PACCAR Compact Broadcast AM Band Radiating Antenna Design Report

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University of Washington, EE497
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Contents

1 Abstract

Our project focuses on testing equipment to be used at the PACCAR Technical Center where research is done on upcoming truck designs. As PACCAR implements additional electronic systems into their trucks, they need to ensure that there is no electrical noise that could interfere with the radio systems. In order to test this, they require a new AM radiating antenna. Their current solution is a 30-foot dipole antenna which has become too difficult and cumbersome to use. The antenna is placed in the same room as the truck and transmits a control tone to the truck where it is received and measured as other systems in the truck are turned on and off. The goal of this test is to check for any static or other noise that exceeds the control signal. The current system they are using is cumbersome and difficult to use and so our goal is to create a new antenna that will be easier to transport and assemble. In this report, we will outline our testing methods, implementations, and results from this quarter.

2 Teams, Roles, Responsibilities

Cole Helms: Project Manager, Design Lead, Calculations Lead

Cole Helms is responsible for making plans to keep the project on track. This entails a variety of tasks from making contact with parties that we need something from to preparing talking points for meetings. In addition, he performs much of the hand and calculator work that is done before the simulations to check the feasibility and efficiency of each design. Finally, Cole puts together the final prototype designs to be built and picks materials for construction. This requires breaking down the costs and benefits of each decision and judging what will produce the best result.

Nick Roberts: Budget Manager, Simulation and Implementation

Nick Roberts is responsible for creating and analyzing the simulations using EZNEC to test potential implementations of the antenna. This involves using values calculated by Cole and judging performance based on values such as SWR, maximum gain, as well as the anticipated far-field shape and strength. Multiple iterations of the simulation were used before we settled on a final design for prototyping and testing. In addition to simulation and implementation, Nick is also in charge of budgeting and ordering materials necessary for this project. This requires keeping a record of all necessary materials, and balancing necessary performance with the potential cost. Nick is also the main contact for anything budgeting related to the project.

Nick Jenkins: Hardware Lead, Simulation and Implementation

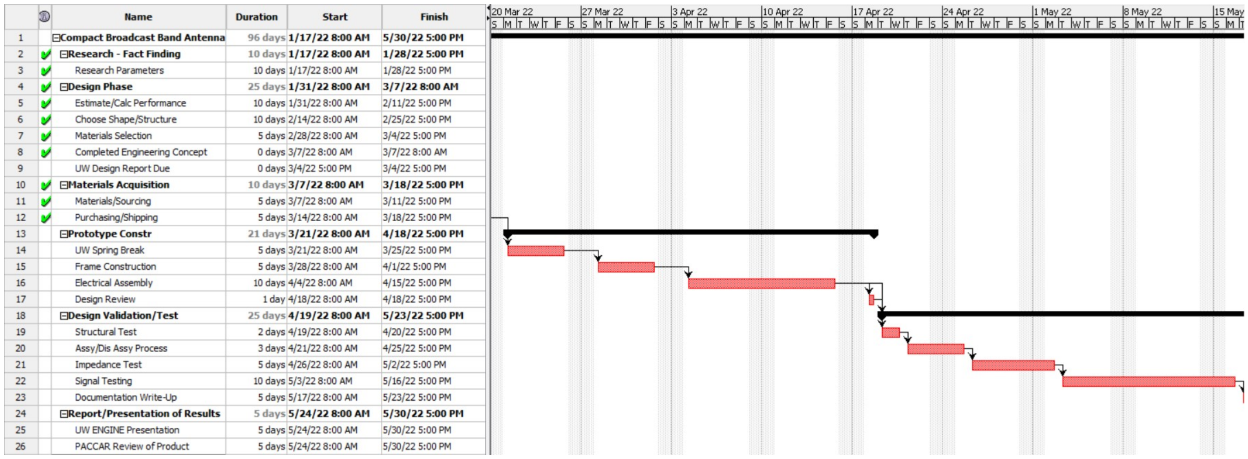
Nick Jenkins is responsible for simulating, iterating through, and improving upon designs using the antenna simulation software EZNEC. By working with Nick Roberts, who also simulated designs, and Cole Helms, who calculated parameters, he was able to help finalize design choices for the antenna. Nick Jenkins also worked primarily to make the simulated designs more closely mirror the real antenna by simulating coupling loops, capacitors, and environments (such as the testing room). In addition, Nick Jenkins also helped to find research documentation – such as research on coupling loop structures – and antenna components – such as vacuum variable capacitors.

Mentors

Kevin Allen: Industry Mentor

Jacques ‘Chris’ Rudell: Faculty Mentor

3 Project Schedule



		Name	Duration	Start	Finish
1		Compact Broadcast Band Antenna	96 days	1/17/22 8:00 AM	5/30/22 5:00 PM
2	✓	Research - Fact Finding	10 days	1/17/22 8:00 AM	1/28/22 5:00 PM
3	✓	Research Parameters	10 days	1/17/22 8:00 AM	1/28/22 5:00 PM
4	✓	Design Phase	25 days	1/31/22 8:00 AM	3/7/22 8:00 AM
5	✓	Estimate/Calc Performance	10 days	1/31/22 8:00 AM	2/11/22 5:00 PM
6	✓	Choose Shape/Structure	10 days	2/14/22 8:00 AM	2/25/22 5:00 PM
7	✓	Materials Selection	5 days	2/28/22 8:00 AM	3/4/22 5:00 PM
8	✓	Completed Engineering Concept	0 days	3/7/22 8:00 AM	3/7/22 8:00 AM
9		UW Design Report Due	0 days	3/4/22 5:00 PM	3/4/22 5:00 PM
10	✓	Materials Acquisition	10 days	3/7/22 8:00 AM	3/18/22 5:00 PM
11	✓	Materials/Sourcing	5 days	3/7/22 8:00 AM	3/11/22 5:00 PM
12	✓	Purchasing/Shipping	5 days	3/14/22 8:00 AM	3/18/22 5:00 PM
13		Prototype Constr	21 days	3/21/22 8:00 AM	4/18/22 5:00 PM
14		UW Spring Break	5 days	3/21/22 8:00 AM	3/25/22 5:00 PM
15		Frame Construction	5 days	3/28/22 8:00 AM	4/1/22 5:00 PM
16		Electrical Assembly	10 days	4/4/22 8:00 AM	4/15/22 5:00 PM
17		Design Review	1 day	4/18/22 8:00 AM	4/18/22 5:00 PM
18		Design Validation/Test	25 days	4/19/22 8:00 AM	5/23/22 5:00 PM
19		Structural Test	2 days	4/19/22 8:00 AM	4/20/22 5:00 PM
20		Assy/Dis Assy Process	3 days	4/21/22 8:00 AM	4/25/22 5:00 PM
21		Impedance Test	5 days	4/26/22 8:00 AM	5/2/22 5:00 PM
22		Signal Testing	10 days	5/3/22 8:00 AM	5/16/22 5:00 PM
23		Documentation Write-Up	5 days	5/17/22 8:00 AM	5/23/22 5:00 PM
24		Report/Presentation of Results	5 days	5/24/22 8:00 AM	5/30/22 5:00 PM
25		UW ENGINE Presentation	5 days	5/24/22 8:00 AM	5/30/22 5:00 PM
26		PACCAR Review of Product	5 days	5/24/22 8:00 AM	5/30/22 5:00 PM

Figure 1: Updated Gantt Chart

Our shape and structure design took an extra week, which pushed everything else down by one week. We had built in a buffer period so this delay is not detrimental to the project. Other changes to the Gantt chart from the beginning of the quarter include adding a timeline for documentation and a timeline for presentation preparation.

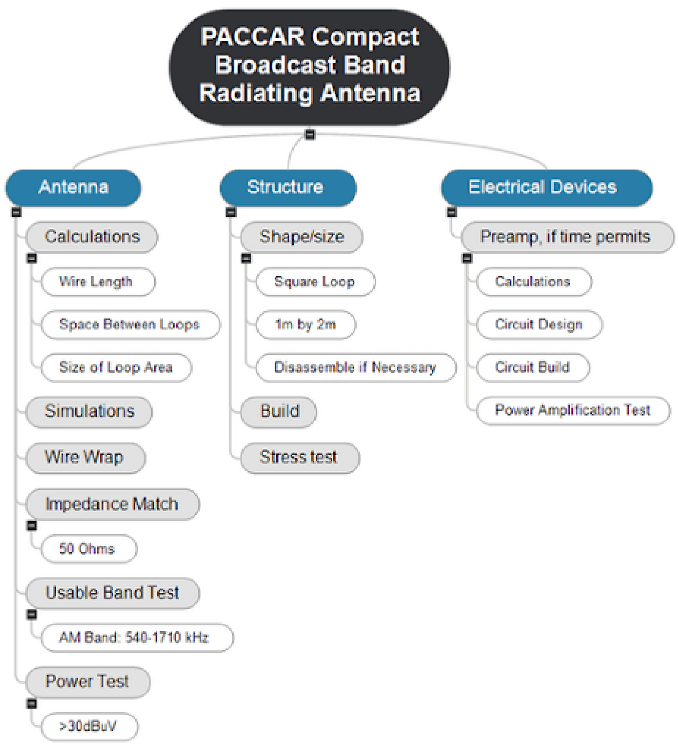


Figure 2: Work breakdown structure

In the Spring quarter, we will still need to:

- Build our simulated antenna
  - Frame/base
  - Antenna main loop
  - Coupling loop
  - Tuning variable capacitor
- Test our built antenna
  - Structural integrity
  - Impedance matching
  - Signal strength
  - Bandwidth coverage
- Document
- Present

4 Project Success Criteria

- Research and understand small antenna designs (Completed)
- In order for this project to be successful we need to create a design for an antenna that is smaller than 2 by 3 meters (Completed)
- Build AM broadcast antenna that can be used by PACCAR for testing their truck radios (In progress)
- Test the antenna power delivery to a 75 Ω antenna 30 ft away (Pending prior criteria)
- This device needs to be able to be adjusted for the majority of the frequency range of AM radio (In progress)
- This device needs to be centered at 0.97 MHz
- Need to deliver 30 $dB\mu V$ to the Truck antenna from the antenna
- Write assembly/disassembly and use instructions (TBD)

5 System Requirements

1. Shall fit through a standard building door of dimensions 0.91 m wide by 2.03 m tall
2. Shall be fully assembled or assembled in less than 5 minutes
3. Shall be smaller than 3 m by 2 m wide when fully assembled
4. Should weigh less than 50 pounds fully assembled
5. Shall generate a signal of > 30 $dB\mu V$ as measured by a spectrum analyzer on the truck antenna network
   (a) Shall produce this received power with a maximum input of 120 $dB\mu V$
   (b) Should work at a distance greater than 50 ft
6. The antenna shall be centered on 970 kHz
   (a) Should be tunable to anywhere on the AM Broadcast band (535-1605 kHz)
7. The source impedance of the antenna shall be 50 Ω
8. Shall survive shock tests
   (a) Shall survive drop test of 1m
   (b) Shall survive being tipped over from resting position

6 Hardware/Software Design

Our project will deliver a working antenna by the end of spring quarter that will be usable for PACCAR's testing procedure on their trucks. It will be an AM broadcasting antenna meaning it will transmit signals in the AM frequency range, specifically at 970 kHz. While it may sound as if this is a product you could buy off the shelf, operating at this frequency with the given restraints is not commonly done due to many of the physical limitations we ran into while designing our antenna.

This device will need to follow all the prescribed conditions, but most notably it needs to be small enough to fit through a standard building doorway, which is about 2 meters tall. This presents a huge problem as our operating wavelength is 309 meters or about 1000 feet meaning if we used a standard dipole or monopole antenna at its largest it would only be around 1% of a wavelength long. Standard antenna theory tells us that without getting to about a half-wavelength dipole antennas will not transmit very well, and below a quarter-wavelength, they perform very poorly when used with a coaxial feedline due to impedance matching problems. This made using a dipole or other very basic antenna structure untenable for our project with such limited space.

We recognized the need to branch out into other antenna designs if we wanted to create something that could transmit at our target. Some unsuitable examples include: ferrite rod, ruled out due to high power requirements and extreme loss, and fractal, which would not be functional as the interference it seeks to exploit does not work with such a low electrical length. We decided that a small magnetic loop antenna design would be most practical for our project. We chose it because of its proven trustworthiness in operating when the antenna length is 10% of the wavelength. These have long been used for both transmission and reception by HAM radio enthusiasts as tracers and tuners due to their strong directional gain, null regions, and compact size.

However, unlike HAM radio we are operating well below the amateur radio frequency leaving us unable to create a loop large enough to achieve 10% λ. This means we will not get the high-efficiency values that can be created by this type of antenna. On the other hand, an advantage for us is that these antennas use a variable capacitor in the antenna loops that can be varied to tune the resonance frequency, letting us use this antenna over the entire AM band given enough variability on the capacitor.

In order to create a small magnetic loop antenna that meets our requirements, we ran through numerous design iterations that will be covered in the following sections. These steps have led us to our final design which is a square small magnetic loop with a side length of 1.8 meters and conductor diameter of 2 millimeters. This design uses a coax cable inductive feed loop inside the main loops which means we will not need to worry about an impedance matching circuit from the 50Ω signal generator.

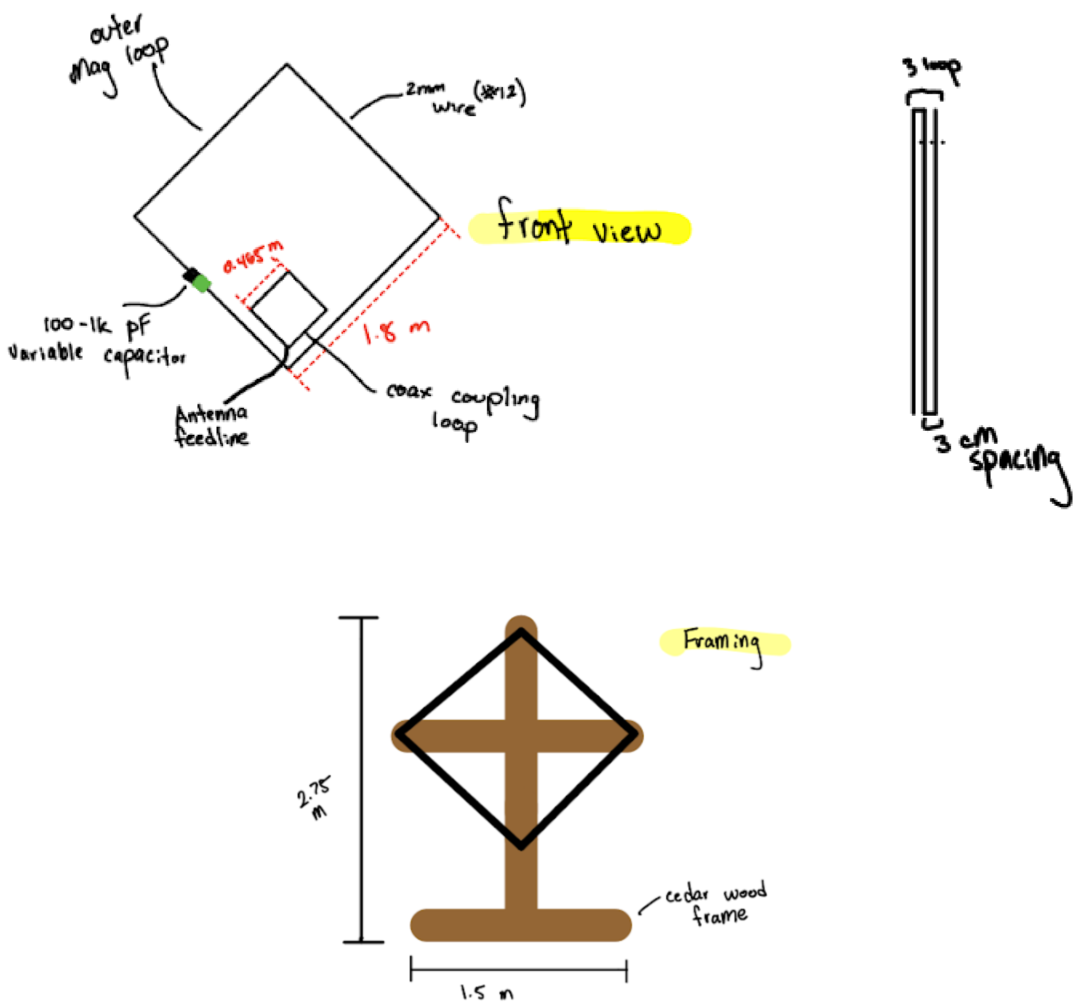


Figure 3: Antenna Sketches

We are using cedar for the frame and support of the antenna due to its lightweight and strength. PVC was another option that we discussed but decided against because of its flexibility and poor malleability. For the coax feed cable and inductive loop, we plan to use LMR 400. LMR 400 is a gold standard of coax due to very low resistance and line loss while still being flexible. The wire we are using for the antenna loops is a 12 gauge (2 millimeter diameter) copper core insulated wire. This thickness was chosen to keep the skin effect from creating too much resistance in the line. We chose solid copper core for its very low resistance and because its resistance change will be minimal with a varying frequency.

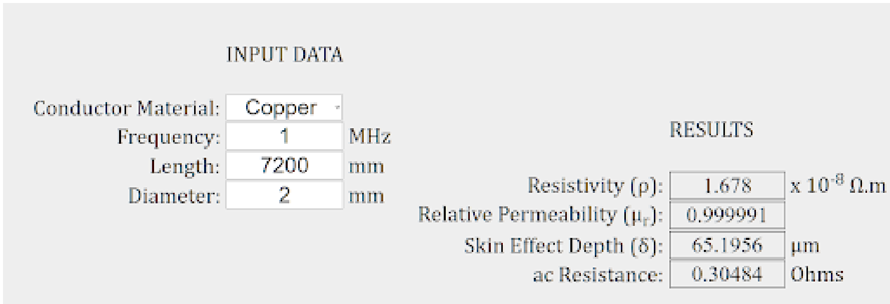


Figure 4: Calculation of Skin Effect and Resistance

We are choosing to use a vacuum variable capacitor for the loop tuner. This device uses capacitive plates in a vacuum-sealed chamber to allow tight spacing between plates to create a very large capacitance. This type of capacitor has two main advantages, first, it can create both very high and low capacitance values, and second that it is usable up to 6 kV across the device. While our final product will not be operating at that high of a voltage it will prove useful when we are testing the prototype. We calculated the range using this equation for resonant frequency:

$$f_0 = \frac{1}{2\pi\sqrt{L(C_{loop} + C_{cap})}}$$

where L and C_{loop} come from the properties of the loop and 0.54-1.71 MHz as the f_0. From this, we calculated that the smallest value we need to be 171 pF and the largest value to be 1422 pF.

Our early simulations and calculations place our current design's efficiency at -39dB. While this does not account for all of the factors at play in the real design it is close to what we can expect out of our prototype. The requirement on our final design is that it has at least a -90dB efficiency which means that we are still well within specifications even accounting for travel losses. While we are not reaching the values we originally envisioned this will still be a successful design for the project.

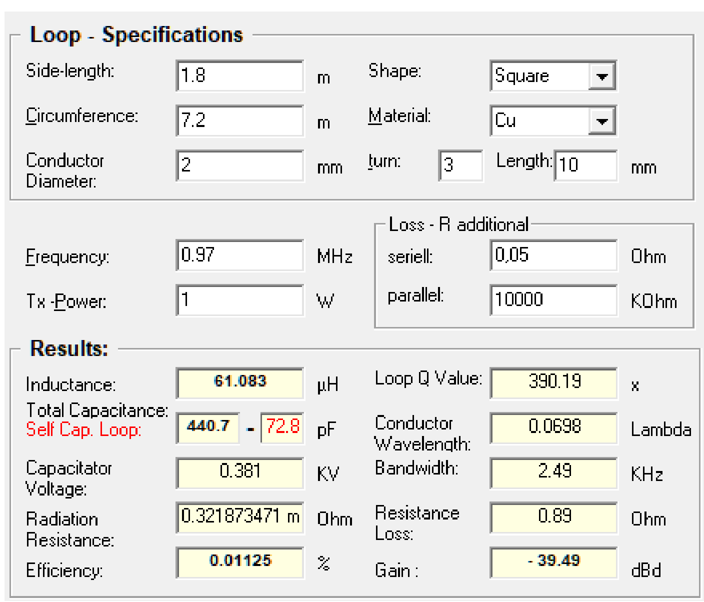


Figure 5: Calculation of Design Performance

Our final design is a small magnetic loop antenna with three turns. Three turns had the best antenna efficiency while maintaining enough inductance to match with our chosen capacitor. Greater detail is provided in the following section. Below are simulation results from EZNEC for a 1.8 meter, three turn small magnetic loop antenna.

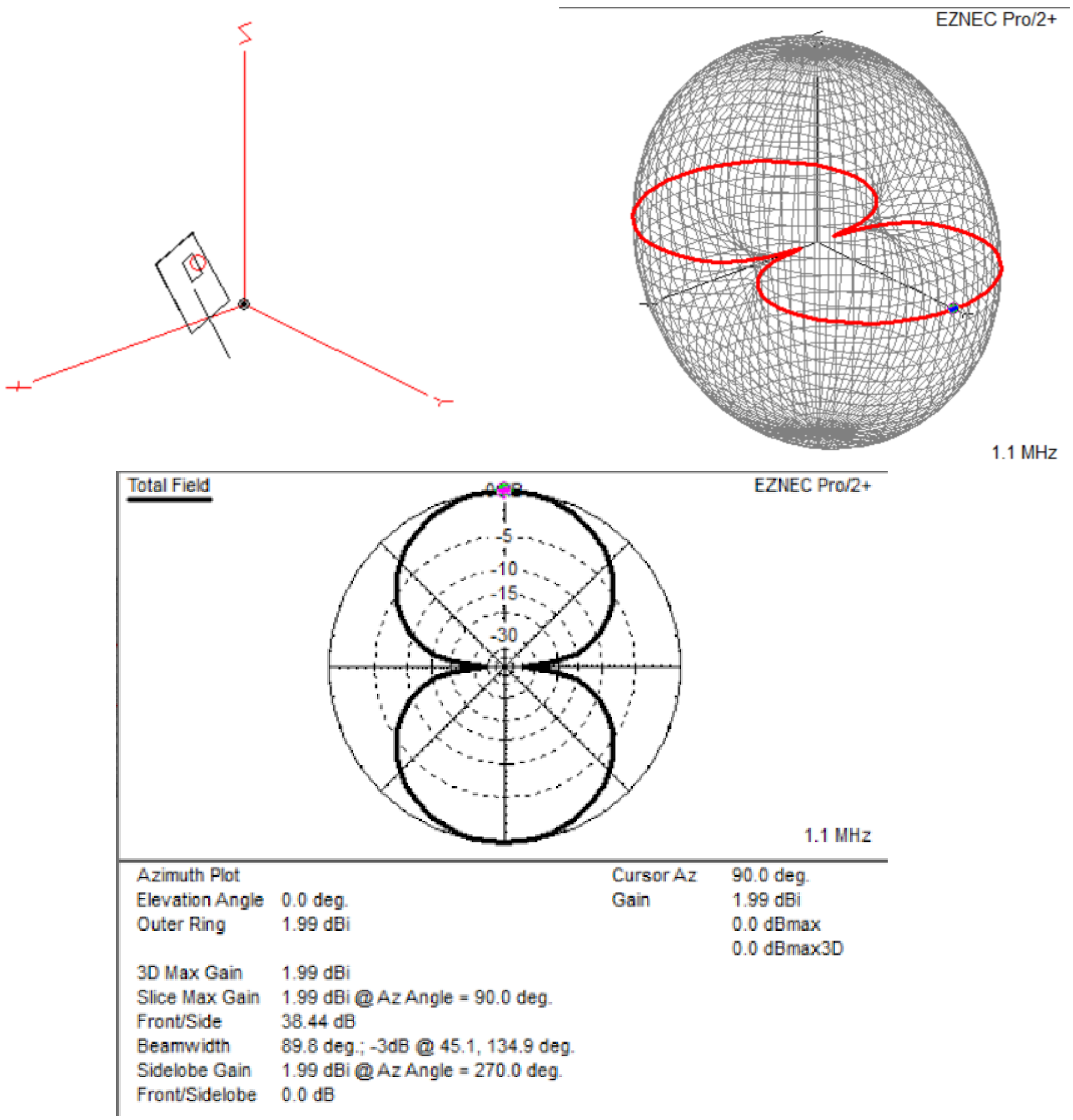
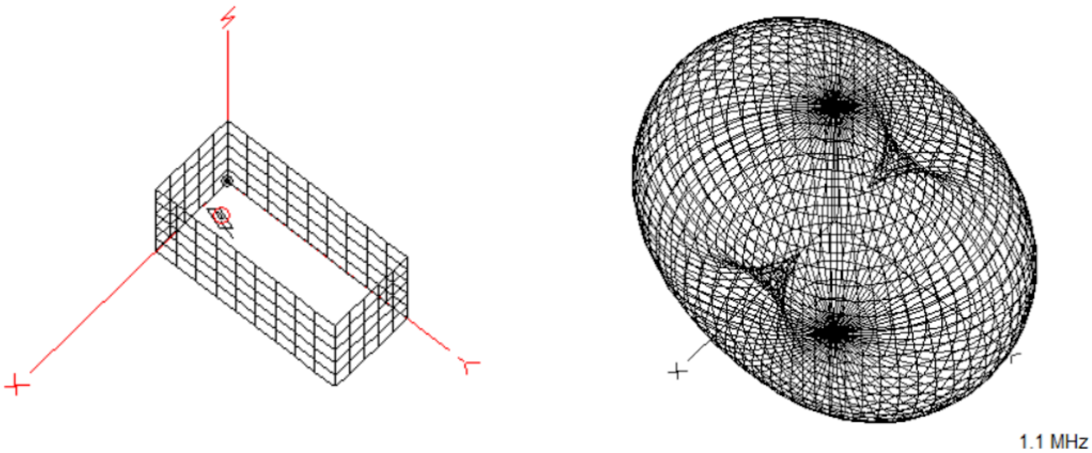


Figure 6: 1.8 meter, 3 turn Magnetic Loop Antenna

We also modeled our final antenna design in the environment in which it will be tested: the testing room at PACCAR Technical Center. Our industry mentor, Kevin Allen, provided us with the dimensions of the room, and we modeled the walls as an array of wires. As seen below, the room does not significantly impact the antenna field in the simulation.




```
Frequency = 1.1 MHz

Source 1      Voltage = 6.986 V at 90.0 deg.
              Current = 1 A at 0.0 deg.
              Impedance = 1.034E-08 + J 6.986 ohms
              Power = 1.034E-08 watts
              SWR (50 ohm system) > 100  (75 ohm system) > 100
```

Figure 7: Antenna modeled in PACCAR Technical Center Testing Room

7 Design Procedures/Methods

We began our design process by first conducting research into antenna theory as all of us have no prior experience or knowledge of antennas. Our industry mentor, Kevin Allen, provided us with documents that helped to direct our initial research. After we felt that we had a basic and fundamental understanding of antennas, we created a Pugh Matrix (shown below), that helped us to decide on an overall antenna shape.

	Dipole	Monopole	Loop	Loop - Square	Loop - Circle	Fractal
Applicable	S	S	S	S	S	S
Size	-	S	+	+	+	+
Ease of Build	-	S	+	++	-	--
Power of Transmission	+	S	-	-	-	+
Low Material Use	-	S	+	+	+	-
Total +	1	0	3	4	2	2
Total -	3	0	1	1	2	3
TOTAL	-2	0	2	3	0	-1

S is same, + is better, ++ is much better, - is worse, -- is much worse

Figure 8: Pugh Matrix Comparing Antenna Types

As the Pugh Matrix above details, we decided to create a small square loop antenna. Given our size constraints, a small magnetic loop antenna is the most efficient design.

The difficulty of design of a small, efficient antenna that operates at a wide bandwidth at low frequencies is of interest. Below is a graph of efficiency vs. frequency using the maximum size constraint of the antenna. As can be seen, the efficiency drops sharply and the AM band is not even on the graph. Due to the power we need to deliver and close proximity of transmission, this drop in efficiency is not too dire.

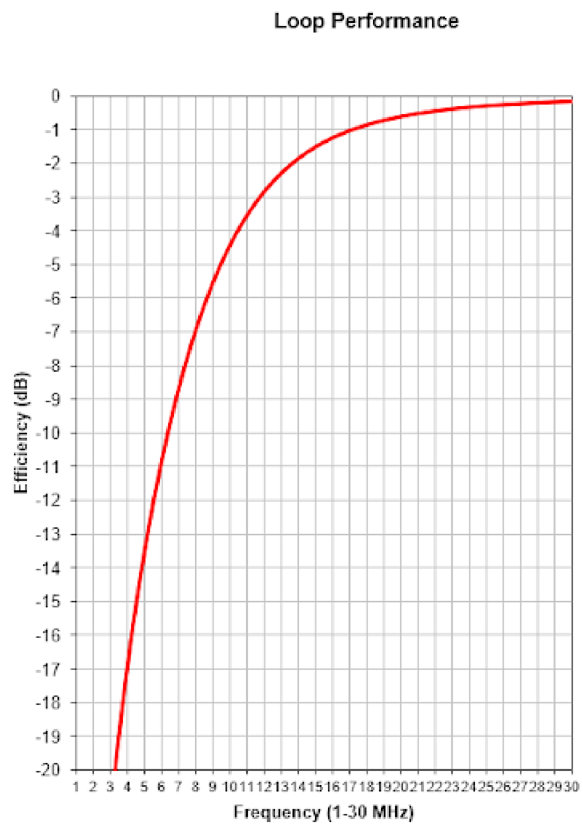


Figure 9: Loop Performance as a Function of Frequency, 1.8 meter side length

Once we had a general design choice in mind, we conducted further research and started calculating some of the specifications for the antenna, such as diameter, number of loops, loop spacing, etc. We maximized the diameter to the size constraint because the larger the diameter, the greater the length of the conductor, and therefore the greater electrical size and greater potential power transmitted by our antenna.

After our initial calculations, our industry mentor recommended to us a free antenna simulation software called EZNEC.

We followed the flowchart below to iterate and improve our design:

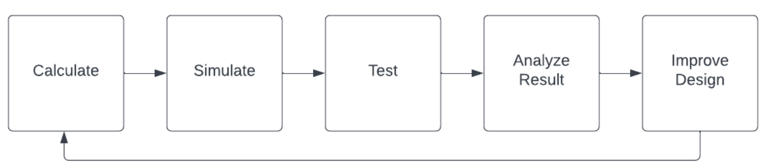


Figure 10: Iterative Design Flow Chart

Because of the very large wavelength at the AM frequencies, we originally thought that we should do a large number of loops to increase the overall length of our conductor, and thus reach greater fractions of our wavelength.

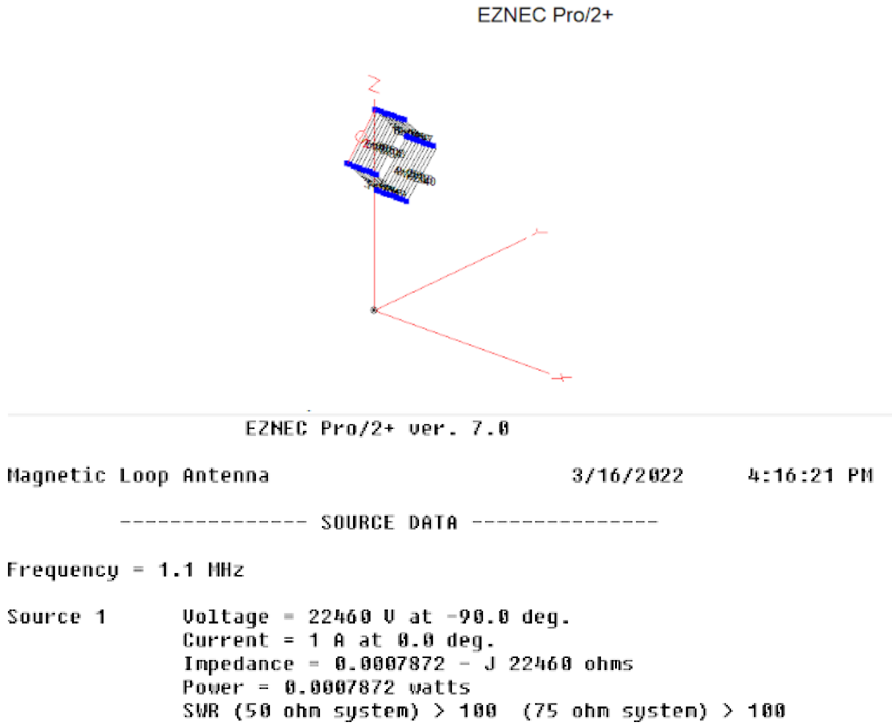
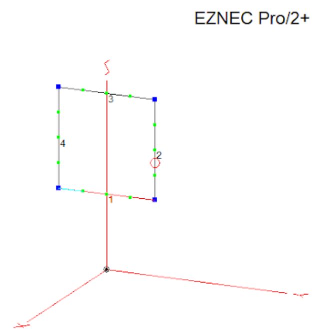


Figure 11: Multi-Loop Design

However, increasing the number of loops actually decreases the efficiency of the design because of the increased resistance through the conductor. It also increased the inductance of the loop to very large values that would make us unable to tune the loop to resonance at our frequency.

During this time, we found documentation in the amateur radio community that detailed the building and usage of single-loop magnetic antennas. Because a large number of loops did not provide the results we had hoped for, we calculated specifications and intended results for a single loop antenna.




```
                 EZNEC Pro/2+ ver. 7.0

Magnetic Loop Antenna                      3/16/2022     4:22:04 PM

         --------------- SOURCE DATA ---------------

Frequency = 1.1 MHz

Source 1       Voltage = 73.76 V at 90.0 deg.
               Current = 1 A at 0.0 deg.
               Impedance = 0.0001182 + J 73.76 ohms
               Power = 0.0001182 watts
               SWR (50 ohm system) > 100  (75 ohm system) > 100
```

Figure 12: Single Loop Design

Because of the limited overall size of our antenna and the singular loop, the length of our conductor was much, much shorter than our wavelength. This caused our gain to drop significantly, as we had expected. This new loop would also require a tuning capacitance that is far larger than is commercially available making it impractical for our design.

From here, we iteratively increased the number of loops until we found the number to give the most ideal gain and inductance.

We found that three loops is the best design to achieve the intended bandwidth with the greatest transmission power.

Once we had an antenna size and shape, we could design a coupling loop that could inductively feed our main loop. This makes the impedance matching to the signal generator significantly easier. We used general small magnetic loop antenna theory to decide that the coupling loop diameter should be approximately $\frac{1}{5}$ the diameter of the main loop.

We also had to calculate the size range and type of variable capacitor so that our antenna can be tuned to specific frequency bands. We considered using either an air-gap "butterfly" variable capacitor or a vacuum variable capacitor, which are two of the most popular variable capacitors. Due to the wide range of capacitance required for our frequency range, we decided on a vacuum variable capacitor. The largest possible capacitance of purchasable air-gap capacitors appeared to be around 1000 pF, whereas vacuum capacitors go much higher (>2000 pF).

In Spring quarter, with our tentative design completed in Winter quarter, we will focus on actually building and testing our antenna. From our design, the size constraints will be met, and we believe from our simulations that the bandwidth and power transmission goals will be achieved. Once built, we can test our antenna, and compare it with our expected results. From there, we can make design adjustments as necessary.

8 Test Design

As we have begun to hit the limits of what modeling software is able to tell us, our next step is the prototyping process. Once the materials required arrive and the prototype is built we will begin by testing the complex impedance of our antenna before placing the tunable capacitor in the loops. Our models predict that without the capacitor we should have a highly inductive load which can then be compensated for via the capacitor. If we get a reading which is inductive we will know our models are correct and we can add the capacitor to the loop.

Once the capacitor is inserted into the loop, its main purpose is to allow our antenna to be tunable to different frequencies. We designed this antenna to have a tunable frequency centered at 970 kHz as per the specifications of our project. We will test this by inputting a frequency of 970 kHz into the inner coax coupling loop and tuning the capacitor on the outer loop to minimize complex impedance as much as possible. We can then test the gain of our antenna and ensure it is up to spec.

In order to accurately test this, we must either buy or borrow an antenna with a characteristic impedance of 75 Ω (which is the impedance of PACCAR truck antennas). Once we have acquired this antenna we can do a frequency sweep and measure the received power on the testing antenna. This test can be done at multiple tuned frequencies to ensure the entire AM band is covered. In addition, this test can be conducted at multiple voltages to ensure that the 30 $dB\mu V$ design power requirement is achieved.

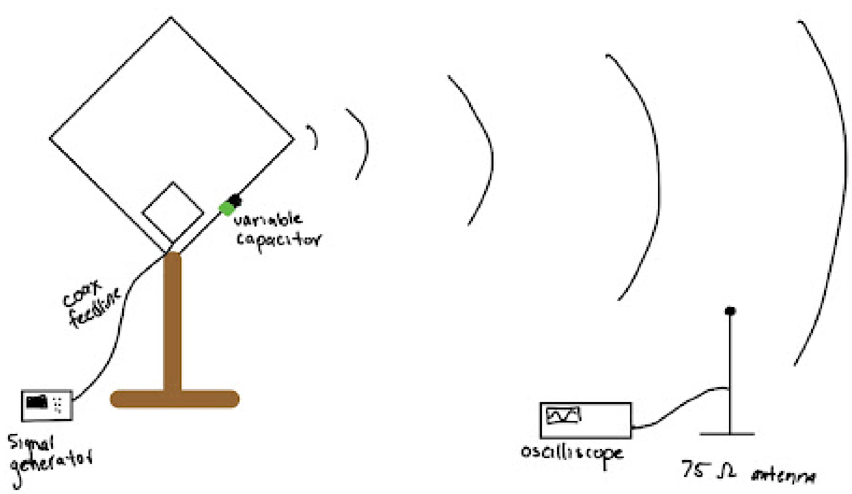


Figure 13: Sketch of Testing Setup

9 Realistic Constraints/Relevant Engineering Standards

Coming into this project we had grand ideas about the antenna we could create. We had an idea of an antenna that works with excellent efficiency and effectiveness as a radio transmitter in addition to a testing device. Our initial research and investigation only reinforced our optimism and made us think that this project would be straightforward to complete. However, we were initially lacking in technical understanding of what this antenna would entail. It quickly became apparent that we were going to run into several fundamental limitations on our final design.

In antenna design, there are a couple of fundamental tradeoffs that can not be avoided, size, efficiency, and bandwidth. If you change one of them the others will need to change as well to compensate. For example, we are trying to minimize the size of our antenna, and that entails a decrease in the efficiency and the bandwidth. When we then sought to improve the efficiency of our design we dropped the bandwidth drastically, which will make tuning and refocusing the central frequency more difficult.

While researching small magnetic loop antennas we noted that they work well around 10% of the wavelength. However, at our targeted frequency of 970 kHz, the wavelength is 309 meters. This means that even the largest loop that stays within the design specifications is only around 1.8% of the wavelength. Further inquiry into compacting our antenna brought us to a paper that included this quote, "Despite decades of investigation, compact antennas in the VLF and low-frequency bands have remained an unattainable holy-grail considered impractical due to the fundamental tradeoff between antenna efficiency and electrical size (Hassanien)." This put to rest our concept of making an efficient antenna and made us trace back our steps to the original design requirements where we are working to improve the efficiency as best we can, which should keep us well within the limit of -90 dB even if it is not the number we originally envisioned.

10 Project Resources/Budget

Vendor	Ham Radio Outlet			
	Item	**Cost per item**	**Quantity**	**Total cost (in $)**
1	150ft lmr400 cable	1.21/foot	150	200.1
			Total:	200.1
Vendor	Amazon			
	Item	**Cost per item**	**Quantity**	**Total cost (in $)**
1	Wood Screws	8.76	1	8.76
			Total:	8.76
Vendor	RF Parts			
	Item	**Cost per item**	**Quantity**	**Total cost (in $)**
1	Vacuum Variable Capacitor	616.16	1	616.16
			Total:	616.16
Vendor	QC Supply			
	Item	**Cost per item**	**Quantity**	**Total cost (in $)**
1	12 Gauge Copper Wire	0.44/foot	300	160.18
			Total:	160.18
Vendor	Home Depot			
	Item	**Cost per item**	**Quantity**	**Total cost (in $)**
1	2in x 2in x 96in	11.89	4	47.57
			Total:	47.57
			GRAND TOTAL:	1032.77

11 Industry Sponsor Comments

NEED KEVIN'S NOTES

12 References

1. Skin Effect Calculator
   https://chemandy.com/calculators/round-wire-ac-resistance-calculator.htm

2. Varification Calculator
   https://earmark.net/gesr/loop/umr_emc_calc.htm

3. Hassanien, A.E., Breen, M., Li, MH. et al. Acoustically driven electromagnetic radiating elements. Sci Rep 10, 17006 (2020).
   https://doi.org/10.1038/s41598-020-73973-6

4. Antenna Theory
   https://sidstation.loudet.org/antenna-theory-en.xhtml

5. Fractal antenna
   https://antenna-theory.com/antennas/fractal.php

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   https://www.sciencedirect.com/topics/computer-science/dipole-antenna

7. EZNEC Pro/2+ v7.0 Antenna Software by W7EL
   https://www.eznec.com/

8. DG0KW's Website and Calculator
   https://www.dl0hst.de/magnetlooprechner.htm

9. LC Resonance Equation Write Up
   http://electronbunker.ca/eb/InductanceCalcRc.html

10. Small Magnetic Loops by Larry Nelson K5IJB
    http://www.webclass.org/k5ijb/antennas/Small-magnetic-loops-K5IJB.htm

11. Small Transmitting Loop Antennas by Steve Yates (AA5TB)
    https://aa5tb.com/loop.html