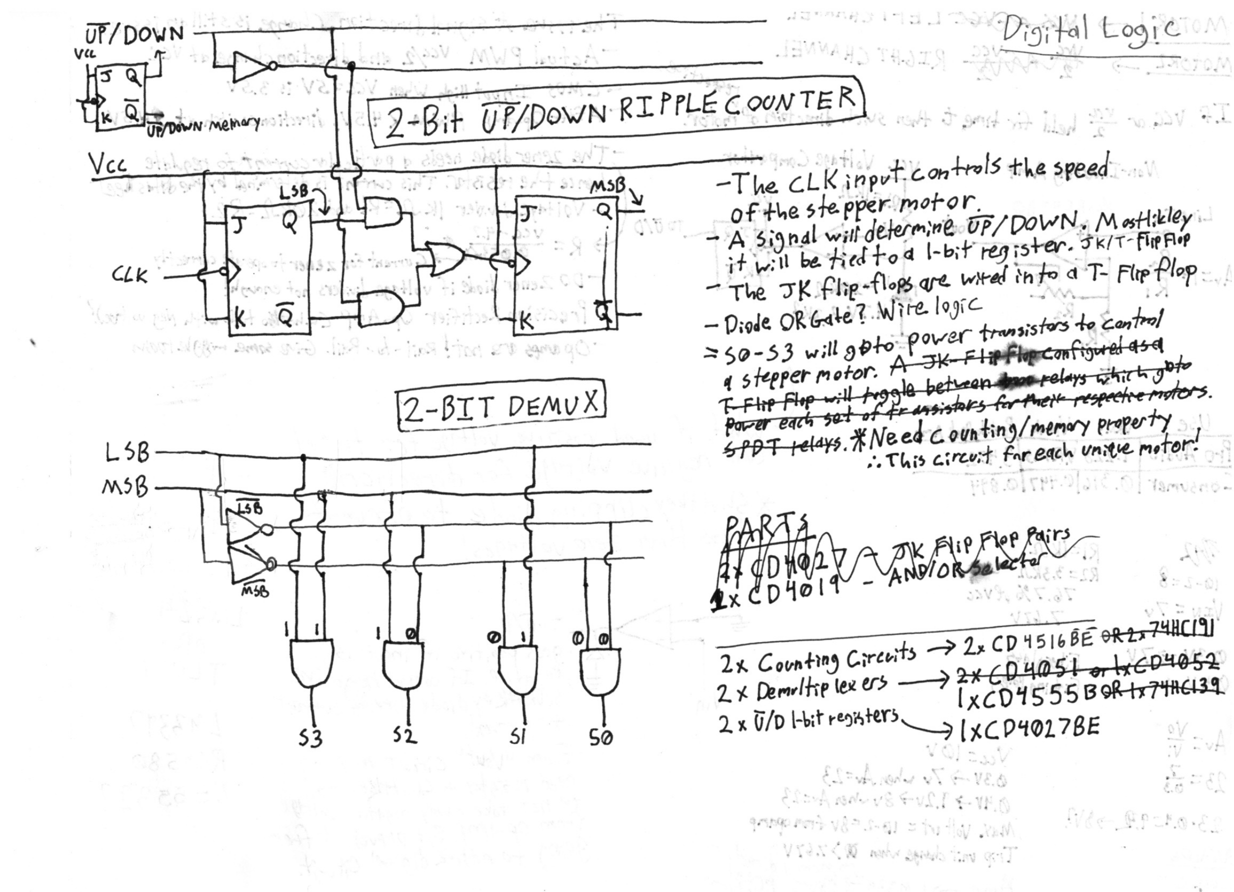
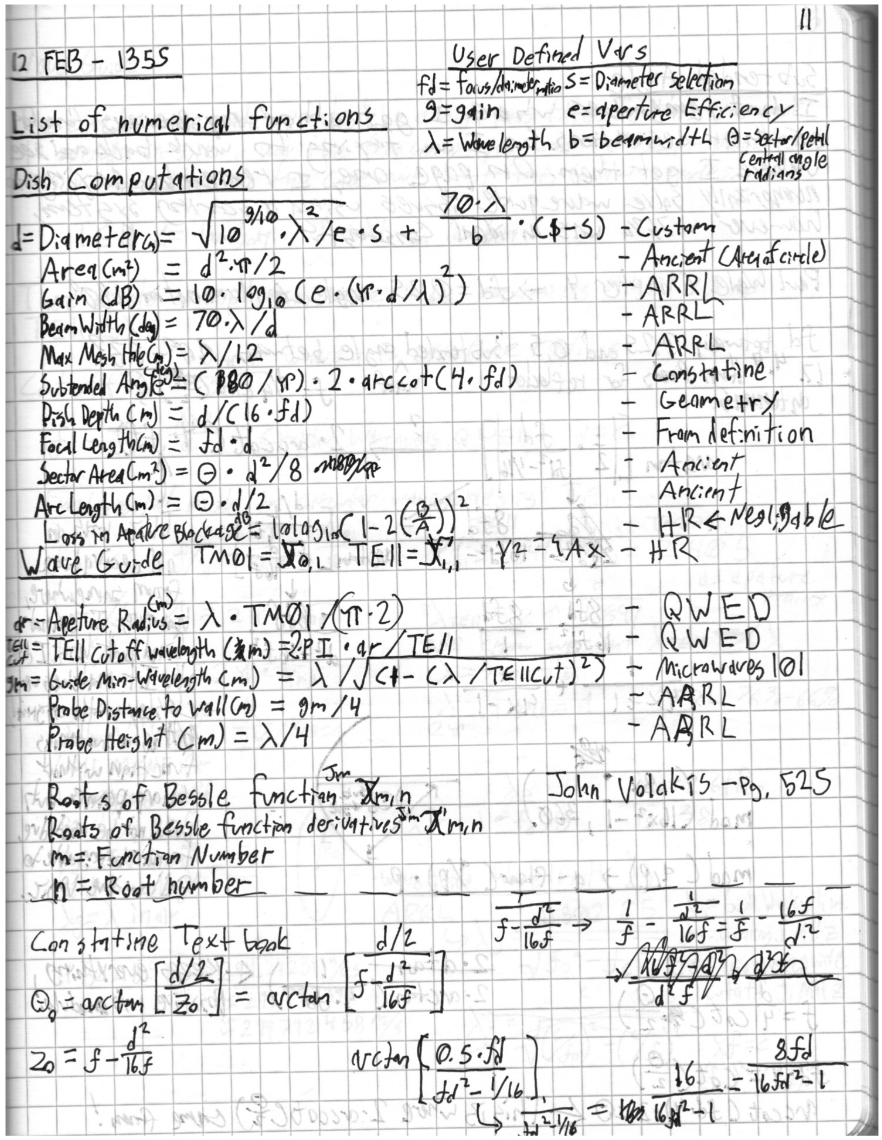


Figure B.2: Digital motor control circuitry.

APPENDIX C: DESIGN JOURNAL ENTRIES



11

12 FEB - 1355

User Defined Vars

fd = focus/diameter ratio, S = Diameter selection

g = gain, e = aperture Efficiency

λ = Wavelength, b = beamwidth, Θ = Sector/petal central angle radians

List of numerical functions

Dish Computations

d = Diameter(m) $= \sqrt{10^{g/10} \cdot \lambda^2 / e} \cdot S + \frac{70 \cdot \lambda}{b} \cdot (1 - S)$ - Custom

Area (m²) $= d^2 \cdot \pi / 2$ - Ancient (Area of circle)

Gain (dB) $= 10 \cdot \log_{10}(e \cdot (\pi \cdot d / \lambda)^2)$ - ARRL

Beam Width (deg) $= 70 \cdot \lambda / d$ - ARRL

Max Mesh Hole (m) $= \lambda / 12$ - ARRL

Subtended Angle (deg) $= (180 / \pi) \cdot 2 \cdot \operatorname{arccot}(4 \cdot fd)$ - Constatine

Dish Depth (m) $= d / (16 \cdot fd)$ - Geometry

Focal Length (m) $= fd \cdot d$ - From definition

Sector Area (m²) $= \Theta \cdot d^2 / 8$ - Ancient

Arc Length (m) $= \Theta \cdot d / 2$ - Ancient

Loss in Aperture Blockage dB $= 10 \log_{10}(1 - 2(\frac{B}{A}))^2$ - HR ← Negligable

Wave Guide $TM01 = \chi_{0,1}$ $TE11 = \chi'_{1,1}$ $Y^2 = 4Ax$ - HR

ar = Apeture Radius (m) $= \lambda \cdot TM01 / (\pi \cdot 2)$ - QWED

TE11 cut = TE11 Cutoff wavelength (m) $= 2 \cdot PI \cdot ar / TE11$ - QWED

gm = Guide Min-Wavelength (m) $= \lambda / \sqrt{(1 - (\lambda / TE11cut)^2)}$ - Microwaves 101

Probe Distance to wall (m) $= gm / 4$ - ARRL

Probe Height (m) $= \lambda / 4$ - ARRL

Roots of Bessle function J_m $\chi_{m,n}$ — John Volakis - Pg. 525

Roots of Bessle function derivatives J'_m $\chi'_{m,n}$

m = Function Number

n = Root number

Constatine Text book

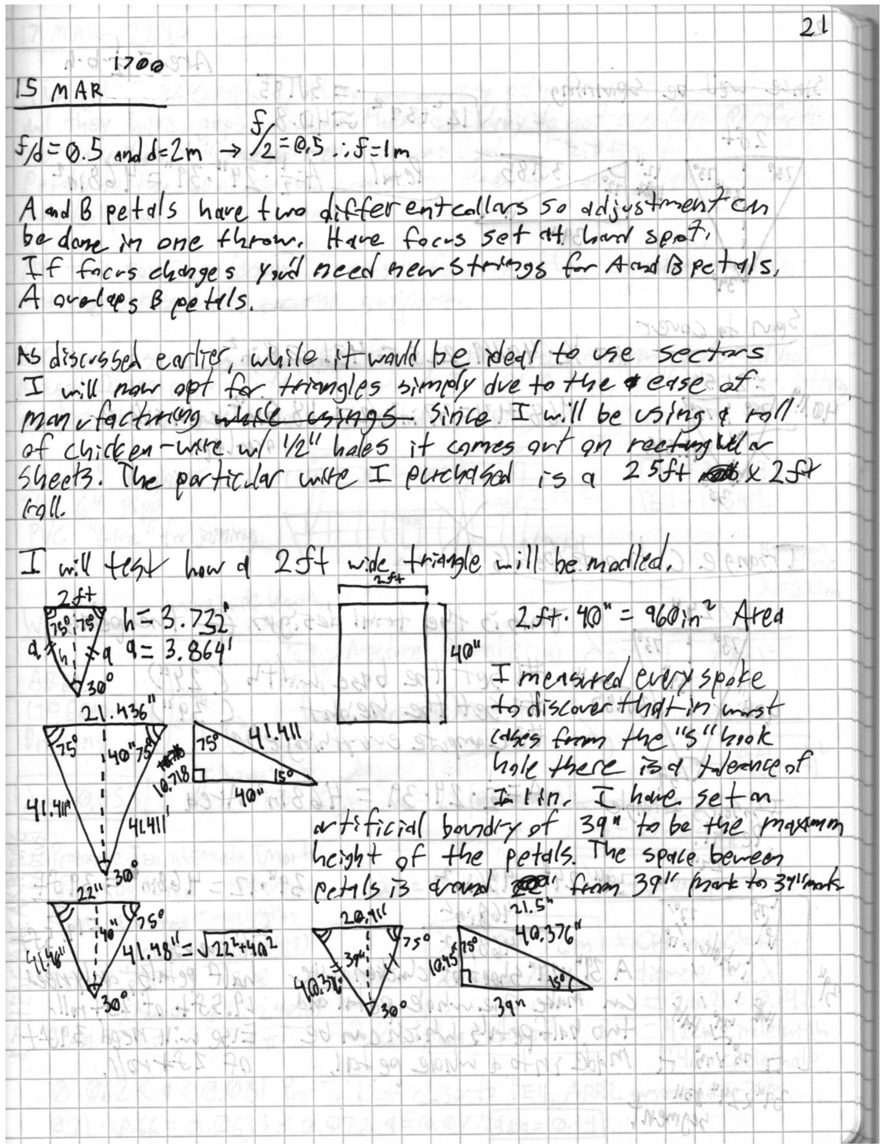
$$\Theta_0 = \arctan\left[\frac{d/2}{Z_0}\right] = \arctan\left[\frac{d/2}{f - \frac{d^2}{16f}}\right]$$

$$Z_0 = f - \frac{d^2}{16f}$$

$$\frac{1}{f - \frac{d^2}{16f}} \rightarrow \frac{1}{f} - \frac{1}{\frac{d^2}{16f}} = \frac{1}{f} - \frac{16f}{d^2}$$

$$\arctan\left[\frac{0.5 \cdot fd}{fd^2 - 1/16}\right] \rightarrow \frac{1}{fd^2 - 1/16} = \frac{16}{16fd^2 - 1} = \frac{8fd}{16fd^2 - 1}$$

Figure C.1: Equations used in DISHCALC and dish design.



21

1700

15 MAR

$f/d = 0.5$ and $d = 2m \rightarrow f/2 = 0.5 \therefore f = 1m$

A and B petals have two different collars so adjustment can be done in one throw. Have focus set at hard spot. If focus changes you'd need new strings for A and B petals. A overlaps B petals.

As discussed earlier, while it would be ideal to use sectors I will now opt for triangles simply due to the ~~$~~ ease of manufacturing ~~while using~~. Since I will be using a roll of chicken-wire w/ 1/2" holes it comes out on rectangular sheets. The particular wire I purchased is a 25ft ~~x~~ x 2ft roll.

I will test how a 2ft wide triangle will be modled.

I measured every spoke to discover that in most cases from the "5" hook hole there is a tolerance of ±1in. I have set an artificial boundry of 39" to be the maximum height of the petals. The space between petals is around ~~20~~' from 39" mark to 37" mark.

Figure C.2: Journal entry 21.

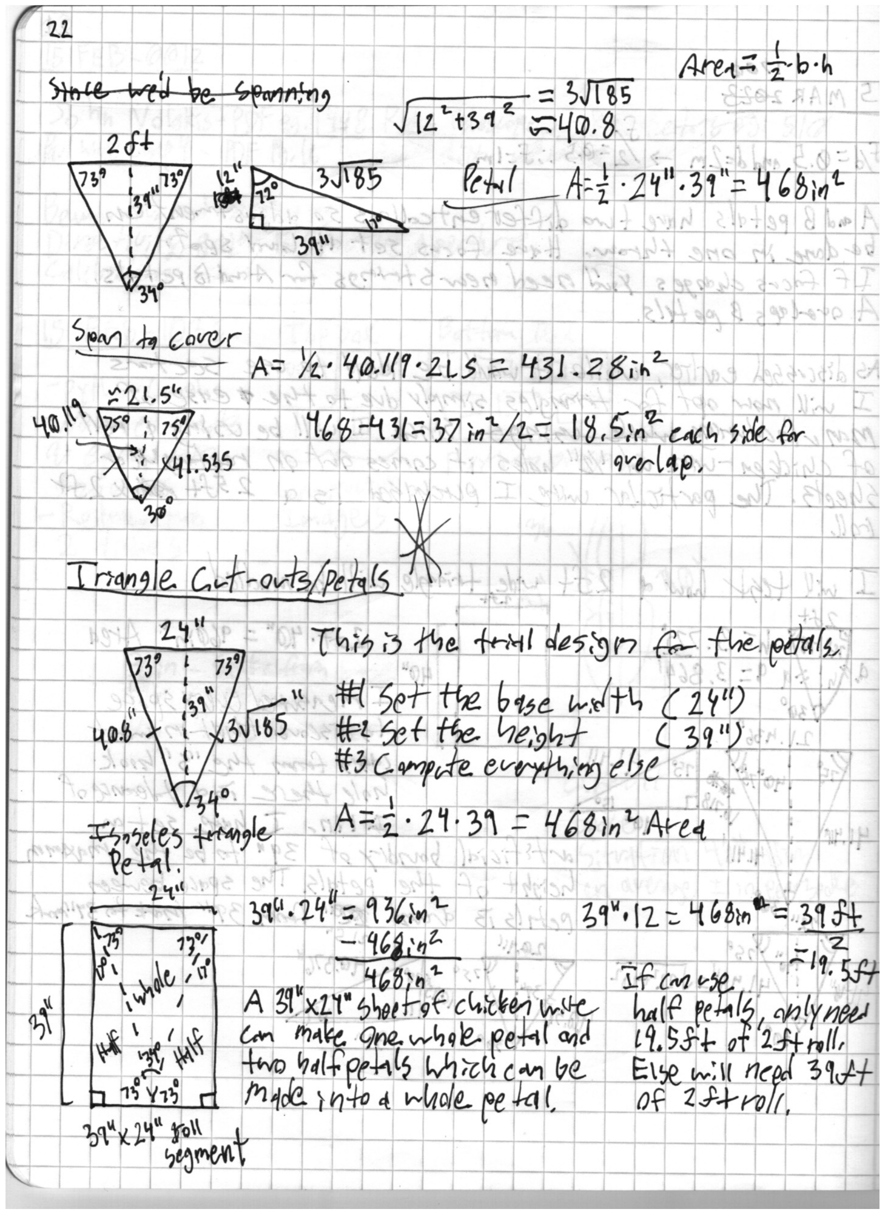
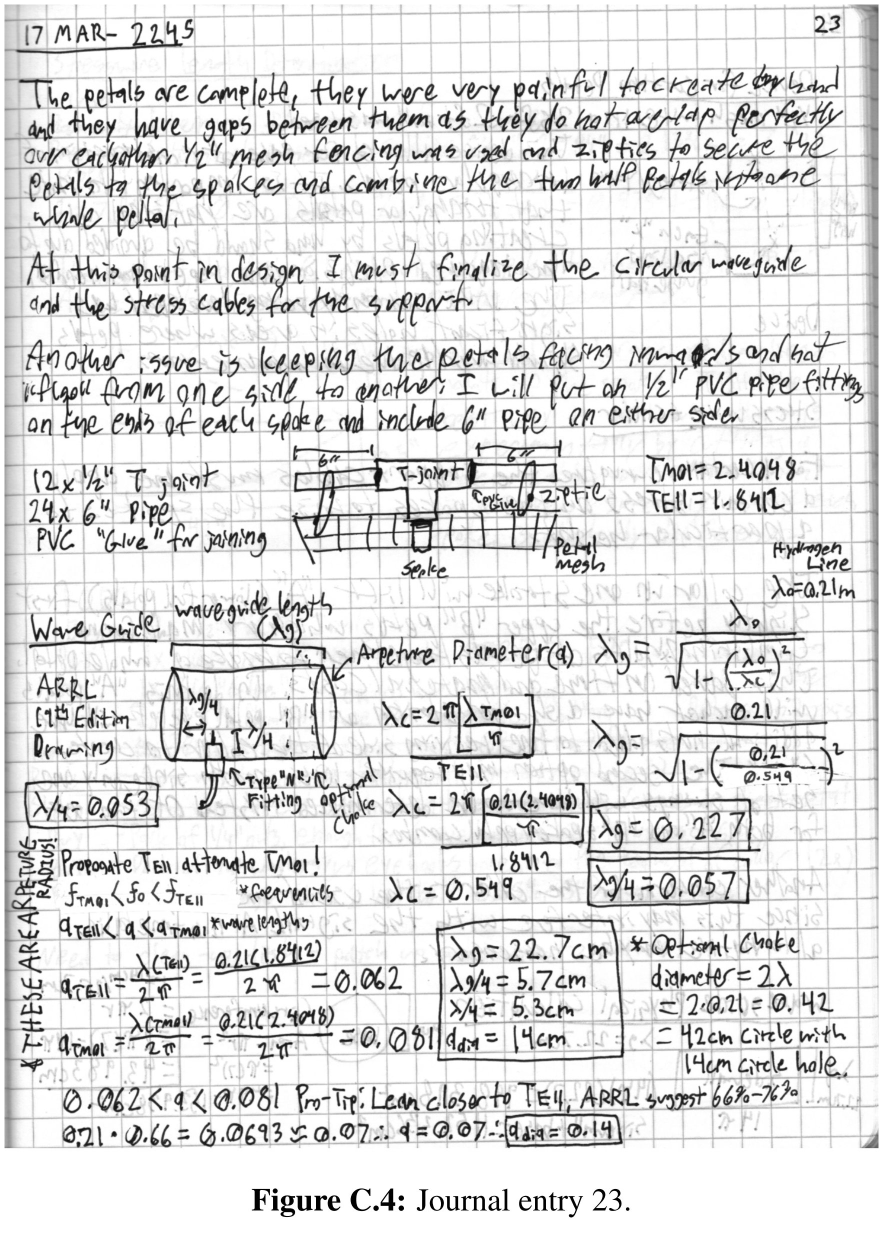


Figure C.3: Journal entry 22.



17 MAR- 2245 | 23

The petals are complete, they were very painful to create by hand and they have gaps between them as they do not overlap perfectly over eachother. 1/2" mesh fencing was used and zipties to secure the petals to the spokes and combine the two half petals into one whole petal.

At this point in design I must finalize the circular waveguide and the stress cables for the support.

Another issue is keeping the petals facing inwards and not flopping from one side to another; I will put an 1/2" PVC pipe fitting on the ends of each spoke and include 6" pipe on either side.

12 x 1/2" T joint
24 x 6" pipe
PVC "Glue" for joining

6" | T-joint | 6" | PVC Glue | ziptie | Spoke | Petal mesh

TM01 = 2.4048
TE11 = 1.8412

Hydrogen Line
$\lambda_0 = 0.21m$

Wave Guide

waveguide length (λg)

Arpeture Diameter(a)

ARRL 19th Edition Drawing

$\lambda g/4$ | $\lambda/4$ | Type "N" ... Fitting | optional Choke

$\boxed{\lambda/4 = 0.053}$

$$\lambda g = \frac{\lambda_0}{\sqrt{1-\left(\frac{\lambda_0}{\lambda c}\right)^2}}$$

$$\lambda c = 2\pi\left[\frac{\lambda\,TM01}{\pi}\right] \quad TE11$$

$$\lambda c = 2\pi\left[\frac{0.21(2.4048)}{\pi}\right] \over 1.8412$$

$\lambda c = 0.549$

$$\lambda g = \frac{0.21}{\sqrt{1-\left(\frac{0.21}{0.549}\right)^2}}$$

$\boxed{\lambda g = 0.227}$

$\boxed{\lambda g/4 = 0.057}$

* THESE ARE ARPETURE RADIUS!

Propogate TE11 attenuate TM01!

$f_{TM01} < f_0 < f_{TE11}$ *frequencies

$a_{TE11} < a < a_{TM01}$ *wave lengths

$$a_{TE11} = \frac{\lambda(TE11)}{2\pi} = \frac{0.21(1.8412)}{2\pi} = 0.062$$

$$a_{TM01} = \frac{\lambda(TM01)}{2\pi} = \frac{0.21(2.4048)}{2\pi} = 0.081$$

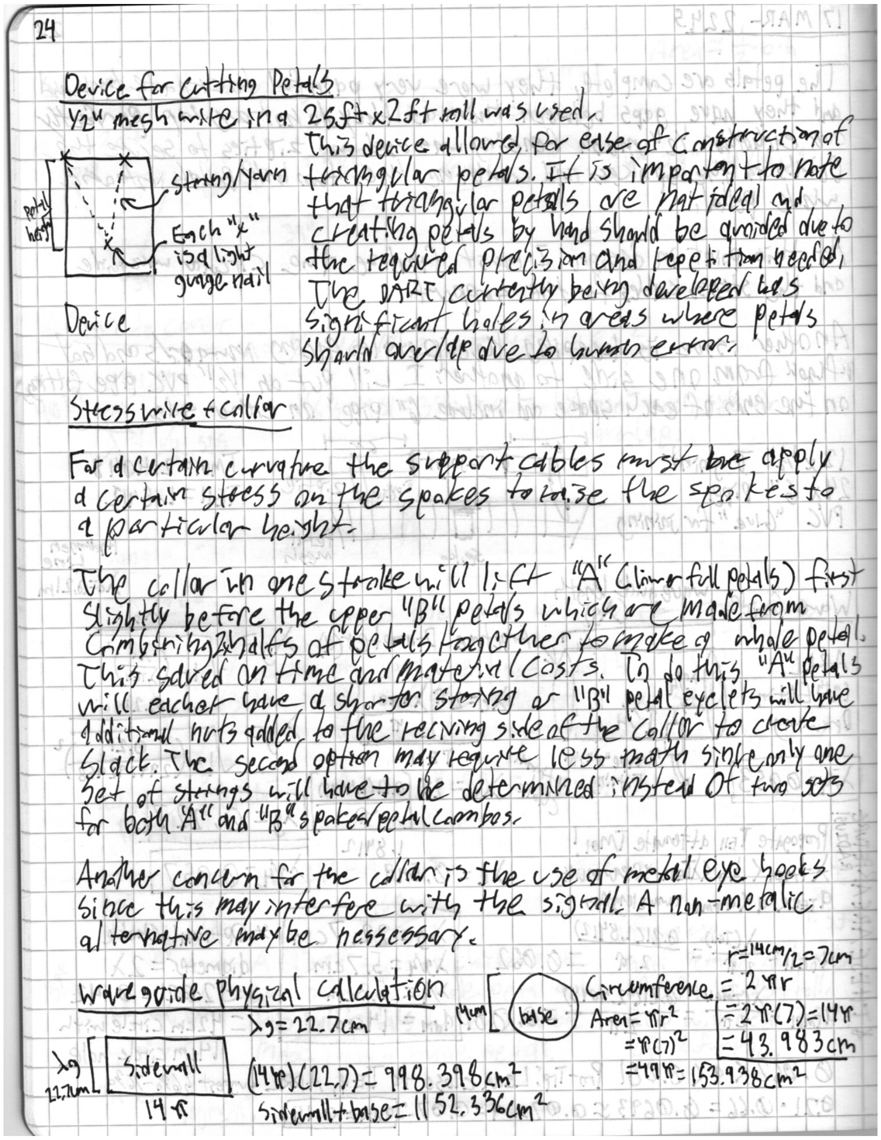
$\lambda g = 22.7cm$
$\lambda g/4 = 5.7cm$
$\lambda/4 = 5.3cm$
$a_{dia} = 14cm$

* Optional Choke
diameter $= 2\lambda$
$= 2 \cdot 0.21 = 0.42$
= 42cm circle with 14cm circle hole.

$0.062 < a < 0.081$ Pro-Tip: Lean closer to TE11, ARRL suggest 66%-76%

$0.21 \cdot 0.66 = 0.0693 \cong 0.07 \therefore a = 0.07 \therefore \boxed{a_{dia} = 0.14}$

Figure C.4: Journal entry 23.


24

Device for cutting Petals

1/2" mesh wire in a 25ft x 2ft roll was used.

This device allowed for ease of construction of triangular petals. It is important to note that triangular petals are not ideal and creating petals by hand should be avoided due to the required precision and repetition needed. The DART currently being developed has significant holes in areas where petals should overlap due to human error.

petal height

string/yarn

Each "x" is a light guage nail

Device

Stress wire + collar

For a certain curvature the support cables must ~~be~~ apply a certain stress on the spokes to raise the spokes to a particular height.

The collar in one stroke will lift "A" (inner full petals) first slightly before the upper "B" petals which are made from combining 2 halfs of petals together to make a whole petal. This saved on time and material costs. To do this "A" petals will eacher have a shorter string or "B" petal eyelets will have additional nuts added to the recieving side of the collar to create slack. The second option may require less math since only one set of strings will have to be determined instead of two sets for both "A" and "B" spokes/petal combos.

Another concern for the collar is the use of metal eye hooks since this may interfere with the signal. A non-metalic alternative may be nessessary.

Waveguide physical calculation

$\lambda g = 22.7cm$

λg 22.7cm [sidewall] 14π

$(14\pi)(22.7) = 998.398cm^2$

sidewall + base = $1152.336cm^2$

14cm [base]

$r = 14cm/2 = 7cm$

Circumference $= 2\pi r$
$= 2\pi(7) = 14\pi$
$\boxed{= 43.983cm}$

Area $= \pi r^2$
$= \pi(7)^2$
$= 49\pi = 153.938cm^2$

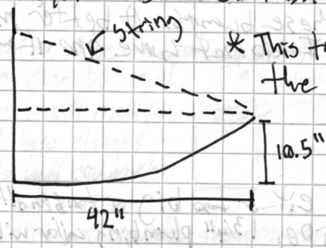
Figure C.5: Journal entry 24.

Stresswire Length Determination

~~Previously~~ user determined f/d ratio = 0.5 f 2m
~~Previously~~ user determined diameter = ~~2m~~ 7ft (42"·2 = 84" = 2.1336m = 7ft)

$d = 7ft,\ f/d = 0.5 \quad \text{Depth} = \frac{d}{16 \cdot f/d} = \frac{7}{16(0.5)} = 0.875ft = \boxed{10.5'' = \text{Depth}}$

The depth of the dish (height of each spoke to the base) is 10.5"
Above equation is derived from parabola geometry.

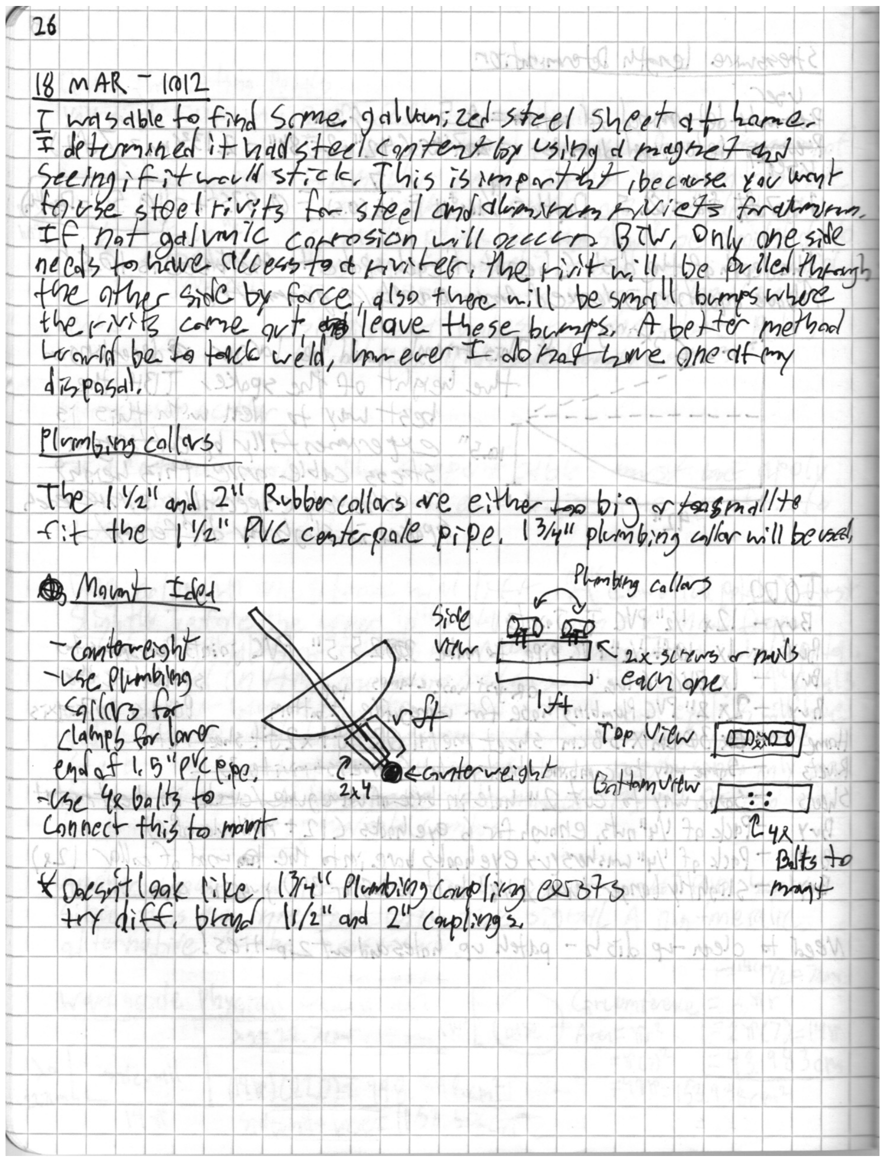


* This triangle would be larger depending on the height of the spoke, TBH, the best way to deal with this is experimentally by cutting a stress cable once this height is achieved, especially since each spoke is slightly different.

TODO
Buy – 12x 1/2" PVC T-Joints
Buy – 1x 10ft 1/2" PVC pipe to make 25 5" PVC joints for spokes to stabilize the petals in Z-axis
Buy – 1x PVC "Glue"
Buy – 2x 2" PVC Plumbing hose for waveguide top + bottom OR just hose clamps
Home – ~~30 cm x 58 cm sheet metal OR 1ft x 2ft sheet metal~~
Rivets – ~~Some way to combine sheet metal (rivets + riviter?)~~
Shears – ~~Some way to cut 2" hole in base of waveguide/circle in sheet metal~~
Buy – Pack of 1/4" nuts, enough for 6 eye hooks (12 + multiples of 6)
Buy – Pack of 1/4" washers (as eye hooks bore into the wood of collar 12x)
Buy – Slightly longer than 2 1/8" bolt (2.5" or 3"), just in case

Need to clean-up dish – patch up holes and cut zip-ties!

Figure C.6: Journal entry 25.



26

18 MAR - 2012

I was able to find some galvanized steel sheet at home. I determined it had steel content by using a magnet and seeing if it would stick. This is important, because you want to use steel rivits for steel and aluminum riviets for aluminum. If not galvanic corrosion will occur. BTW, Only one side needs to have access to a riviter, the rivit will be pulled through the other side by force, also there will be small bumps where the rivits come out, ~~an~~ leave these bumps. A better method would be to tack weld, however I do not have one at my disposal.

Plumbing callars

The 1 1/2" and 2" Rubber collars are either too big or too small to fit the 1 1/2" PVC centerpole pipe. 1 3/4" plumbing collar will be used.

Mount Idea

- counterweight
- use plumbing callars for clamps for lower end of 1.5" PVC pipe.
- use 4x bolts to connect this to mount

* Doesn't look like 1 3/4" Plumbing coupling exists try diff. brand 1 1/2" and 2" couplings.

Figure C.7: Journal entry 26.

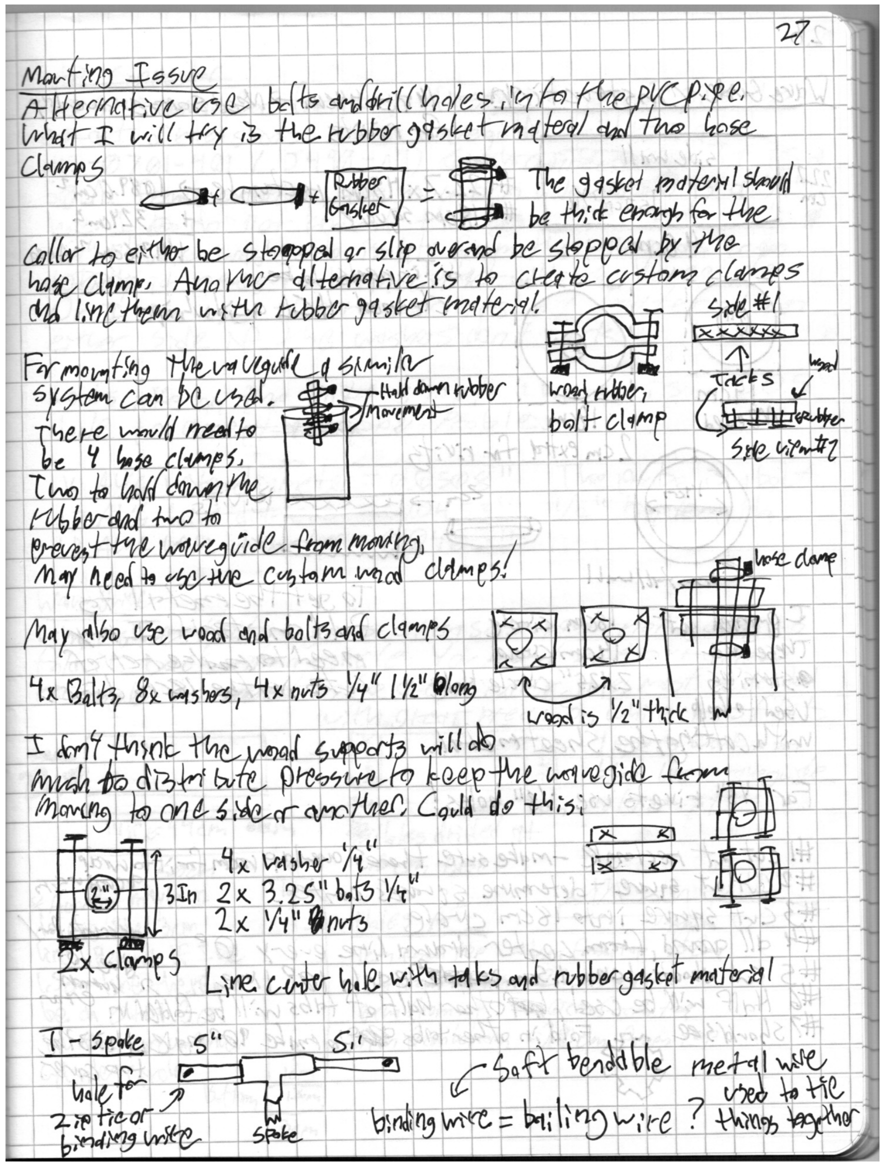
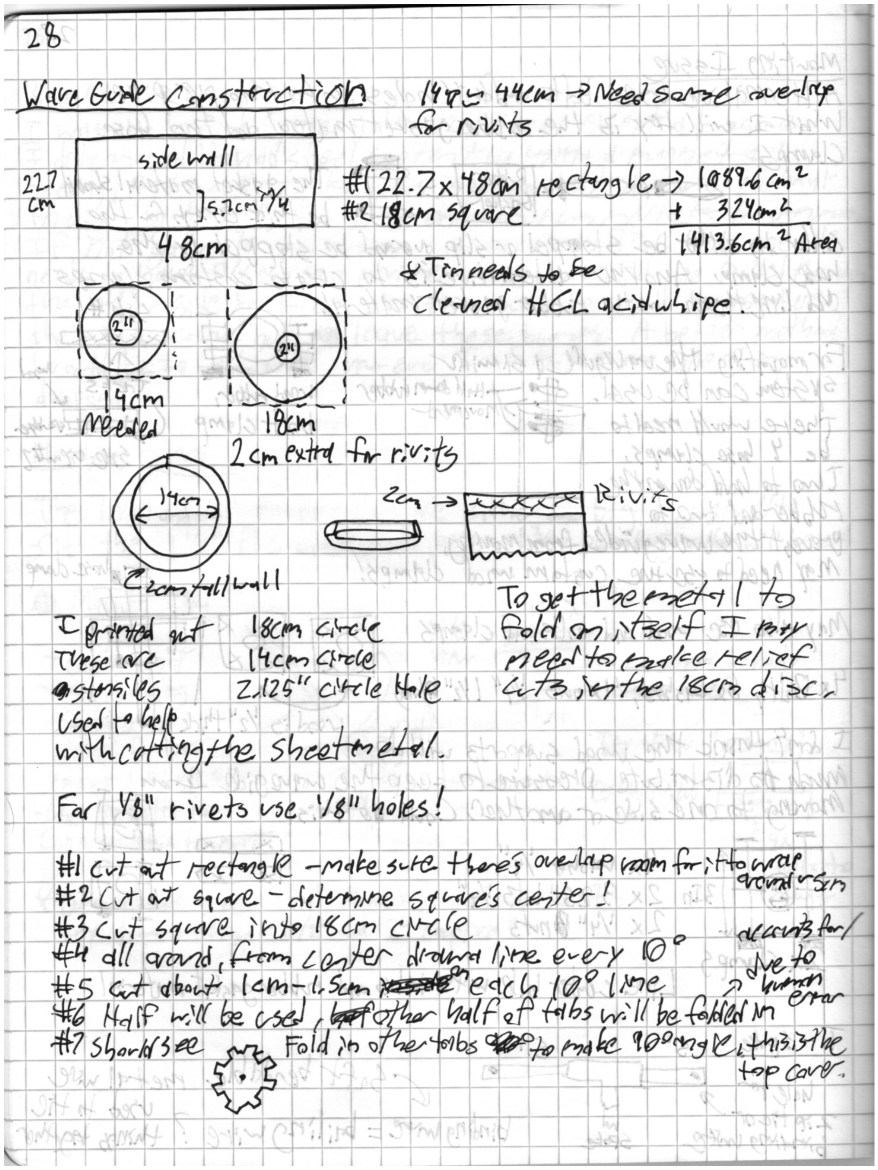


Figure C.8: Journal entry 27.



28

Wave Guide Construction 14π ≈ 44cm → Need some overlap for rivits

side wall
22.7 cm
5.7cm ×4
48cm

#1 22.7 x 48cm rectangle → 1089.6 cm²
#2 18cm square + 324cm²
1413.6cm² Area

& Tin needs to be cleaned HCL acid whipe.

2"
14cm
needed

2"
18cm

2cm extra for rivits

14cm
2cm tall wall

2cm → Rivits

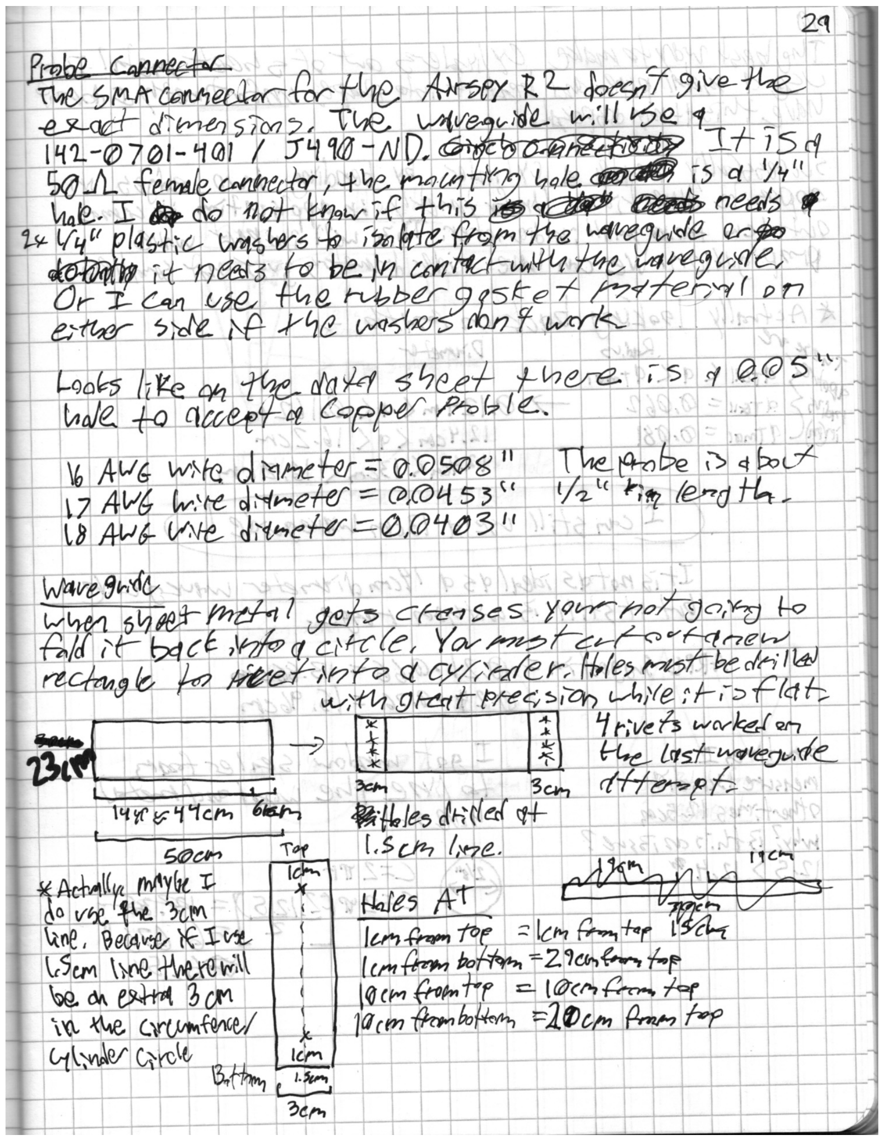
I printed out these are stensiles used to help with cutting the sheetmetal.
18cm circle
14cm circle
2.125" circle hole

To get the metal to fold on itself I may need to make relief cuts in the 18cm disc.

For 1/8" rivets use 1/8" holes!

#1 Cut out rectangle - make sure there's overlap room for it to wrap around ~5cm
#2 Cut out square - determine square's center!
#3 Cut square into 18cm circle
#4 all around, from center draw a line every 10° accounts for/due to human error
#5 Cut about 1cm-1.5cm ~~each~~ each 10° line
#6 Half will be used, ~~half~~ other half of tabs will be folded in
#7 Should see Fold in other tabs ~~90°~~ to make 90° angle, this is the top cover.

Figure C.9: Journal entry 28.



29

Probe Connector
The SMA connector for the Airspy R2 doesn't give the exact dimensions. The waveguide will use a 142-0701-401 / J490-ND. ~~Circle connection~~ It is a 50 Ω female connector, the mounting hole ~~...~~ is a 1/4" hole. I do not know if this ~~...~~ needs a 2x 1/4" plastic washers to isolate from the waveguide or ~~...~~ it needs to be in contact with the waveguide. Or I can use the rubber gasket material on either side if the washers don't work.

Looks like on the data sheet there is a 0.05" hole to accept a copper probe.

16 AWG wire diameter = 0.0508"
17 AWG wire diameter = 0.0453"
18 AWG wire diameter = 0.0403"

The probe is about 1/2" in length.

Waveguide
When sheet metal gets creases your not going to fold it back into a circle. You must cut out a new rectangle for sheet into a cylinder. Holes must be drilled with great precision while it is flat.

23cm
14 & 44cm 6cm
50cm
3cm 3cm
Holes drilled at 1.5cm line.

4 rivets worked on the last waveguide attempt.

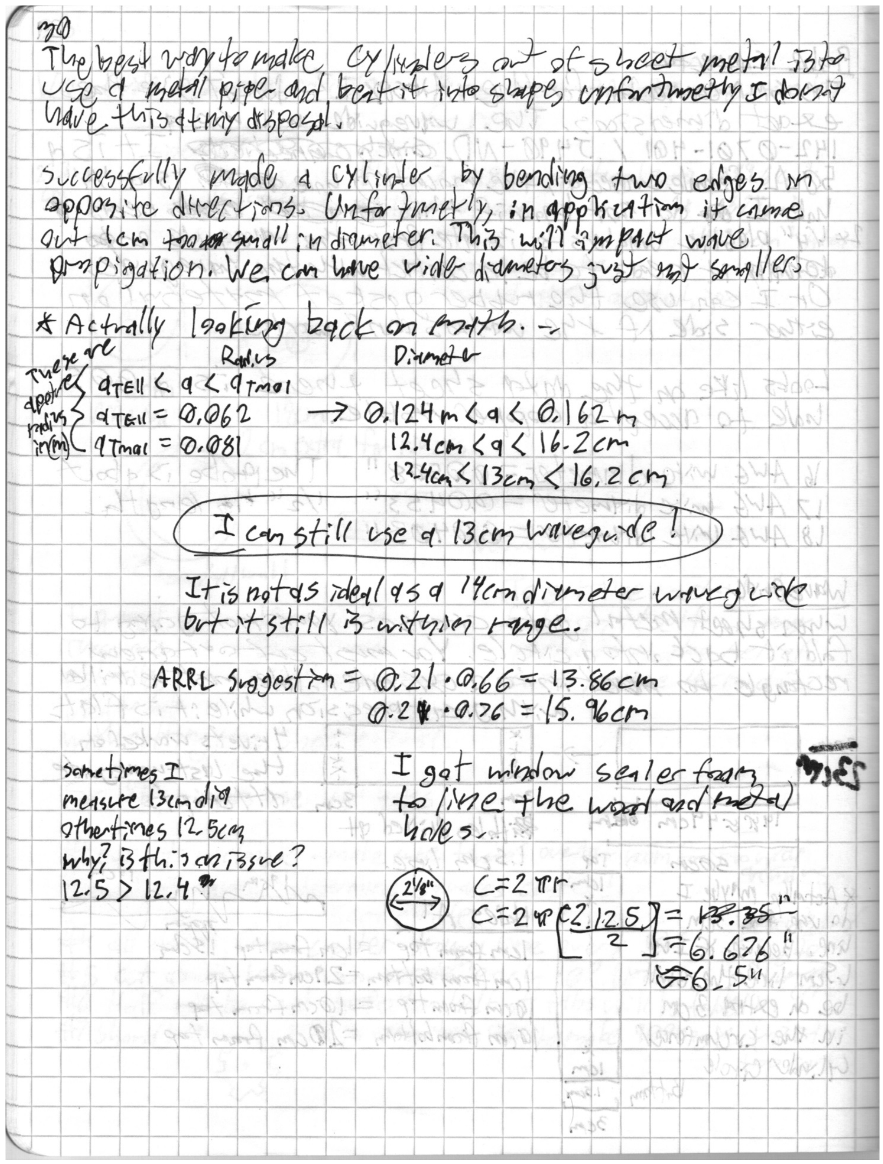
* Actually maybe I do use the 3cm line. Because if I use 1.5cm line there will be an extra 3cm in the circumfence/cylinder circle

Top
1cm
1cm
Bottom
1.5cm
3cm

19cm 19cm

Holes At
1cm from top = 1cm from top
1cm from bottom = 29cm from top
10cm from top = 10cm from top
10cm from bottom = 20cm from top

Figure C.10: Journal entry 29.



30

The best way to make cylinders out of sheet metal is to use a metal pipe and bent it into shape, unfortunately I don't have this at my disposal.

successfully made a cylinder by bending two edges in opposite directions. Unfortunately, in application it came out 1cm ~~too~~ small in diameter. This will impact wave propigation. We can have wide diameters just not smaller.

* Actually looking back on math. →

There are approx radius in (m)

Radius	Diameter
$a_{TE11} < a < a_{TM01}$	
$a_{TE11} = 0.062$	→ $0.124\,m < a < 0.162\,m$
$a_{TM01} = 0.081$	$12.4\,cm < a < 16.2\,cm$
	$12.4\,cm < 13\,cm < 16.2\,cm$

I can still use a 13cm waveguide!

It is not as ideal as a 14cm diameter waveguide but it still is within range.

ARRL suggestion = $0.21 \cdot 0.66 = 13.86\,cm$
$0.21 \cdot 0.76 = 15.96\,cm$

sometimes I measure 13cm dia other times 12.5cm why? is this an issue?
$12.5 > 12.4$

I got window sealer foam to line the wood and metal holes.

2⅛"

$C = 2\pi r$
$C = 2\pi\left[\frac{2.125}{2}\right] = \cancel{13.35}'' \approx 6.676''$
$\approx 6.5''$

Figure C.11: Journal entry 30.

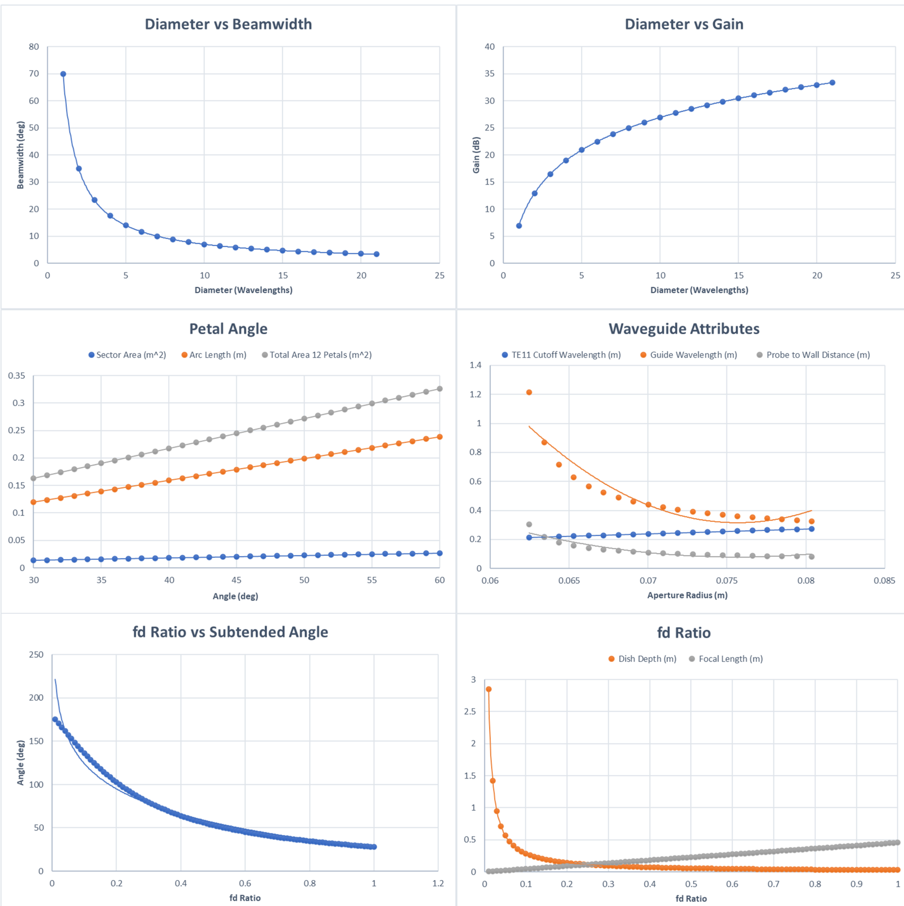
APPENDIX D: DISHCALC

```
C:\Users\Precision 7530\Desktop>echo badSampleInput | dishCalc
 DISHCALC (c) 25 FEB 2023 APCV - FLOATS (0<l, 0<b<360, 0<g, 0<=s<=1, 0<=e<=1):
***DISHCALC***
Andy Cox V (APCV) - Copyright 25 FEB 2023
PURPOSE: DART style parabolic dish antenna design tool.
USAGE: echo l b g s e | dishCalc > out
INPUT (5 floats):
   l = lambda 0 < l; Wavelength in meters.
   b = beamwidth 0 < b < 360; Beamwidth in degrees.
   g = gain 0 < g; Gain in dB.
   s = selection 0 <= s <= 1; Sets diameter parameters. Values close to one favor gain and values close to zero favor beamwidth.
   e = aperture efficiency 0 <= e <= 1; Sets efficiency of the dish (typically 0.5-0.6).
OUTPUT: One input and four dish design parameter tables, each element in each respective table is fully labled below.
All lengths are in meters, areas in meters squared, angles in degrees, gain in decibels, and Selection, Aperture Efficiency, and FD is unitless.
   DATAIN (Input Data) = Wavelength, Gain, Beamwidth, Selection, Aperture Efficiency
   WAVEGUDE (Circular Wave Guide) = Apeture radius, TE11 Cutoff Wavelength, Guide Wavelength Minimum, Probe to Wall Distance, Probe Height
   DISHCNST (Dish Constants) = Diameter, Area, Gain, Beamwidth, Mesh Max Hole
   DISHDESN (Dish Designs) = fd Ratio (unitless), Subtended Angle, Dish Depth, Focal Length
   PETALS = Angle, Area Sector, Arc Length, Area Total
REMARKS:
   Input values shall be present and in order as described in usage.
   Any deviation from the required input specifications will lead to an input error.
   The output data is space seperated.
```

Figure D.1: DISHCALC output when fed bad input.

```
C:\Users\Precision 7530\Desktop>echo 0.21 10.0 24.0 0.5 0.5 | dishCalc
 DISHCALC (c) 25 FEB 2023 APCV - FLOATS (0<l, 0<b<360, 0<g, 0<=s<=1, 0<=e<=1):
 ****DATAIN****
  WAV_m     GAN_dB    BW_deg    SEL       AEF
  0.210000 10.000000 24.000000  0.500000  0.500000
 ***MISCCNST***
  DIA_m^2    ARE_m^2   GAN_dB     BW_deg     MMH_m      PH_m
  0.455720   0.163112  13.662276  32.256638  0.017500   0.052500
 ***WAVEGIDE***
  AR_m       TEC_m      GWM_m      PWD_m
  0.062479   0.213214   1.214020   0.303505
  0.063421   0.216428   0.868090   0.217022
  0.064363   0.219642   0.716625   0.179156
  0.065305   0.222856   0.627354   0.156838
  0.066247   0.226070   0.567114   0.141778
```

Figure D.2: DISHCALC output when fed good input.



dishCalc Input				
Wave-length (m)	Gain (dB)	Beam-width (deg)	Selection	Aperture Efficiency
0.21	10.0	24.0	0.5	0.5

Diameter

Diameter vs Gain
y = 8.6859ln(x) + 6.9327
$R^2 = 1$
Diameter vs Beamwidth
y = 70x-1
$R^2 = 1$

Petals

Total Area
y = 0.0054x - 2E-07
$R^2 = 1$
Arc Length
y = 0.004x - 3E-07
$R^2 = 1$
Sector Area
y = 0.0005x + 2E-07
$R^2 = 1$

Waveguide Attributes

Guide Wavelength
y = 3815.8x2 - 577.47x + 22.163
$R^2 = 0.885$
TE11 Cutoff Wavelength
y = 3.4125x + 5E-06
$R^2 = 1$
Probe to Wall Distance
y = 953.96x2 - 144.37x + 5.5409
$R^2 = 0.885$

fd Ratio

Focal Length
y = 0.4557x - 8E-08
$R^2 = 1$
Dish Depth
y = 0.0285x-1
$R^2 = 1$
Subtended Angle
y = -42.27ln(x) + 26.996
$R^2 = 0.969$

Diameter (m)	Area (m^2)	Gain (dB)	Beamwidth (deg)	Max Mesh Hole (m)	Probe Height (m)
0.45572	0.163112	13.662276	32.256638	0.0175	0.0525

Figure D.3: DISHCALC results sample processed into graphics.

```
DISHCALC (c) 25 FEB 2023 APCV - FLOATS (0<1, 0<b<360, 0<g, 0<=s<=1, 0<=e<=1):
****DATAIN****
 WAV_m     GAN_dB    BW_deg    SEL       AEF
 0.210000 10.000000 24.000000  0.500000  0.500000
***MISCCNST***
 DIA_m^2    ARE_m^2   GAN_dB     BW_deg      MMH_m      PH_m
 0.455720   0.163112  13.662276  32.256638   0.017500   0.052500
***WAVEGIDE***
 AR_m       TEC_m      GWM_m      PWD_m
 0.062479   0.213214   1.214020   0.303505
 0.063421   0.216428   0.868090   0.217022
 0.064363   0.219642   0.716625   0.179156
 0.065305   0.222856   0.627354   0.156838
 0.066247   0.226070   0.567114   0.141778
 0.067189   0.229285   0.523138   0.130785
 0.068130   0.232499   0.489334   0.122334
 0.069072   0.235713   0.462381   0.115595
 0.070014   0.238927   0.440297   0.110074
 0.070956   0.242141   0.421814   0.105453
 0.071898   0.245355   0.406082   0.101520
 0.072840   0.248569   0.392504   0.098126
 0.073782   0.251783   0.380650   0.095163
 0.074723   0.254997   0.370200   0.092550
 0.075665   0.258211   0.360910   0.090227
 0.076607   0.261426   0.352591   0.088148
 0.077549   0.264640   0.345095   0.086274
 0.078491   0.267854   0.338301   0.084575
 0.079433   0.271068   0.332114   0.083029
 0.080375   0.274282   0.326455   0.081614
***DISHDESN***
 FD        SUA_deg     DD_m       FL_m
 0.010000 175.418762   2.848251   0.004557
 0.020000 170.852158   1.424125   0.009114
 0.030000 166.314438   0.949417   0.013672
 0.040000 161.819443   0.712063   0.018229
 0.050000 157.380127   0.569650   0.022786
 0.060000 153.008530   0.474708   0.027343
 0.070000 148.715500   0.406893   0.031900
 0.080000 144.510651   0.356031   0.036458
 0.090000 140.402252   0.316472   0.041015
 0.100000 136.397171   0.284825   0.045572
 0.110000 132.501007   0.258932   0.050129
 0.120000 128.717987   0.237354   0.054686
 0.130000 125.051125   0.219096   0.059244
 0.140000 121.502350   0.203447   0.063801
 0.150000 118.072487   0.189883   0.068358
 0.160000 114.761513   0.178016   0.072915
 0.170000 111.568604   0.167544   0.077472
 0.180000 108.492226   0.158236   0.082030
 0.190000 105.530327   0.149908   0.086587
 0.200000 102.680382   0.142413   0.091144
 0.210000  99.939484   0.135631   0.095701
 0.220000  97.304451   0.129466   0.100258
 0.230000  94.771889   0.123837   0.104816
 0.240000  92.338280   0.118677   0.109373
 0.250000  90.000008   0.113930   0.113930
 0.260000  87.753395   0.109548   0.118487
 0.270000  85.594795   0.105491   0.123044
 0.280000  83.520599   0.101723   0.127602
 0.290000  81.527214   0.098216   0.132159
 0.300000  79.611153   0.094942   0.136716
 0.310000  77.768997   0.091879   0.141273
 0.320000  75.997475   0.089008   0.145830
 0.330000  74.293381   0.086311   0.150388
 0.340000  72.653664   0.083772   0.154945
 0.350000  71.075356   0.081379   0.159502
 0.360000  69.555672   0.079118   0.164059
 0.370000  68.091873   0.076980   0.168616
 0.380000  66.681419   0.074954   0.173174
 0.390000  65.321831   0.073032   0.177731
 0.400000  64.010765   0.071206   0.182288
 0.410000  62.746014   0.069470   0.186845
 0.420000  61.525444   0.067816   0.191402
 0.430000  60.347042   0.066238   0.195960
 0.440000  59.208904   0.064733   0.200517
 0.450000  58.109211   0.063294   0.205074
 0.460000  57.046246   0.061919   0.209631
 0.470000  56.018360   0.060601   0.214188
 0.480000  55.024006   0.059339   0.218746
 0.490000  54.061722   0.058128   0.223303
 0.500000  53.130112   0.056965   0.227860
 0.510000  52.227829   0.055848   0.232417
 0.520000  51.353634   0.054774   0.236974
 0.530000  50.506329   0.053741   0.241532
 0.540000  49.684780   0.052745   0.246089
 0.550000  48.887917   0.051786   0.250646
 0.560000  48.114704   0.050862   0.255203
 0.570000  47.364182   0.049969   0.259760
 0.580000  46.635422   0.049108   0.264318
 0.590000  45.927547   0.048275   0.268875
 0.600000  45.239727   0.047471   0.273432
 0.610000  44.571175   0.046693   0.277989
 0.620000  43.921127   0.045940   0.282546
 0.630000  43.288872   0.045210   0.287104
 0.640000  42.673717   0.044504   0.291661
 0.650000  42.075020   0.043819   0.296218
 0.660000  41.492161   0.043155   0.300775
 0.670000  40.924541   0.042511   0.305332
 0.680000  40.371605   0.041886   0.309890
 0.690000  39.832809   0.041279   0.314447
 0.700000  39.307648   0.040689   0.319004
 0.710000  38.795624   0.040116   0.323561
 0.720000  38.296272   0.039559   0.328119
 0.730000  37.809147   0.039017   0.332676
 0.740000  37.333820   0.038490   0.337233
 0.750000  36.869892   0.037977   0.341790
 0.760000  36.416965   0.037477   0.346347
 0.770000  35.974667   0.036990   0.350905
 0.780000  35.542641   0.036516   0.355462
 0.790000  35.120541   0.036054   0.360019
 0.800000  34.708046   0.035603   0.364576
 0.810000  34.304840   0.035164   0.369133
 0.820000  33.910625   0.034735   0.373691
 0.830000  33.525105   0.034316   0.378248
 0.840000  33.148010   0.033908   0.382805
 0.850000  32.779076   0.033509   0.387362
 0.860000  32.418045   0.033119   0.391919
 0.870000  32.064674   0.032739   0.396477
 0.880000  31.718727   0.032366   0.401034
 0.890000  31.379980   0.032003   0.405591
 0.900000  31.048218   0.031647   0.410148
 0.910000  30.723225   0.031299   0.414705
 0.920000  30.404810   0.030959   0.419263
 0.930000  30.092781   0.030626   0.423820
 0.940000  29.786942   0.030301   0.428377
 0.950000  29.487118   0.029982   0.432934
 0.960000  29.193146   0.029669   0.437491
 0.970000  28.904850   0.029363   0.442049
 0.980000  28.622078   0.029064   0.446606
 0.990000  28.344671   0.028770   0.451163
 1.000000  28.072481   0.028483   0.455720
****PETALS****
ANG_deg     AS_m^2     ARC_m      AT_m^2
30.000000   0.013593   0.119307   0.163112
31.000000   0.014046   0.123284   0.168549
32.000000   0.014499   0.127261   0.173986
33.000000   0.014952   0.131238   0.179423
34.000000   0.015405   0.135215   0.184860
35.000000   0.015858   0.139192   0.190297
36.000000   0.016311   0.143169   0.195735
37.000000   0.016764   0.147146   0.201172
38.000000   0.017217   0.151123   0.206609
39.000000   0.017670   0.155099   0.212046
40.000000   0.018124   0.159076   0.217483
41.000000   0.018577   0.163053   0.222920
42.000000   0.019030   0.167030   0.228357
43.000000   0.019483   0.171007   0.233794
44.000000   0.019936   0.174984   0.239231
45.000000   0.020389   0.178961   0.244668
46.000000   0.020842   0.182938   0.250105
47.000000   0.021295   0.186915   0.255542
48.000000   0.021748   0.190892   0.260979
49.000000   0.022201   0.194869   0.266417
50.000000   0.022654   0.198845   0.271854
51.000000   0.023108   0.202822   0.277291
52.000000   0.023561   0.206799   0.282728
53.000000   0.024014   0.210776   0.288165
54.000000   0.024467   0.214753   0.293602
55.000000   0.024920   0.218730   0.299039
56.000000   0.025373   0.222707   0.304476
57.000000   0.025826   0.226684   0.309913
58.000000   0.026279   0.230661   0.315350
59.000000   0.026732   0.234638   0.320787
60.000000   0.027185   0.238615   0.326224
```

Figure D.4: DISHCALC raw output: echo 0.21 10 24 0.5 0.5 | dishCalc.exe > sampleData.txt

APPENDIX E: DISHCALC FORTRAN SOURCE CODE

Plain text and base64 encoded versions of DISHCALC are provided. Copy and paste the base64 encoded version into a base64 to text converter, this will decode the base64 encoded text into the original FORTRAN source code, which can be compiled and edited. The FORTRAN source code is provided with syntax highlighting.

Base64 Encoded FORTRAN Source Code

dGVyYXRpdmUuDQogICAgDQogICAgISAtLS0gQ29tcHV0ZSBkaXNoIGRpYW1ldGVyIGFuZCBkaXNoIGRh
dGEgLS0tDQogICAgZGlhID0gKChzcXJ0KDEwICoqIChnIC8gMTApICogbCAqKiAyIC8gZSkgLyBQSSkg
KiBzKSArICgoNzAgKiBsIC8gYikgKiAoMSAtIHMpKQ0KICAgIA0KICAgICEgLS0tIExvYWQgZGF0YSBp
bnRvIGRpc2hBcnIgLS0tDQogICAgZGlzaEFycigxKSA9IGRpYSAgICAgICAgICAgICAgICAgICAgICAg
ICAgICAgICAgICAgICEgU3RvcmUgZGlzaCBkaWFtZXRlci4NCiAgICBkaXNoQXJyKDIpID0gKGRpYSAq
KiAyKSAqIFBJIC8gNCAgICAgICAgICAgICAgICAgICAgISBTdG9yZSBhcmVhIG9mIGRpc2guDQogICAg
ZGlzaEFycigzKSA9IDEwICogbG9nMTAoZSAqIChQSSAqIGRpYSAvIGwpICoqIDIpICAgICEgU3RvcmUg
aWRlYWwgaXNvdHJvcGljIGdhaW4gb2YgYW50ZW5uYS4NCiAgICBkaXNoQXJyKDQpID0gNzAgKiBsIC8g
ZGlhICAgICAgICAgICAgICAgICAgICAgICAgICAgISBTdG9yZSBpZGVhbCBiZWFtd2lkdGggb2YgZGlz
aCBpbiBkZWdyZWVzLg0KICAgIGRpc2hBcnIoNSkgPSBsIC8gMTIgICAgICAgICAgICAgICAgICAgICAg
ICAgICAgICAhIFN0b3JlIG1heGltdW0gaG9sZSBzaXplIG9mIG1lc2guDQoNCiAgICAhIC0tLSBO
dW1lcmljYWxseSBjb21wdXRlIHBldGFsIGFyZWFzIGZyb20gMzAgZGVnIChwaS82KSB0byA2MCBkZWcg
KHBpLzMpIC0tLQ0KICAgIGRvIHdoaWxlIChpIC5sZS4gUEVUX0xFTikgICAgICAgICAgICAgICEgMzAgaXRl
cmF0aW9ucyBpcyBsb2dpY2FsbHkgZXF1YWwgdG8gcEFuZ2xlIDwgUEkgLyAzLg0KICAgICAgICBwQW5n
bGUgPSBwQW5nbGUgKyAoUEkgLyAxODApICAgICEgSW5jcmVtZW50IHRoZSBhbmdsZSBvZiB0aGUgc2Vj
dG9yIGJ5IDEgZGVncmVlLg0KICAgICAgICBwQXJlYSA9IHBBbmdsZSAqIChkaWEgKiogMikgLyA4ICEg
QXJlYSBvZiBzZWN0b3IuDQogICAgICAgIA0KICAgICAgICAhIC0tLSBMb2FkIGRhdGEgaW50byBwZXRh
bHMgYXJyYXkgLS0tDQogICAgICAgIHBldGFsc0FycihpLCAxKSA9IGZsb29yKHBBbmdsZSAqICgxODAg
LyBQSSkpICAgICEgU3RvcmUgY2VudHJhbCBhbmdsZSB2YWx1ZS4NCiAgICAgICAgcGV0YWxzQXJyKGks
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ICAgICAgICBwZXRhbHNBcnIoaSwgMykgPSBwQW5nbGUgKiBkaWEgLyAyICAgICAgICAgICAgICAhIFN0
b3JlIGFyYyBsZW5ndGggb2YgdGhlIHNlY3Rvci9wZXRhbC4NCiAgICAgICAgcGV0YWxzQXJyKGksIDQp
ID0gcEFyZWEgKiAxMiAgICAgICAgICAgICAgICAgICAgISBTdG9yZSBpbiB0b3RhbCBhcmVhIGZvciBl
bnRpcmUgZGlzaC4NCiAgICAgICAgaSA9IGkgKyAxDQogICAgZW5kZG8NCg0KICAgICEgLS0tIE51bWVy
aWNhbGx5IGNvbXB1dGUgZGlmZmVyZW50IGRpc2ggZGVzaWducyBmcm9tIGZkIDAuMDEgdG8gMSAtLS0N
CiAgICBpID0gMQ0KICAgIGRvIHdoaWxlIChpIC5sZS4gRkREX0xFTikgICAhIDEwMCBpdGVyYXRpb25z
IGlzIGxvZ2ljYWxseSBlcXVhbCB0byBmZCA8IDEuDQogICAgICAgIGZkID0gZmQgKyAwLjAxICAgICAg
ICAgICEgSW5jcmVtZW50IGZkIHJhdGlvIGJ5IDElLg0KICAgICAgICANCiAgICAgICAgISAtLS0gTG9h
ZCBkYXRhIGludG8gZmREZXMgYXJyYXkgLS0tDQogICAgICAgIGZkRGVzQXJyKGksIDEpID0gZmQNCiAg
ICAgICAgZmREZXNBcnIoaSwgMikgPSAzNjAgLyBQSSAqIGF0YW4oMSAvICg0ICogZmQpKSAgISBTdG9y
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ZiBkaXNoIHRvIGZvY3VzLg0KICAgICAgICBmZERlc0FycihpLCAzKSA9IGRpYSAvICgxNiAqIGZkKSAg
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bmRzdWJyb3V0aW5lIGRpc2gNCg0KISAqKiogV0FWRUdVSURFICoqKg0KISBJTlBVVCAoZmxvYXQpOiBs
DQohIE9VVFBVVCAoYXJyYXkpOiB3YXZlQXJyDQohIERFU0NSSVBUSU9OOiBDb21wdXRlcyB3YXZlZ3Vp
ZGUgY29uc3RydWN0aW9uIGF0dHJpYnR1ZXMuDQpzdWJyb3V0aW5lIHdhdmVHdWlkZShsLCB3YXZlQXJy
KQ0KICAgIHVzZSBjb25zdGFudHMNCiAgICBpbXBsaWNpdCBub25lDQogICAgDQogICAgISAtLS0gQ29u
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IFdBVl9FTF9MRU4pLCBpbnRlbnQob3V0KSA6OiB3YXZlQXJyICAgICEgU3RvcmUgYWxsIGNvbXB1dGVk
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Lg0KICAgIHJlYWwgOjogYXIgICAgICAgICAgICAgICAgICAgICEgQXBlcnR1cmUgcmFkaXVzIGluIG1ldGVycy4NCiAg
ICAgIHJlYWwgOjogVEUxMUN1dCAgICAgICAgICAgICEgQ3V0b2ZmIHdhdmVsZW5ndGggZm9yIFRFMTEuDQog
ICAgcmVhbCA6OiBndWlkZSAgICAgICAgICAgICAgISBHdWlkZSB3YXZlbGVuZ3RoLg0KICAgIA0KICAgIGRv
IHdoaWxlIChpIC5sZS4gV0FWX0xFTikNCiAgICAgICAgc2xpZGUgPSBzbGlkZSArIDAuMDUgICAgISBN
YWtlIDUlIGluY3JlbWVudHMgZnJvbSBUTTExIChsb3dlciBib3VuZCkgdG8gVE0wMSAodXBwZXIgYm91
bmQpLg0KICAgICAgICBhciA9IGwgKiAoVE0wMSAqIHNsaWRlIC0gVEUxMSAqIHNsaWRlICsgVEUxMSkg
LyAoMiAqIFBJKQ0KICAgICAgICBURTExQ3V0ID0gMiAqIFBJICogYXIgLyBURTExDQogICAgICAgIGd1
aWRlID0gbCAvIHNxcnQoMSAtIChsIC8gVEUxMUN1dCkgKiogMikNCiAgICAgICAgDQogICAgICAgICEg
LS0tIFN0b3JlIHdhdmVndWlkZSBkYXRhIC0tLQ0KICAgICAgICB3YXZlQXJyKGksIDEpID0gYXINCiAg
ICAgICAgd2F2ZUFycihpLCAyKSA9IFRFMTFDdXQNCiAgICAgICAgd2F2ZUFycihpLCAzKSA9IGd1aWRl
DQogICAgICAgIHdhdmVBcnIoaSwgNCkgPSBndWlkZSAvIDQgICAhIFN0b3JlIGRpc3RhbmNlIGZyb20g
cHJvYmUgdG8gYmFjayB3YWxsIG9mIGNpcmN1bGFyIHdhdmVndWlkZS4NCiAgICAgICAgaSA9IGkgKyAx
DQogICAgZW5kZG8NCiAgICBlbmQgc3Vicm91dGluZSB3YXZlR3VpZGUNCg0KISAqKiogRElTSENBTEMg
KioqDQohIElOUFVUOiBGcm9tIHRlcm1pbmFsIHN0YW5kYXJkIGlucHV0LiEgT1VUUFVUOiBUbyB0
ZXJtaW5hbCBzdGFuZGFyZCBJL08uDQohIERFU0NSSVBUSU9OOiBNYWluIHByb2dyYW0gcHJvY2Vzc2lu
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cHJvYmUgdG8gYmFjayB3YWxsIG9mIGNpcmN1bGFyIHdhdmVndWlkZS4NCiAgICAgICAgaSA9IGkgKyAx

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```fortran
! AUTH: Andy Cox V
! DATE: Copyright 25 FEB 2023
! LANG: Intel FORTRAN
! USAG: echo l b g s e q | dishCalc > output
! DESC: Command line program to compute DART style parabolic dish antenna design recommendations on user input.
! The purpose for having the full text display on error is to aid in data cleanup.

! *** PROGRAM CONSTANTS ***
module constants
    implicit none
    integer, parameter :: FDD_LEN = 100     ! Length of fd design array.
    integer, parameter :: PET_LEN = 31      ! Length of petal array 30deg to 60deg inclusive [30, 60].
    integer, parameter :: WAV_LEN = 20      ! Length of wave guide array.
    integer, parameter :: DSH_LEN = 5       ! Length of dish array.
    integer, parameter :: WAV_EL_LEN = 4    ! Length of elements for waveguide array.
    integer, parameter :: FDD_EL_LEN = 4    ! Length of elements for fd design array.
    integer, parameter :: PET_EL_LEN = 4    ! Length of elements for petal array.
    real, parameter :: PI = 4 * atan(1.0)   ! Value of PI as defined by machine precision.
    endmodule constants

! *** DISH ***
! INPUT (floats): l, b, g, s, e
! OUTPUT (arrays): fdDesArr, petalsArr, dishArr
! DESCRIPTION: Computes general dish constants and numerical construction parameters for the dish and dish petals.
subroutine dish(l, b, g, s, e, fdDesArr, petalsArr, dishArr)
    use constants
    implicit none

    ! --- Input ---
    real, intent(in) :: l       ! Observed wavelength in meters.
    real, intent(in) :: g       ! Desired gain of the antenna.
    real, intent(in) :: b       ! Desired maximum beam width in degree of parabolic dish.
    real, intent(in) :: s       ! Select diameter [0, 1]; values close to one favor gain and values close to zero favor beamwidth.
```

```fortran
    real, intent(in) :: e       ! Aperture efficiency of front feed dish is typically ~50%-60%, choosing worst case.

    ! --- Output ---
    real, dimension(FDD_LEN, FDD_EL_LEN), intent(out) :: fdDesArr   ! Array for different designs based on increment fd ratios from 0.01 to 1.
    real, dimension(PET_LEN, PET_EL_LEN), intent(out) :: petalsArr  ! Array for petals from 30 deg to 60 deg; 60 is max physical limit till touching adjacent spokes.
    real, dimension(DSH_LEN), intent(out) :: dishArr                ! Array for dish data.

    ! --- Internal ---
    integer :: i = 1                    ! Index for array and increment for loop.
    real :: fd = 0.0                    ! Iterative; f/D ratio.
    real :: pAngle = 29 * PI / 180      ! Iterative; default minimum central angle for a segment of a regular dodecagon is 30 degrees, one less degree due to loop.
    real :: dia                         ! Diameter of parabolic dish in meters.
    real :: pArea                       ! Area of the petal, iterative.

    ! --- Compute dish diameter and dish data ---
    dia = ((sqrt(10 ** (g / 10) * l ** 2 / e) / PI) * s) + ((70 * l / b) * (1 - s))

    ! --- Load data into dishArr ---
    dishArr(1) = dia                                   ! Store dish diameter.
    dishArr(2) = (dia ** 2) * PI / 4                   ! Store area of dish.
    dishArr(3) = 10 * log10(e * (PI * dia / l) ** 2)    ! Store ideal isotropic gain of antenna.
    dishArr(4) = 70 * l / dia                          ! Store ideal beamwidth of dish in degrees.
    dishArr(5) = l / 12                                ! Store maximum hole size of mesh.

    ! --- Numerically compute petal areas from 30 deg (pi/6) to 60 deg (pi/3) ---
    do while (i .le. PET_LEN)           ! 30 iterations is logically equal to pAngle < PI / 3.
        pAngle = pAngle + (PI / 180)    ! Increment the angle of the sector by 1 degree.
        pArea = pAngle * (dia ** 2) / 8 ! Area of sector.

        ! --- Load data into petals array ---
        petalsArr(i, 1) = floor(pAngle * (180 / PI))    ! Store central angle value.
        petalsArr(i, 2) = pArea                        ! Store area of petal.
```

```
        petalsArr(i, 3) = pAngle * dia / 2              ! Store arc length of the sector/petal.
        petalsArr(i, 4) = pArea * 12                    ! Store in total area for entire dish.
        i = i + 1
    enddo

    ! --- Numerically compute different dish designs from fd 0.01 to 1 ---
    i = 1
    do while (i .le. FDD_LEN)   ! 100 iterations is logically equal to fd < 1.
        fd = fd + 0.01          ! Increment fd ratio by 1%.

        ! --- Load data into fdDes array ---
        fdDesArr(i, 1) = fd
        fdDesArr(i, 2) = 360 / PI * atan(1 / (4 * fd))  ! Store subtended angle/angle of illumination in degree from tip of dish to
    focus.
        fdDesArr(i, 3) = dia / (16 * fd)                ! Store depth of dish in meters.
        fdDesArr(i, 4) = fd * dia                       ! Store focal length of dish in meters.
        i = i + 1
    enddo
    endsubroutine dish

! *** WAVEGUIDE ***
! INPUT (float): l
! OUTPUT (array): waveArr
! DESCRIPTION: Computes waveguide construction attribtues.
subroutine waveGuide(l, waveArr)
    use constants
    implicit none

    ! --- Constants ---
    real, parameter :: TE11 = 1.8412        ! Zero of derivative of the bessle function J'1,1.
    real, parameter :: TM01 = 2.4048        ! Zero of bessle function J0,1

    ! --- Output ---
    real, dimension(WAV_LEN, WAV_EL_LEN), intent(out) :: waveArr    ! Store all computed waveguide parameters.

```

```
    ! --- Input---
    real, intent(in) :: l   ! Observed wavelength in meters.

    ! --- Internal ---
    integer :: i = 1        ! Iterator to load array.
    real :: slide = 0.0     ! Slider from TE11 to TM01 - Recommend using 0.43 and above (close to half).
    real :: ar              ! Apeture radius in meters.
    real :: TE11Cut         ! Cutoff wavelength for TE11.
    real :: guide           ! Guide wavelength.

    do while (i .le. WAV_LEN)
        slide = slide + 0.05    ! Make 5% increments from TM11 (lower bound) to TM01 (upper bound).
        ar = l * (TM01 * slide - TE11 * slide + TE11) / (2 * PI)
        TE11Cut = 2 * PI * ar / TE11
        guide = l / sqrt(1 - (l / TE11Cut) ** 2)

        ! --- Store waveguide data ---
        waveArr(i, 1) = ar
        waveArr(i, 2) = TE11Cut
        waveArr(i, 3) = guide
        waveArr(i, 4) = guide / 4   ! Store distance from probe to back wall of circular waveguide.
        i = i + 1
    enddo
    end subroutine waveGuide

! *** DISHCALC ***
! INPUT: From terminal standardard I/O.
! OUTPUT: To terminal standard I/O.
! DESCRIPTION: Main program processing I/O and error handeling.
! Printing to output and lines longer than 132 columns may cause errors for non-Intel FORTRAN compilers.
program dishCalc
    use constants
    implicit none

    ! --- Input variables ---
```

```fortran
real :: l   ! Observed wavelength in meters.
real :: g   ! Desired gain of the antenna.
real :: b   ! Desired maximum beam width in degree of parabolic dish.
real :: s   ! Select diameter [0, 1]; values close to one favor gain and values close to zero favor beamwidth.
real :: e   ! Aperture efficiency of front feed dish is typically ~50%-60%, choosing worst case.
real :: q   ! Quiet mode. Any non-zero value will display the welcome prompt.

! --- Internal vars ---
real, dimension(FDD_LEN, FDD_EL_LEN) :: fdDesArr    ! Array for different designs (100, 4): fd, subtended angle, dish depth, focal length.
real, dimension(PET_LEN, PET_EL_LEN) :: petalsArr   ! Array for different petals (31, 4): central angle, area, arc length, total area.
real, dimension(WAV_LEN, WAV_EL_LEN) :: waveArr     ! Array for wave guide (10, 5): Aperture radius, TE11 Cut off wavelength, guide wavelength min, probe to back wall distance, probe height distance.
real, dimension(DSH_LEN) :: dishArr                 ! Array for dish (5): diameter, area, gain, beamwidth, max mesh holes.

! --- Welcome Message ---
print *, "DISHCALC (c) 25 FEB 2023 APCV - FLOATS (0<l, 0<b<360, 0<g, 0<=s<=1, 0<=e<=1):"

! --- Read input from command line (piped from console) ---
read(*, *, ERR=100) l, g, b, s, e   ! Read from stdin (pipe): Wavelength, gain, beamwidth, selection, aperture efficiency.

! --- Check for valid input ---
if(l .le. 0 .or. &                  ! Wavelength must be positive.
    g .le. 0 .or. &                 ! Gain must be positive.
    b .le. 0 .or. b .ge. 360 .or. & ! Beamwidth must be between 0 and 360
    s .lt. 0 .or. s .gt. 1 .or. &   ! Selection must be between 0 and 1 inclusive.
    e .lt. 0 .or. e .gt. 1) then    ! Aperture efficiency must be between 0 and 1 inclusive.
        goto 100
    endif

! --- Compute dish and waveguide data ---
! Sample: 0.21 10.0 24.0 0.5 0.5
call dish(l, b, g, s, e, fdDesArr, petalsArr, dishArr)
call waveGuide(l, waveArr)
```

```
print *, "****DATAIN****"
write (*, "(a7, 1x, a10, 1x, a9, 1x, a6, 1x, a9, 1x)"), "WAV_m", "GAN_dB", "BW_deg", "SEL", "AEF"
write (*, "(5(f10.6), 1x)"), l, g, b, s, e
print *, "***MISCCNST***"
write (*, "(a9, 1x, a10, 1x, a8, 1x, a10, 1x, a10, 1x, a9, 1x)"), "DIA_m^2", "ARE_m^2", "GAN_dB", "BW_deg", "MMH_m", "PH_m"     ! Diameter, Area, Gain, Beamwidth, max mesh hole, waveguide probe height.
write (*, "(6(f10.6, 1x))"), dishArr, (l / 4)                                                                                  ! Dish constants follow by l / 4 is waveguide probe height.
print *, "***WAVEGIDE***"
write (*, "(a6, 1x, a11, 1x, a10, 1x, a10, 1x, a9, 1x)"), "AR_m", "TEC_m", "GWM_m", "PWD_m" ! Apeture radius, TE11 Cutoff, Guide Wavelength, probe wall distance.
write (*, "(4(f10.6, 1x))"), transpose(waveArr)
print *, "***DISHDESN***"
write (*, "(a4, a14, a10, a11)"), "FD", "SUA_deg", "DD_m", "FL_m"                   ! fd ratio (unitless), subtended angle, dish depth, focal length.
write (*, "(4(f10.6, 1x))"), transpose(fdDesArr)
print *, "****PETALS****"
write (*, "(a8, a11, a10, a12)"), "ANG_deg", "AS_m^2", "ARC_m", "AT_m^2"            ! Angle, area sector, arc length, area total
write (*, "(4(f10.6, 1x))"), transpose(petalsArr)
stop

! --- Error handling ---
100 write (*, "(a)", advance="no"), "***DISHCALC***" // achar(13) // achar(10) // &
&"Andy Cox V (APCV) - Copyright 25 FEB 2023" // achar(13) // achar(10) // &
&"PURPOSE: DART style parabolic dish antenna design tool." // achar(13) // achar(10) // &
&"USAGE: echo l b g s e | dishCalc > out" // achar(13) // achar(10) // &
&"INPUT (5 floats):" // achar(13) // achar(10) // &
&"   l = lambda 0 < l; Wavelength in meters." // achar(13) // achar(10) // &
&"   b = beamwidth 0 < b < 360; Beamwidth in degrees." // achar(13) // achar(10) // &
&"   g = gain 0 < g; Gain in dB." // achar(13) // achar(10) // &
&"   s = selection 0 <= s <= 1; Sets diameter parameters. Values close to one favor gain and values close to zero favor beamwidth." // achar(13) // achar(10) // &
&"   e = aperture efficiency 0 <= e <= 1; Sets efficiency of the dish (typically 0.5-0.6)." // achar(13) // achar(10) // &
&"OUTPUT: One input and four dish design parameter tables, each element in each respective table is fully labled below." // achar(13) // achar(10) // &
```

```
&"All lengths are in meters, areas in meters squared, angles in degrees, gain in decibels, and Selection, Aperture Efficiency, and FD is unitless." // achar(13) // achar(10) // &
&"   DATAIN (Input Data) = Wavelength, Gain, Beamwidth, Selection, Aperture Efficiency" // achar(13) // achar(10) // &
&"   WAVEGUDE (Circular Wave Guide) = Apeture radius, TE11 Cutoff Wavelength, Guide Wavelength Minimum, Probe to Wall Distance, Probe Height" // achar(13) // achar(10) // &
&"   DISHCNST (Dish Constants) = Diameter, Area, Gain, Beamwidth, Mesh Max Hole" // achar(13) // achar(10) // &
&"   DISHDESN (Dish Designs) = fd Ratio (unitless), Subtended Angle, Dish Depth, Focal Length" // achar(13) // achar(10) // &
&"   PETALS = Angle, Area Sector, Arc Length, Area Total" // achar(13) // achar(10) // &
&"REMARKS:" // achar(13) // achar(10) // &
&"   Input values shall be present and in order as described in usage." // achar(13) // achar(10) // &
&"   Any deviation from the required input specifications will lead to an input error." // achar(13) // achar(10) // &
&"   The output data is space seperated." // achar(13) // achar(10)
stop
endprogram dishCalc
```