Oklahoma State University
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Critical Design Review: Horizontal HF

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Team and Team Structure

Roles and Responsibilities

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Report contributions:

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4. Performance and Operational Requirements
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Report contributions:

1. Applicable Industry or Professional Standards
2. Design Details: EZNEC Simulations
3. Design Details: Layout and Construction Details
4. Appendix: MATLAB code for EZNEC

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Report contributions:

1. Design Strategy: Whip Antenna
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3. Design Strategy: LPDA Antenna
4. Environmental, Health, Safety, Sustainability, Social, Cultural, Global, Ethical, and Professional Considerations

Chapter 2

Problem Statement

Naval vessels are outfitted with shipboard electronics which must withstand HF communication fields. The Naval Surface Warfare Center Dahlgren Division tests how these electronic systems respond to EM fields before deployment. Standard testing (HERO, EMV) uses a vertical whip/telescoping antenna with the missile suspended vertically, as shown in figure 2.1. The problem that arises lies in the fact that large missiles cannot be lifted with available cranes, and the testing procedure is challenging in general. Thus emerges the need for a horizontal broadband HF antenna system to test missiles.

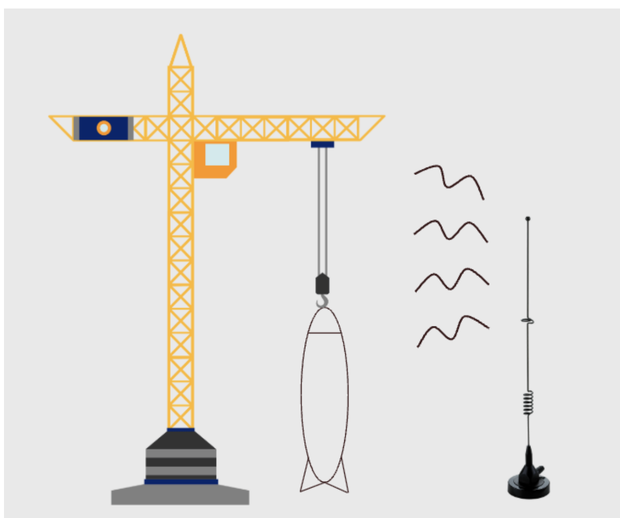


Figure 2.1: Cartoon Graphic of EMF Testing Setup

The proposed antenna system is shown below in figure 2.2.

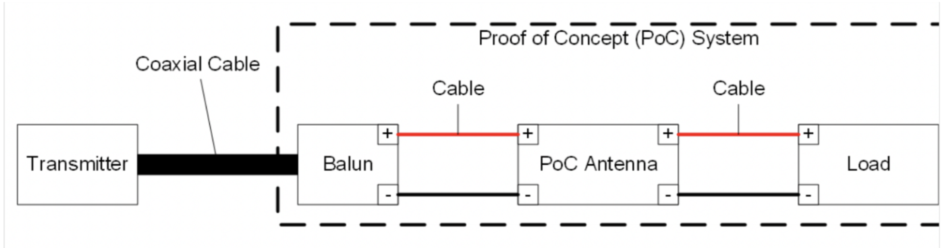


Figure 2.2: Image Provided by Dalgren Demonstrating Proposed Antenna System

This project requires a broadband antenna with a large 3dB beamwidth on the horizontal plane to be designed for HF communications. This antenna will need to be able to operate at high power, but the proof of concept does not need to be tested at this high power. It is sufficient to demonstrate means of scalability. The resulting antenna should have a reasonable VSWR at all expected frequencies and have a sufficiently large (40'x6'x6'), uniform (-3dB to +3dB) electromagnetic field for all HERO and EMV testing purposes.

Chapter 3

Design Constraints and Considerations

3.1 Performance and Operational Requirements

1. Transmit/receive on 5–10 frequencies between 13-27MHz, or show coverage (expected transmit frequencies shown in figure 3.1.
2. Include balun or 50Ω impedance match for 10 kW HF transmitter.
3. Generate sufficiently uniform horizontal 3dB EM field over 40' x 6' x 6' volume for HF HERO and EMV testing purposes.
4. Demonstrate scalability for 10 kW transmit power.
5. No size constraint, but within reason.

Test Frequencies (MHz)	
4.040	13.530
4.803	16.060
5.385	17.048
6.400	18.036
6.970	19.270
7.595	20.510
7.990	21.460
9.050	23.180
9.803	24.450
11.064	26.875
12.045	

Figure 3.1: Expected Frequencies

3.2 Applicable Industry or Professional Standards

1. FCC Part 97 - general license required to transmit in HF band
   - Juliette Reeder has obtained her general license to transmit at select frequencies in the HF band.
2. FAA 14 CFR Part 77 - maximum height of antennas and distance from airports
   - The maximum height is well above the designed height of the antenna. Additionally, the antenna will only transmit at low power and at Richmond Hill.
3. IEEE/ANSI C63 Series - standards on EMC
4. IEEE Std 149 - standards on testing antenna power and field strength
   - The antenna is set to only transmit at a maximum of 20 dBm, well below the maximum power strength.
5. IEEE Std 291 - standards on spurious emissions
6. MIL-STD-461 - standards on EMC
7. MIL-STD-464 - standards on Electromagnetic Environments (EMEs)
8. MIL-HDBK-240 - standards on testing under ordnance

3.3 Environmental, Health, Safety, Sustainability, Social, Cultural, Global, Ethical, and Professional Considerations

Our environmental and sustainability considerations would include minimizing waste during fabrication, keeping ROHS compliant by avoiding using toxic materials, and minimizing the use of electricity during high-power testing (if any) to limit our environmental impact. If we do not do high-power testing during the duration of this project, we can also reduce electricity use by turning off RF equipment when not in use.

Some important health and safety considerations include following ICNIRP guidelines; 27.7 V/m is the 5-minute occupational limit for electric field exposure. A 1kW HF antenna can reach this field strength at more than 30 feet away, so we are unlikely to be able to safely test at power levels anywhere close to this example power.

Some cultural and global factors to consider include how more efficient electromagnetic compatibility (EMC) testing might reduce costs, how operating on the allocated frequencies can affect bandwidth and communication interference, and what would happen in the case a missile does not detonate when intended.

Ethical and professional considerations primarily focus on conducting antenna testing responsibly and producing an accurate design. Inaccurate EMC testing (due to poor design) could lead to missile false positive tests and accidental detonations, which would have immense negative effects. To avoid this we need to be honest and transparent about the limitations of our design so the testing system is not overly relied upon. We also must ensure we conduct tests responsibly as to not communicate outside amateur frequency bands and to avoid FCC violations.

Chapter 4

Design Strategy

Design Options and Trade-offs

- Whip Antenna
  - Straight monopole antenna
  - The main issue with using a whip antenna is its narrow bandwidth and immense physical length. To decrease the physical length, we can add an inductive loading coil at the base of the antenna to change its electrical length. This inductive load can cause an increase in current and electrically lengthen a physically shorter antenna.

Frequency (MHz)	Length (m)	Inductance (nH)
13.53	5.5394	424.73604
16.06	4.6668	264.90732
17.048	4.3963	220.51907
18.036	4.1555	182.97347
19.27	3.8894	143.58235
20.51	3.6542	110.51624
21.46	3.4925	88.65497
23.18	3.2333	54.98091
24.45	3.0654	33.90309
26.875	2.7888	0

Figure 4.1: Chosen physical lengths and load inductance for each frequency

- To regulate the common-mode current off of the antenna, a 1:1 balun is used. Additional inductors and capacitors can be used to help tune the antenna at specific frequencies.
- This design has several drawbacks, including the high price of variable capacitors, a large enclosure and switching network would be needed to adjust the antenna, and that the components needed are heavily dependent on testing and would need be be changed throughout. Some advantages are that it would be relatively simple to show scalability, and that it well tuned at each specific test frequency.

• End Fed Long (Random) Wire Antenna

- Consists of a single long wire
- Wire length chosen such that it has equally bad SWR for all required frequencies, ideally below 2 for all.
- The balun would be a 9:1 unun with a trifilar winding wound nine times around a toroid core.
- For the tuner, a capacitor is needed, or you can use a quarter wavelength transformer (QWT) with an inductor. The capacitor may need to be picked experimentally based on its resonance with the 9:1 unun. Finally, a 4.7 kΩ resistor is needed, or alternatively a 1 meter wire can be used as a "counterpoise".

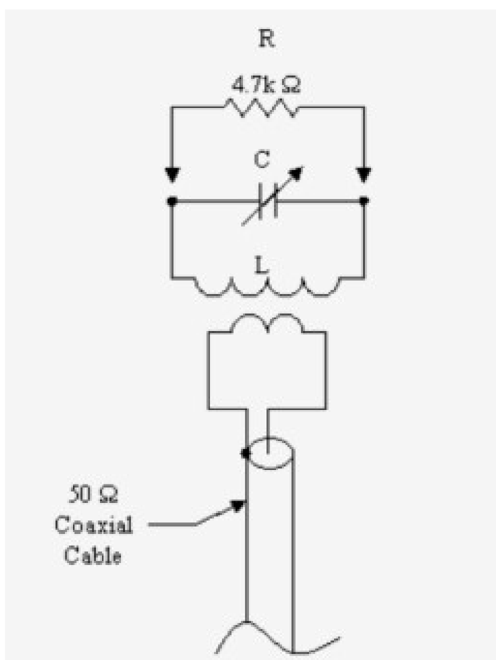


Figure 4.2: EFLW Tuner with Resistor

• Log-Periodic Dipole Antenna

- A Log-Periodic Dipole Antenna (LPDA) consists of many half-wavelength dipole elements placed along a central boom support in alternating phase.

- The elements are spaced following a logarithmic function, and additionally, the length of the elements increase logarithmically.
- This antenna type is unidirectional with the greater gain in the direction of the end of the boom support with the shortest elements (see figure 7.6).
- Each element is resonant at a wavelength that is twice its length. The desired maximum and minimum frequencies and the length and spacing scaling factors (τ and σ) can be used to calculate the specs of the LPDA. A greater τ and smaller σ lead to improved performance but greater cost and overall antenna size.

Element	Length(ft)	Position(ft)	Frequency
1	37.8	0	13
2	35.2	3.5	13.978
3	32.7	6.8	15.031
4	30.4	9.8	16.162
5	28.3	12.7	17.378
6	26.3	15.3	18.687
7	24.5	17.7	20.093
8	22.8	20	21.605
9	21.2	22.1	23.232
10	19.7	24.1	24.98
11	18.3	25.9	26.86
12	17	27.6	28.882
13	15.8	29.2	31.056
14	14.7	30.7	33.394

Figure 4.3: LPDA specs for a frequency range of 13-26 MHz, $\tau = 0.93$, and $\sigma = 0.05$

- Final Selection and Justification
  - The final choice for a transmitter is the LPDA design.
  - The LPDA has the best SWR for a true broadband design.
  - No tuner is needed for the LPDA, which simplifies the design cost.
  - While the LPDA can be complicated, it is easy to demonstrate scalability through simulation.
  - While it initially appears difficult to fabricate, a design consisting of rope and wire keeps the antenna lightweight and simple to construct and take down.

Chapter 5

Design Details

5.1 EZNEC Simulations

Using a free software called EZNEC, a preliminary design of the antenna was created. EZNEC is also able to run simple simulations that calculate the SWR and FF Plots of the antenna for a specified frequency or frequency range. Figure 5.1 shows the finalized EZNEC design. Take note of the coordinate system displayed. Figure 5.2 is a 3-dimensional plot of the far field for a frequency of 20 MHz. The coordinate system shown aligns with the coordinate system of Figure 5.1.

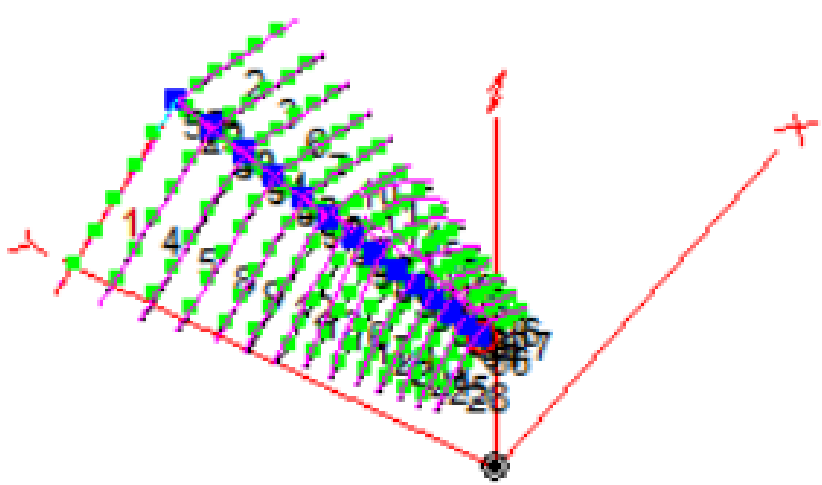


Figure 5.1: EZNEC model of the designed antenna.

The EZNEC model is created by specifying the start and end coordinates of wires. Each wire can be given a diameter and connected, which allows for the creation of a more complex structure, like an antenna. Each element is too large to be a flat, straight wire, elevated into

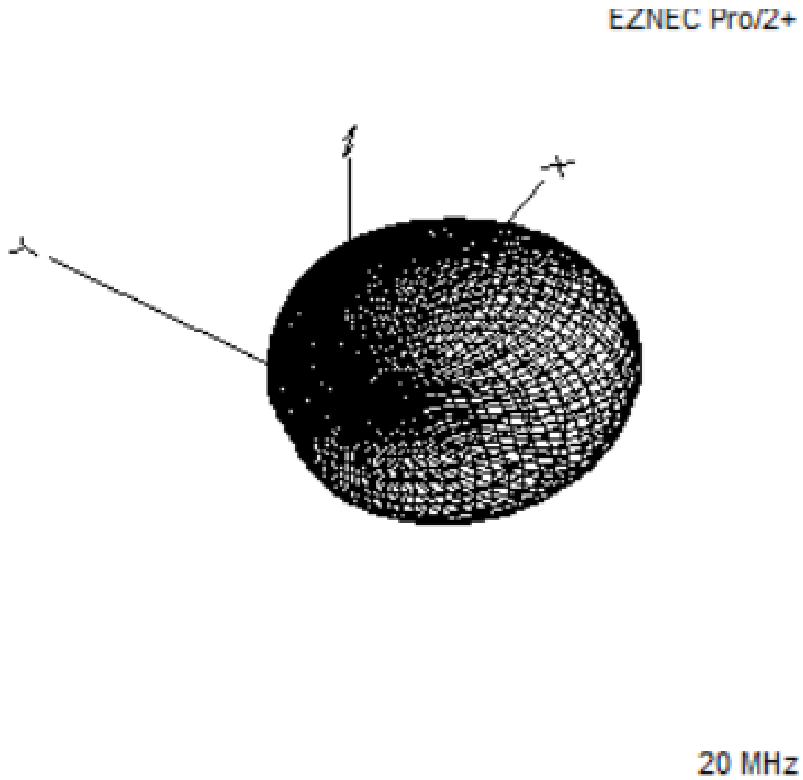


Figure 5.2: 3-dimensional far-field plot calculated for 20 MHz through EZNEC.

the air (for reference, the largest dipole is nearly 40 feet). Because of this, each element must bend and be supported using a tight rope tied to the ground. This adds some complexity to calculating individual start and end coordinates of the wires. To account for this, a MATLAB script was created to calculate specific coordinates and allow for the user to adjust factors like the angle of the elements, the angle of the boom, frequency changes, and height above the ground. This code can be found in Appendix B.

Beyond just the 3D far-field plots, EZNEC also generates azimuth and elevation plots, see Figure 5.3, and EZNEC can run a simulation to calculate SWR for a specified frequency range, see Figure 5.4. For good performance, SWR needs to be below 2:1, which the EZNEC simulation easily accomplished. By running an SWR simulation and creating multiple plots, EZNEC can generate a theoretical SWR, beamwidth, and maximum gain for each of the test frequencies the antenna must transmit.

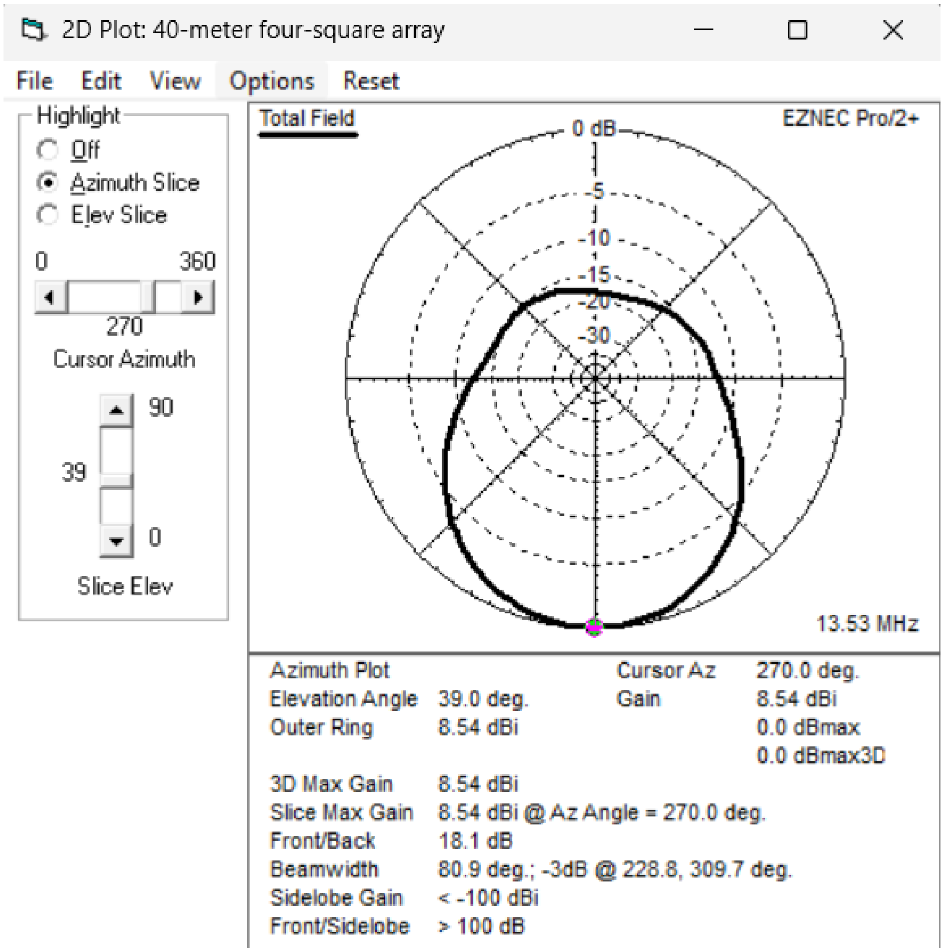


Figure 5.3: Azimuth plot for EZNEC simulation at 13.53 MHz.

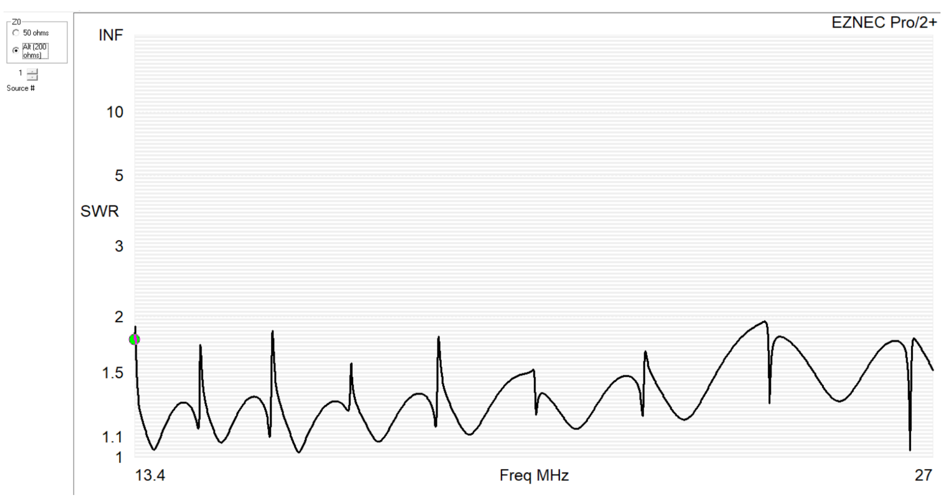


Figure 5.4: EZNEC SWR simulation for a range of 13.4-27.0 MHz. The step interval is 0.01 MHz.

Frequency (MHz)	Max Gain (dBi)	SWR
13.53	8.54	1.19
16.06	9.09	1.11
17.05	10.66	1.26
18.04	9.4	1.31
19.27	9.38	1.17
20.51	9.18	1.31
21.46	9.53	1.39
23.18	9.49	1.4
24.45	9.22	1.79
26.88	9.4	1.63

5.2 Layout and Construction Details

- N-Type Connectors were chosen for this design, for the following reasons:
  - Support up to 11 GHz (standard versions) or 18 GHz (precision versions).
  - Durable
  - Weather resistant.
  - Handle high-power RF well.
  - Ideal Use Cases:
    - Base stations and outdoor antennas.
    - Military and aerospace systems.
    - High-power RF applications.
- 18-Gauge Stranded Bare copper wire was chosen for the following reasons:
  - Stranded wire is flexible to ease antenna construction
  - Bare wire needed to properly transmit power
  - At low power, the maximum current should not be produced
  - 18-Gauge is lightweight and fairly inexpensive
- Nylon rope was chosen for the following reasons:
  - Very weather-resistant and durable
  - Inexpensive and easily obtained
  - Useful for guy lines
- RBA 4:1 Voltage Balun
  - Antenna is designed for 200 Ω, so a 4:1 conversion is needed
  - Has a working frequency range of 1.8-30 MHz
  - Packaged in a weather-proof enclosure

- Coax 50-ohm Cable
  - Needs to be 50 Ω to match signal generator output and RBA 4:1 input.
  - No connectors on the cable initially to fit potential design changes.

A 13-foot pole created for a previous capstone project will serve to elevate the antenna. Three ropes will attach to this pole and serve as guy lines for stability. They will be planted in the ground using simple stakes. More of the Nylon will make a 20-degree angle with the ground and be connected via a stake. This will serve as the central boom of the antenna, and wire will wrap around this line, acting as the supply and return for each element. Using the spacing calculated with the EZNEC simulations, wire will be strung from the central boom at an angle of approximately 20 degrees. The wire will be connected to a dog-bone insulator using a bowline knot. On the other end of the insulator, Nylon is connected via a bowline and then connected to a stake using a taught-line hitch before it is secured to the ground. Bowlines are stable knots that are used to keep tension in ropes, while a taught-line hitch allows for tension to be increased or released as needed. Both knots are simple and easy to tie and untie.

At the short end of the antenna, the RBA 4:1 balun is connected to both the power and return wires on the boom. The balun supports a bare wire connection. On the opposite end of the balun, the coaxial cable is connected using a male UHF connector. This connector has a crimp connection to attach to the cable. The other end of the cable is crimped to a male N-type connector and attached to a signal generator. The generator will control the power and frequency of the transmitted signal.

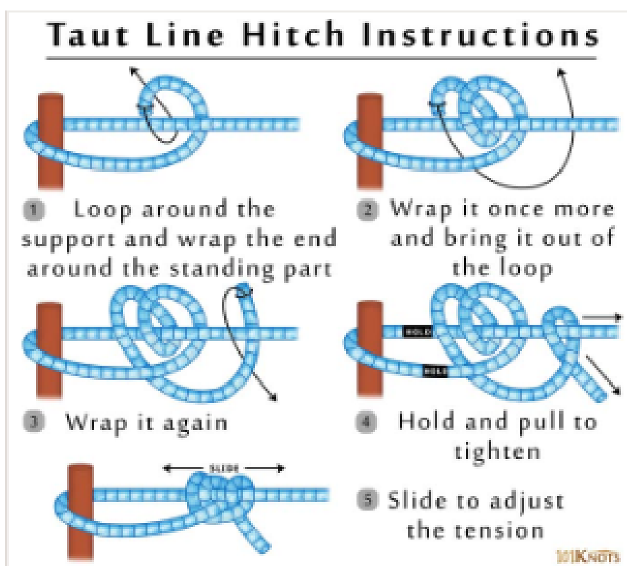


Figure 5.5: Instructions to tie a Taut-Line Hitch.

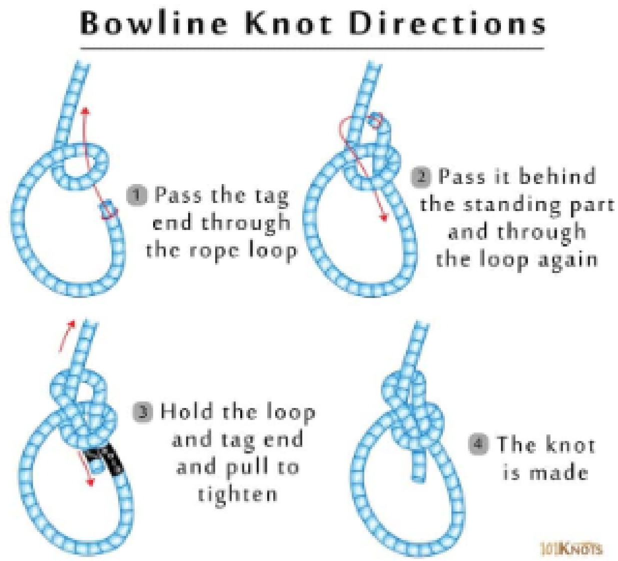


Figure 5.6: Instructions to tie a Bowline.

5.3 Critical Dimensions, Orientations, and Mounting Arrangements

Figure 5.7 shows a sketch of the designed antenna to be constructed.

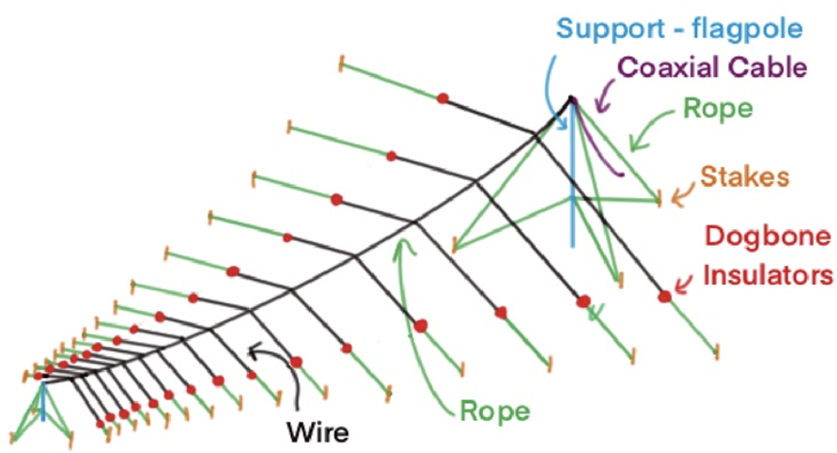


Figure 5.7: Sketch of antenna to be constructed.

Shown below are the dimensions for the elements, calculated using MATLAB:

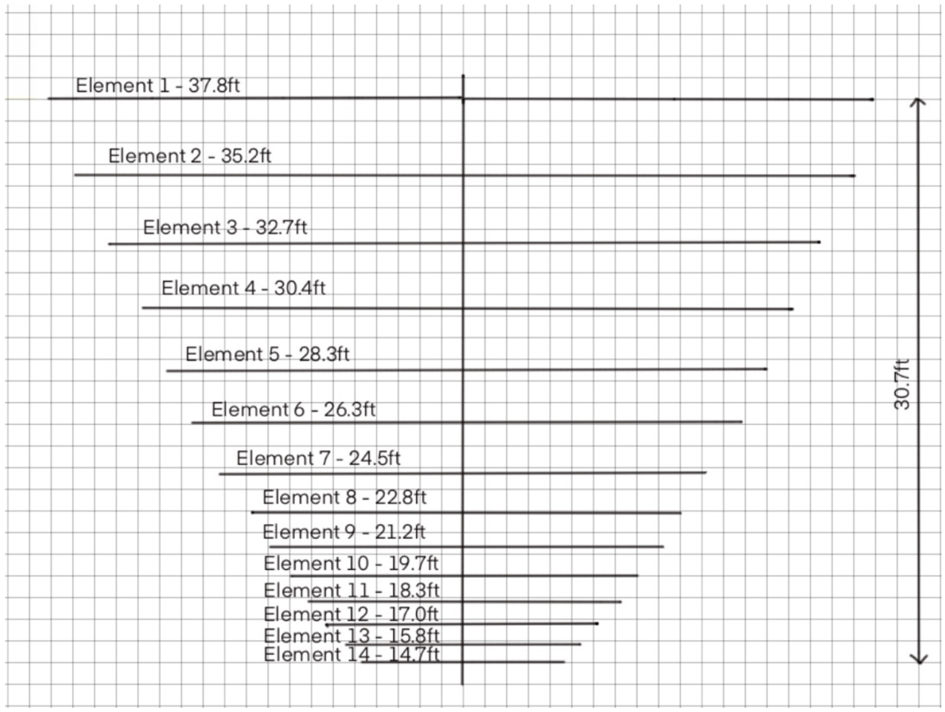


Figure 5.8: Image showing dimensions of antenna elements.

Figure 5.9 Shows the coaxial connection from antenna to balun to signal generator.

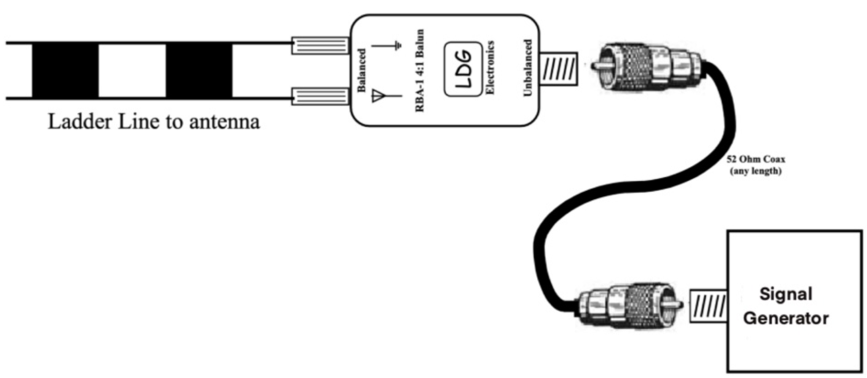


Figure 5.9: Coaxial connection from antenna to balun to signal generator.

5.4 Theory of Operation and Operating Instructions

1. Preparation

a) Inspect all antenna components for wear or damage (wires, rope, insulators, stakes, poles, balun, and coax).

b) Verify site safety: level ground, no overhead lines, and adequate distance for HF operation.

c) Lay out the 32ft boom on the ground and confirm element spacing per the design chart.

2. Initial Assembly

a) Attach each wire element to a dog-bone insulator using a bowline knot.

b) Connect rope between insulator and stake point using a taut-line hitch for adjustable tension.

c) Erect the 13ft main support pole (with tethers and stakes) and 4ft secondary support (PVC pipe).

d) Raise the boom between supports so that large elements reach approximately 13ft in height and shortest elements 3ft.

3. Deployment

a) Unroll each element and secure to its respective stake, keeping uniform spacing and alignment.

b) Attach the 4:1 balun at the feedpoint and connect the coaxial feedline with proper strain relief.

c) Confirm all elements are under even tension and not contacting the ground or other wires.

4. Operation

a) Ensure the transceiver and power supply are properly grounded.

b) Connect the feedline from the balun to the transceiver output.

c) Verify that the antenna tuner (if used) is in bypass or set for the intended frequency band.

d) Begin with low RF power ($\leq$ 10 W) and verify acceptable SWR.

e) Gradually increase power until reaching 100 W PEP (**DO NOT EXCEED 1500 W PEP** – General class limit per FCC Part 97).

f) During operation, regularly monitor:

f)i. SWR readings for sudden increases (indicating detuning or loose connections)

f)ii. Support stability (tensioned ropes and stakes)

f)iii. Feedline strain relief and connector integrity

g) If high SWR or instability occurs, immediately cease transmission and inspect connections and element tension.

5. Testing

a) Perform continuity and impedance checks before applying RF power.

b) Measure VSWR across the HF band; adjust element tension or height as needed.

c) During test operation, monitor for arcing, imbalance, or high SWR and correct immediately.

6. Takedown

a) Power down and disconnect all RF connections.

b) Detach elements, coiling each wire around its insulator for storage.

c) Remove boom and support poles; collect all stakes, tethers, and cables separately.

d) Protect RF connectors with caps and store all components in a dry container.

e) Store equipment with ropes and wires loosely coiled to prevent kinking.

Chapter 6

Design Execution Plan

This project will be executed in four phases, shown in figure 6.1. Phase One is now complete, which involved research, project planning, and creating preliminary design options. Phase Two is nearly complete, in which the design was fine tuned and testing strategy efficacy was verified experimentally. Phase Three will begin soon, with material procurement and fabrication. Finally, the bulk of the project will be in Phase Four, directed toward testing and validation of the design.

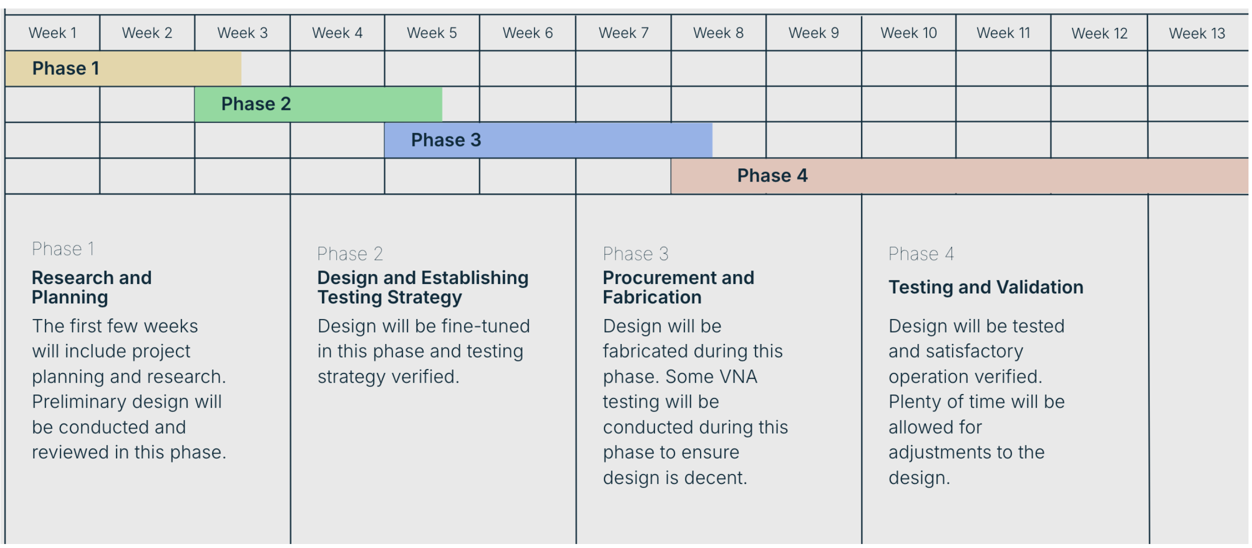
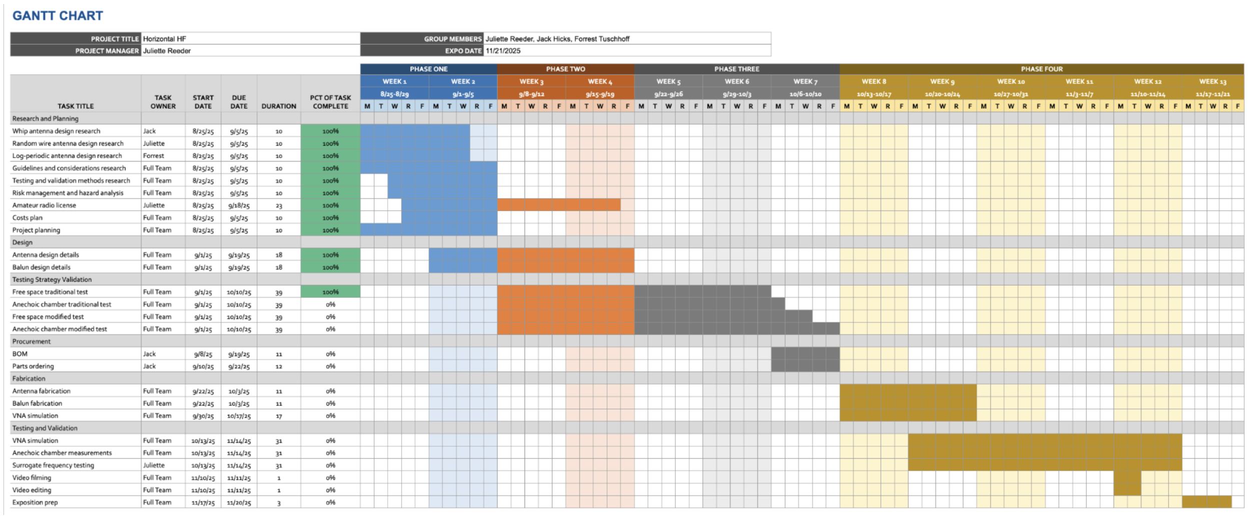


Figure 6.1: Overview of Project Plan

A more detailed Gantt Chart is shown below in figure 6.2.



GANTT CHART

PROJECT TITLE	Horizontal HF	GROUP MEMBERS	Juliette Reeder, Jack Hicks, Forrest Tuschhoff
PROJECT MANAGER	Juliette Reeder	EXPO DATE	11/21/2025

PHASE ONE: WEEK 1 (8/25-8/29), WEEK 2 (9/1-9/5); PHASE TWO: WEEK 3 (9/8-9/12), WEEK 4 (9/15-9/19); PHASE THREE: WEEK 5 (9/22-9/26), WEEK 6 (9/29-10/3), WEEK 7 (10/6-10/10); PHASE FOUR: WEEK 8 (10/13-10/17), WEEK 9 (10/20-10/24), WEEK 10 (10/27-10/31), WEEK 11 (11/3-11/7), WEEK 12 (11/10-11/14), WEEK 13 (11/17-11/21)

TASK TITLE	TASK OWNER	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
Research and Planning					
Whip antenna design research	Jack	8/25/25	9/5/25	10	100%
Random wire antenna design research	Juliette	8/25/25	9/5/25	10	100%
Log-periodic antenna design research	Forrest	8/25/25	9/5/25	10	100%
Guidelines and considerations research	Full Team	8/25/25	9/5/25	10	100%
Testing and validation methods research	Full Team	8/25/25	9/5/25	10	100%
Risk management and hazard analysis	Full Team	8/25/25	9/5/25	10	100%
Amateur radio license	Juliette	8/25/25	9/18/25	23	100%
Costs plan	Full Team	8/25/25	9/5/25	10	100%
Project planning	Full Team	8/25/25	9/5/25	10	100%
Design					
Antenna design details	Full Team	9/1/25	9/19/25	18	100%
Balun design details	Full Team	9/1/25	9/19/25	18	100%
Testing Strategy Validation					
Free space traditional test	Full Team	9/1/25	10/10/25	39	100%
Anechoic chamber traditional test	Full Team	9/1/25	10/10/25	39	0%
Free space modified test	Full Team	9/1/25	10/10/25	39	0%
Anechoic chamber modified test	Full Team	9/1/25	10/10/25	39	0%
Procurement					
BOM	Jack	9/8/25	9/19/25	11	0%
Parts ordering	Jack	9/10/25	9/22/25	12	0%
Fabrication					
Antenna fabrication	Full Team	9/22/25	10/3/25	11	0%
Balun fabrication	Full Team	9/22/25	10/3/25	11	0%
VNA simulation	Full Team	9/30/25	10/17/25	17	0%
Testing and Validation					
VNA simulation	Full Team	10/13/25	11/14/25	31	0%
Anechoic chamber measurements	Full Team	10/13/25	11/14/25	31	0%
Surrogate frequency testing	Juliette	10/13/25	11/14/25	31	0%
Video filming	Full Team	11/10/25	11/11/25	1	0%
Video editing	Full Team	11/10/25	11/11/25	1	0%
Exposition prep	Full Team	11/17/25	11/20/25	3	0%

Figure 6.2: Detailed Gantt Chart as of October 3, 2025

Chapter 7

Testing Strategy

SAS-510-2 Log Periodic Antenna Details

Shown are details about the pair of small Log Periodic Antennas used to verify the testing strategy for this project. Shown are design specifications, expected VSWR, gain, and Azimuthal plot of gain for this antenna.

Table 7.1: SAS-510-2 Log Periodic Antenna Specifications

Parameter	**Specification**
Model	SAS-510-2 Log Periodic Antenna
Frequency Range	290 MHz – 2000 MHz
Antenna Factor	14 to 32 dB/m
Average Gain	6.5 dBi
Maximum Continuous Power	1000 W
Max Radiated Field	200 V/m
Pattern Type	Directional
3dB Beamwidth (E-Field)	45°
3dB Beamwidth (H-Field)	100°
Impedance	50 Ω
VSWR	1.45:1 (typ.), 2.2:1 (max)
Connector	N-Type, female
Mounting Base	1/4–20 thread, female
Physical Dimensions	
Length	24.7 in (62.7 cm)
Width	20.1 in (51.1 cm)
Weight	1.4 lb (0.64 kg)

Figure 7.1: Photograph of antenna from datasheet.

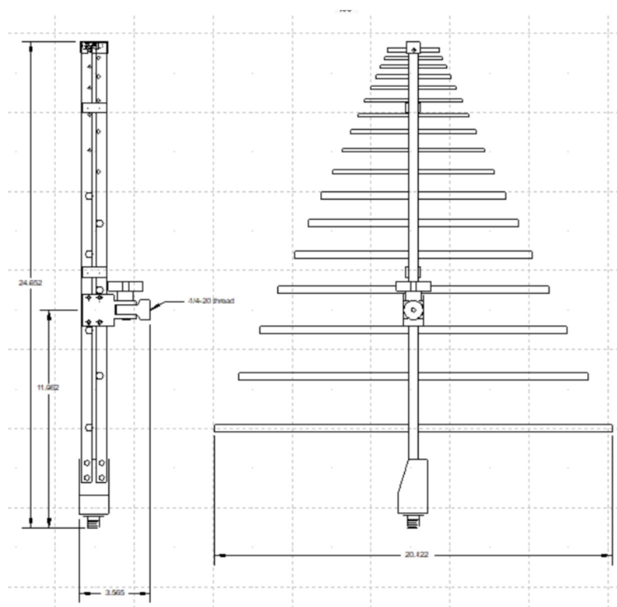


Figure 7.2: Diagram of antenna from datasheet.

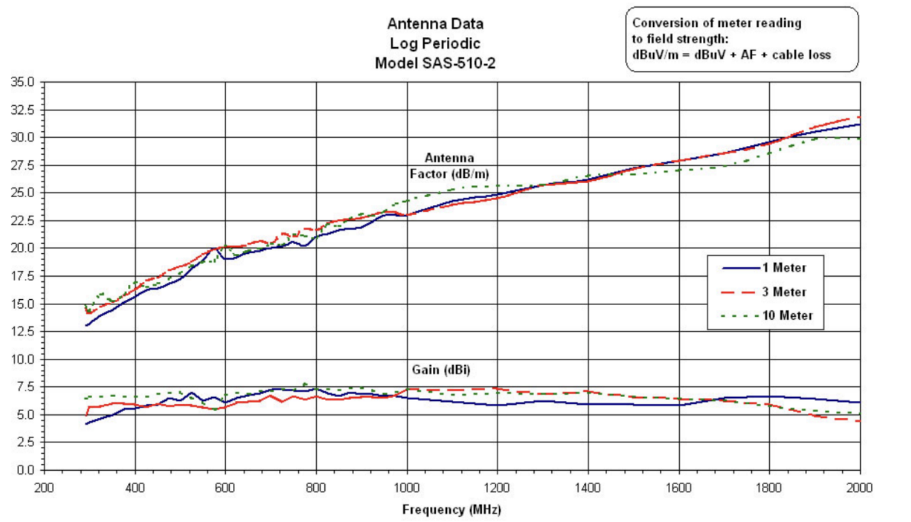


Figure 7.3: Plot of antenna gain from datasheet.

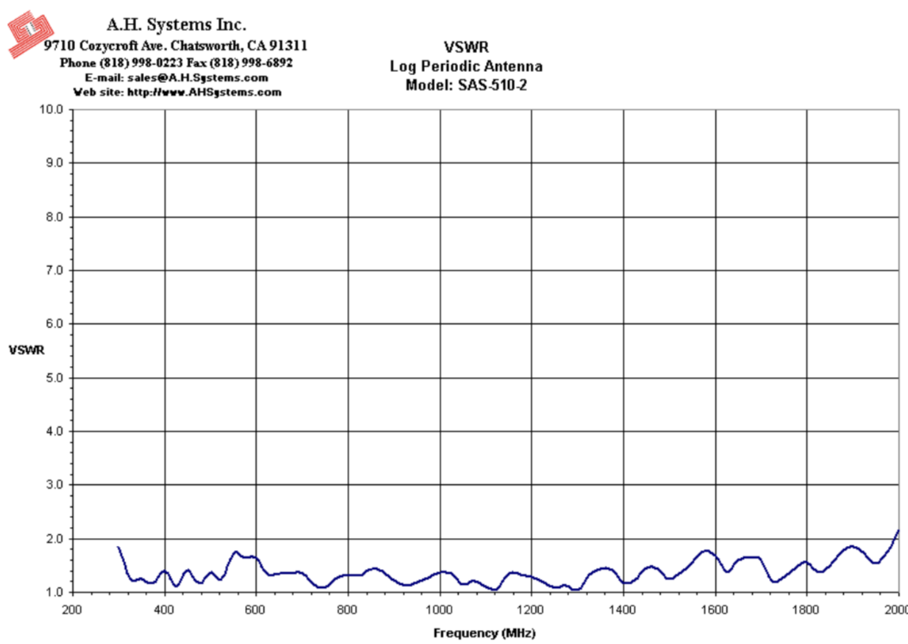


Figure 7.4: Plot of antenna VSWR from datasheet.

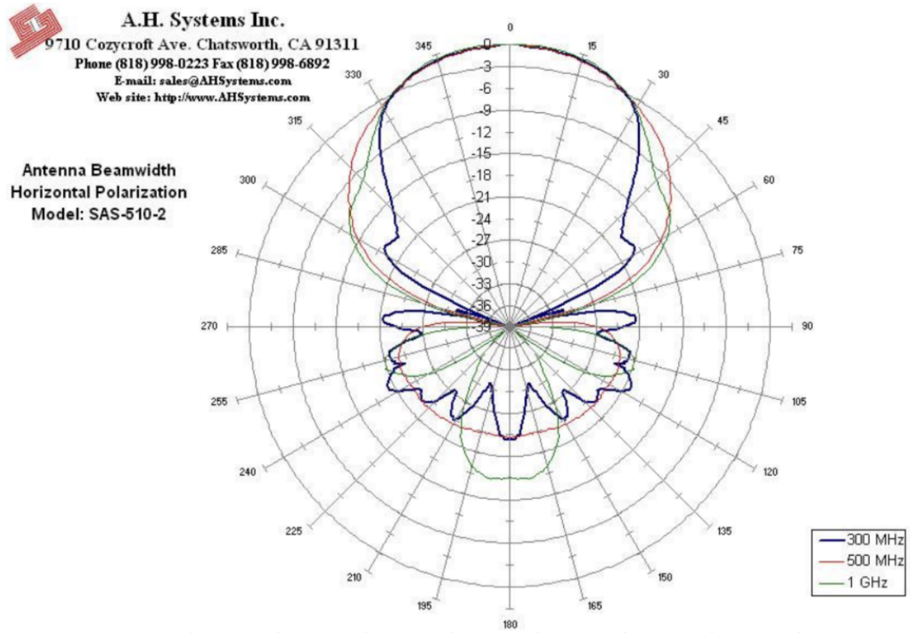


Figure 7.5: Azimuth plot of antenna gain from datasheet.

Test 1: Traditional 3dB Modeling

As shown in figure 7.6, the first test will be a more traditional method of validating an antenna's 3dB beamwidth. Two matching LPDA antennas (290 MHz to 2 GHz) will be used to determine the 3dB beamwidth in two steps. First, the field antenna will be moved further from the DUT (increasing d), then the DUT will be rotated about a pivot point based on the excited dipole. These two tests will be conducted at a frequency at the high end of the antenna's bandwidth, the low end, and the middle.

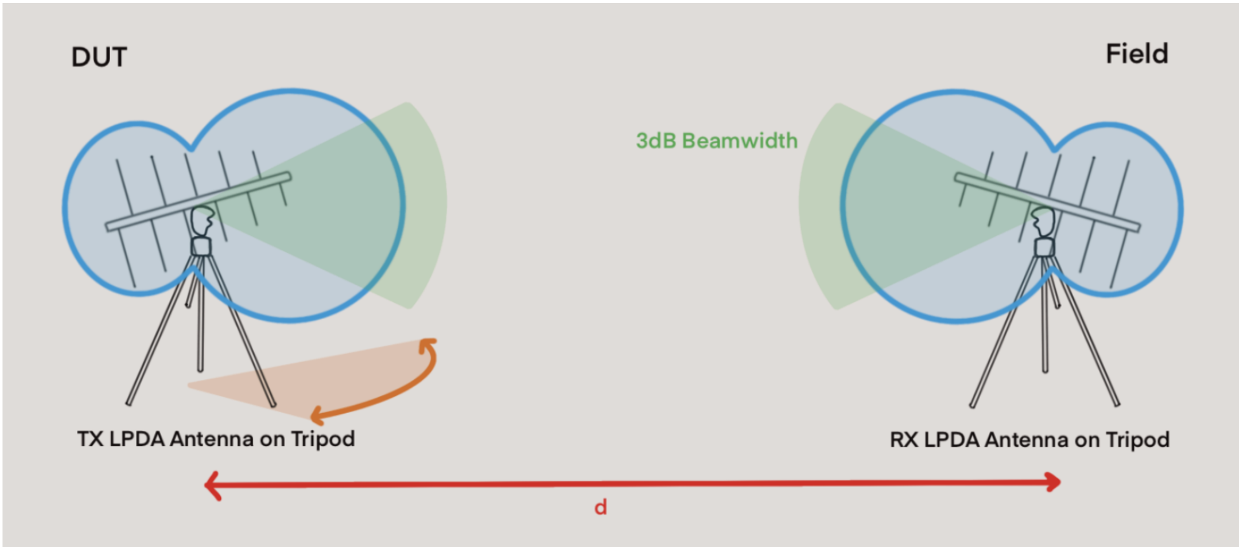


Figure 7.6: Setup for Test 1: Traditional 3dB Modeling

Test 2: Modified 3dB Modeling

As shown in figure 7.7, the second test will be a modified method of validating an antenna's 3dB beamwidth. Two matching LPDA antennas (290 MHz to 2 GHz) will again be used to determine the 3dB beamwidth. This time, the DUT will remain fixed, while the field antenna is moved along an arc with a fixed radius r between the two excited dipoles. The tests will be conducted at a frequency at the high end of the antenna's bandwidth, the low end, and the middle, matching the frequencies of test 1.

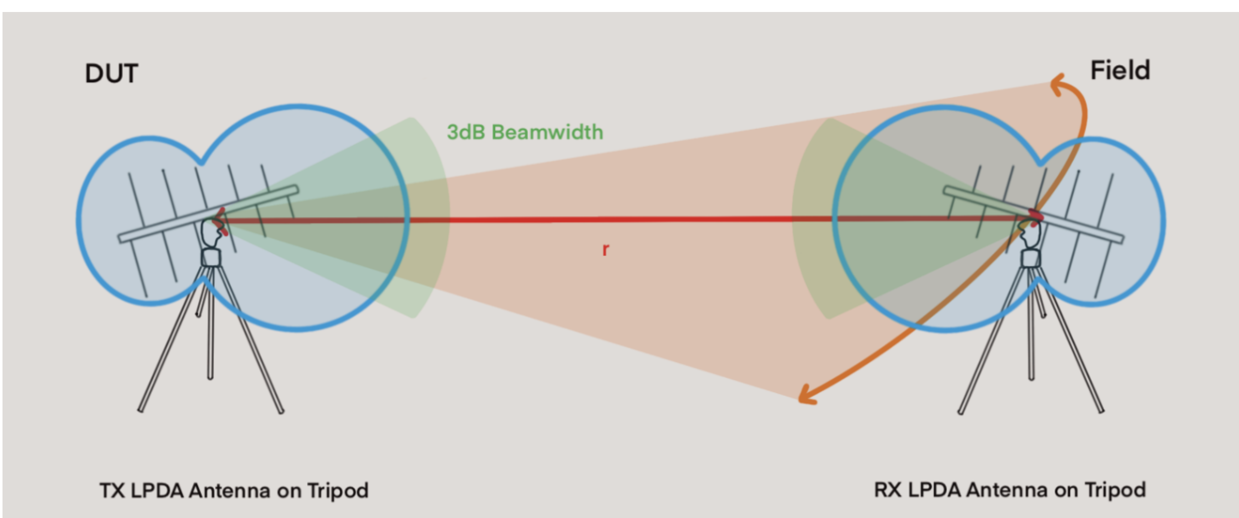


Figure 7.7: Setup for Test 2: Modified 3dB Modeling

Test 3: Modified 3dB Modeling with Designed Antenna

As shown in figure 7.8, the third test will be a modified method of determining the large designed antenna's 3dB beamwidth. Where before two matching LPDA antennas (290 MHz to 2 GHz) were used, now one smaller LPDA will serve as the field antenna while the designed antenna is the DUT. The test will resemble test 2; the DUT will remain fixed, while the field antenna is moved along an arc with a fixed radius r between the two excited dipoles. The tests will be conducted at a frequency at the high end of the antenna's bandwidth, the low end, and the middle.

A Lumiloop E-Field probe will also be used to determine the E-Field radiated by the antenna at at least 50 discrete points, for five different frequencies.

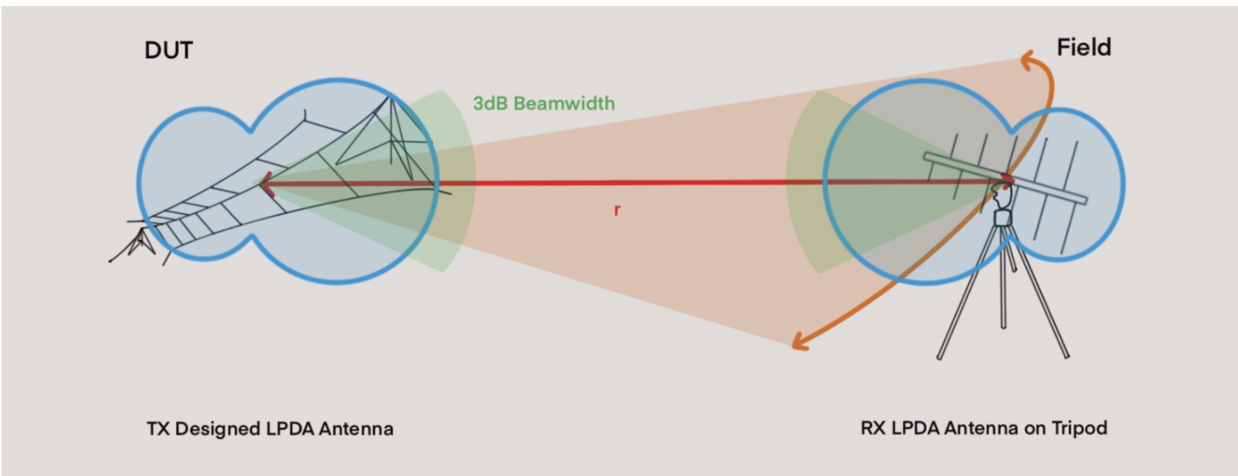


Figure 7.8: Setup for Test 3: Modified 3dB Modeling with Designed Antenna

Chapter 8

Testing Results

Test 1: Traditional 3dB Modeling

Shown below are the raw data results of this test at three frequencies, 2.000GHz, 0.446GHz, and 0.290GHz.

2.00 GHz	-20 dBm transmit	d=0.12 m		0.446 GHz	-20 dBm transmit	d = 0.7472 m		0.29 GHz	-20 dBm transmit	d=1.2192m		
Distance (m)	Power (dBm)	Angle (deg)	Power (dBm)	Distance (m)	Power (dBm)	Angle (deg)	Power (dBm)	Distance (m)	Power (dBm)	Angle (deg)	Power (dBm)	Distance between antennas (in)
0.0874	-27.2	-65	-41.8	0.5694	-28.5	-65	-47.1	1.016	-33.8	-65	-49.9	1
0.1128	-29.7	-55	-38.3	0.5948	-28.5	-55	-42.1	1.0414	-34.3	-55	-43.9	1.5
0.11915	-30.2	-45	-34.8	0.6202	-29.4	-45	-38.7	1.0668	-34.3	-45	-41.4	2
0.1255	-30.2	-35	-32.8	0.6456	-29.9	-35	-35.7	1.0922	-34.3	-35	-37.9	2.5
0.13185	-30.7	-25	-31.8	0.671	-29.9	-25	-33.4	1.1176	-34.8	-25	-36.9	3
0.1382	-30.7	-20	-31.3	0.6964	-29.9	-20	-32.4	1.143	-34.8	-20	-35.9	3.5
0.1636	-31.7	-15	-30.8	0.7218	-30.4	-15	-31.4	1.1684	-34.8	-15	-35.4	4
0.189	-33.2	-10	-29.8	0.7472	-30.4	-10	-30.9	1.1938	-34.8	-10	-34.9	4.5
0.2144	-34.2	-5	-30.3	0.7726	-30.4	-5	-30.4	1.2192	-34.8	-5	-34.9	5
0.2398	-34.7	0	-30.5	0.798	-31.4	0	-30.4	1.2446	-35.3	0	-34.4	5.5
		5	-30.5	0.8234	-31.4	5	-30.4	1.27	-35.3	5	-34.5	6
		10	-30.5	0.8488	-31.9	10	-31.4	1.2954	-35.3	10	-34.9	6.5
		15	-31	0.925	-32.9	15	-31.9	1.3716	-35.8	15	-35.9	7
		20	-31.5	1.0012	-33.9	20	-32.9	1.4478	-35.8	20	-35.9	7.5
		25	-32	1.0774	-34.4	25	-33.9	1.524	-36.3	25	-36.4	8
		35	-34			35	-35.6	1.6002	-38.3	35	-37.9	8.5
		45	-34.5			45	-38.1	1.7526	-40.3	45	-40.4	9
		55	-37.9			55	-42.1			55	-42.9	9.5
		65	-45.3			65	-46.1			65	-43.9	10

Figure 8.1: Raw Tabular Data from Test 1: Traditional 3dB modeling

At 2.000GHz, the -3dB crossing occurs at a distance of 0.11915m and an angle of -35° and +29°. Plots of the distance versus power and angle versus power are shown in figures 8.2 and 8.3.

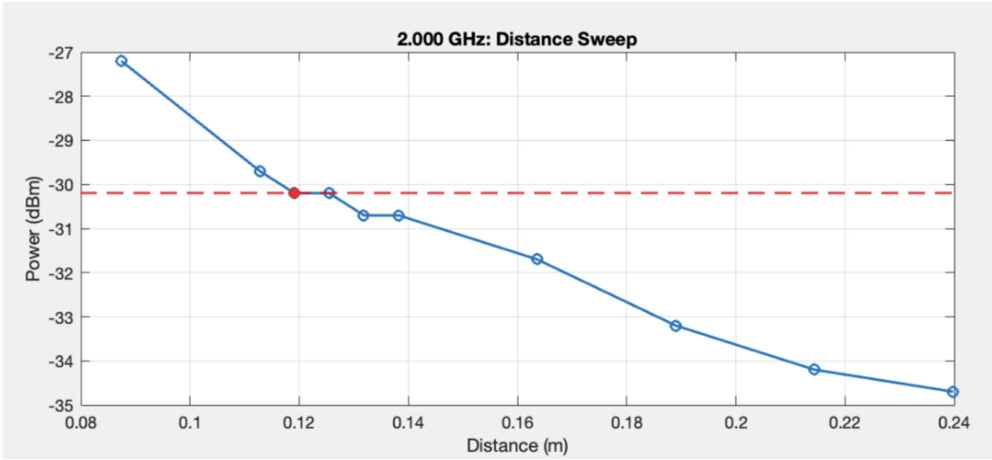


Figure 8.2: Plot of Distance versus Power at 2.000GHz

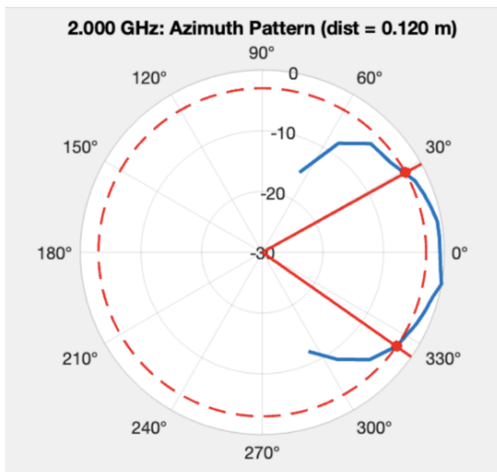


Figure 8.3: Azimuth Plot of Angle versus Power at 2.000GHz (d = 0.120m)

At 0.446GHz, the -3dB crossing occurs at a distance of 0.82848m and an angle of -25° and +22.5°. Plots of the distance versus power and angle versus power are shown in figures 8.4 and 8.5.

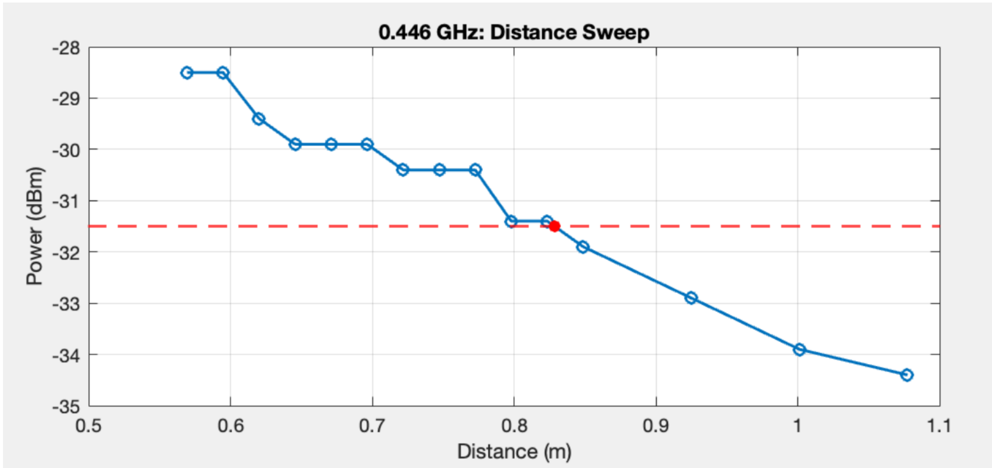


Figure 8.4: Plot of Distance versus Power at 0.446GHz

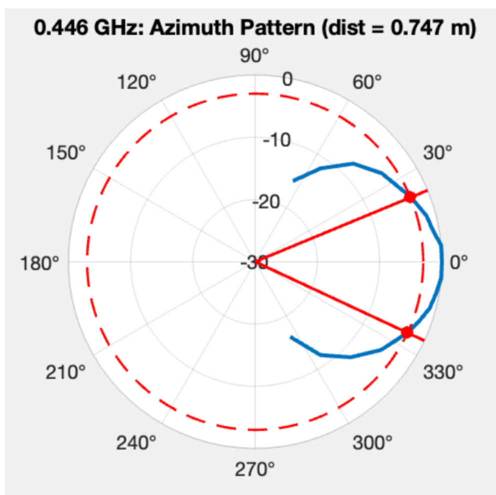


Figure 8.5: Azimuth Plot of Angle versus Power at 0.446GHz (d = 0.747m)

At 0.290GHz, the -3dB crossing occurs at a distance of 1.5431m and an angle of -30° and +31.7°. Plots of the distance versus power and angle versus power are shown in figures 8.6 and 8.7.

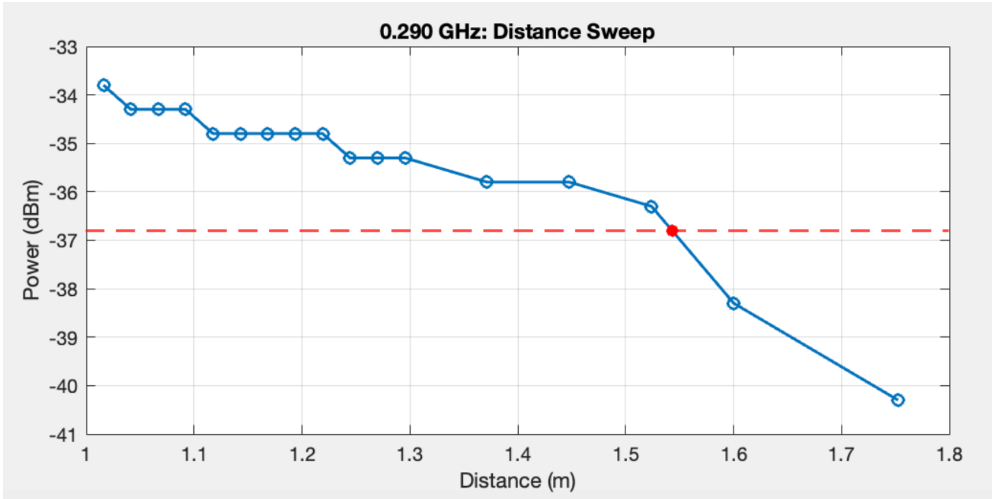


Figure 8.6: Plot of Distance versus Power at 0.290GHz

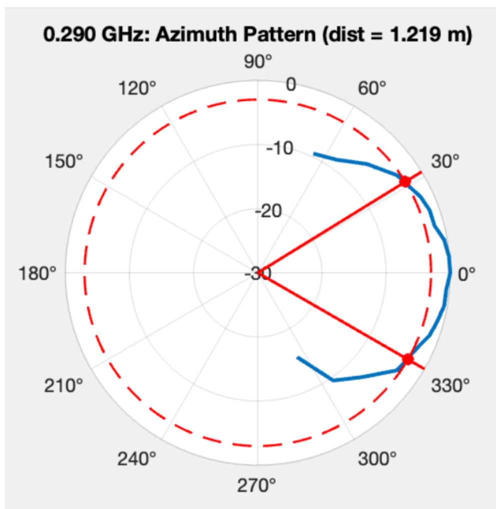


Figure 8.7: Azimuth Plot of Angle versus Power at 0.290GHz (d = 1.219m)

All MATLAB code used to plot the raw test data can be found in the Appendix.

Test 2: Modified 3dB Modeling

This testing is not yet complete, but will be completed before proceeding with designed HF LPDA verification.

Chapter 9

Risk Management

Risk Mitigation:

- Ask Dahlgren about obtaining test equipment early
- Check equipment before testing
- Order parts earlier than needed
- Have faculty review designs multiple times to ensure no components are missing

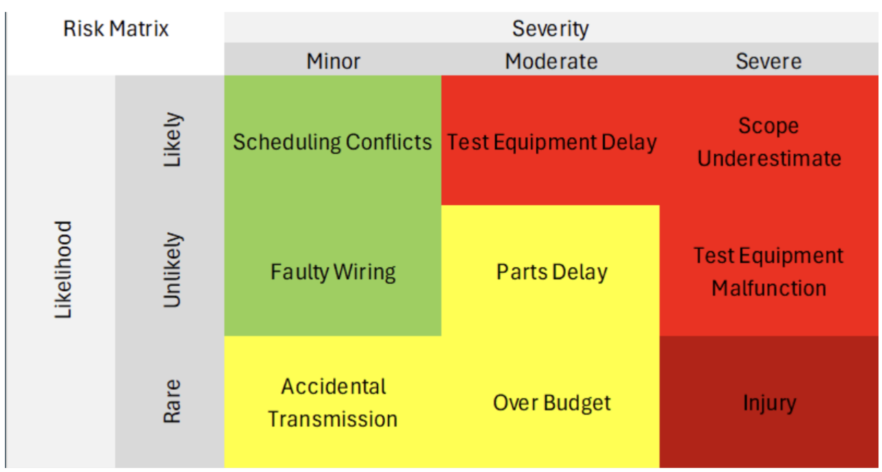


Figure 9.1: Project Risk Matrix

This risk matrix was developed for the preliminary design review (PDR). So far, the initial risk assessment has been fairly accurate. Scheduling conflicts have been the primary delay, but have only caused small issues. For testing, an E-field probe was needed from Dahlgren. Knowing that the process to obtain the probe can take time, the probe was requested during week 2 of the semester. This early request proved to be the correct move, as the probe only just arrived during semester week 8. Other complications have arisen due to academic and work schedules, but the delays to the project have been minimal overall.

Chapter 10

Budget Summary

10.1 Part Lists

- **Rope:** 500 ft. Fluorescent Yellow Braided Nylon Mason's Line
  - Boom support, 23 ft
  - Tension cables, $\sim$100 ft
- **Wire:** 250 ft. 18-Gauge Stranded SD Bare Copper Grounding Wire
- **Stakes:** 0.31 in. $\times$ 16 in. Rebar Stakes J Hook Extra Heavy-Duty, Garden Stake Steel Stakes Tent Stakes (48-Pack)
- **Coaxial Cable:** LMR-400 coax cable, 50 ft
- **Balun:** LDG Electronics RBA-4:1, 100-watt, 1.8–30 MHz
- **Connectors:** UHF M for balu, N-Type M, F
- **Insulators:** 30+ Dogbone Insulators
- **Support:** Flagpole (13 ft pole from Moonbounce)
- **Cable Spools:** As necessary, mostly use dogbone insulators

10.2 Purchasing Information

Table 10.1: Bill of Materials

Type	Item	Description	Source	Lead Time	Price per	Qty	Total	Link
Antenna	Rope	500 ft. Fluorescent Yellow Braided Nylon Mason's Line	Home Depot	In Stock	$10.97	1	$10.97	link
Antenna	Wire	250 ft. 18-Gauge Stranded SD Bare Copper Grounding Wire	Home Depot	In Stock	$18.98	1	$18.98	link
Antenna	Stakes	0.31 in. x 16 in. Rebar Stakes J Hook Extra Heavy-Duty, Garden Stake Steel Stakes Tent Stakes (48-Pack)	Home Depot	In Stock	$74.34	1	$74.34	link
Antenna	Coax	LMR-400 coax cable, 50ft	Digikey	In Stock	$2.31	50	$115.55	link
Antenna	Dogbone Insulators	Dog bone plastic (polyethylene) Extra High Strength, UV resistant. White, $\frac{1}{4}$" holes on each end.	Dx Ham Radio Supply	In Stock	$1.09	20	$21.80	link
Antenna	Support	13' pole from Moonbounce, includes support ropes	N/A		$0	1	$0	
Antenna	Cable Spools	Use dogbone connectors	N/A		$0	1	$0	
Connectors	N-Type F	Standard N Female Connector Crimp/Solder Attachment for LMR-400, PE-C400	Pasternack	In Stock	$26.99	2	$53.98	link
Connectors	N-Type M	N Male Connector Crimp/Solder Attachment for LMR-400, PE-C400, PE-B405 IP67 Rated	Pasternack		$20.39	2	$40.78	link
Connectors	UHF M	UHF Male Connector Crimp/Solder Attachment for PE-B400, PE-B405, PE-C400, LMR-400, 0.400 inch	Pasternack	In Stock	$27.39	2	$54.78	link
Balun	Balun	LDG Electronics RBA-4:1: 100-watt 1.8–30 MHz	Dx Engineering	In Stock	$29.99	1	$29.99	link

Total Cost: $336.40

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Chapter 11

Appendices

Appendix: MATLAB Code

```
clear all, close all, clc;

%% Settings
dataFile = 'lpda_pattern.csv';
Pt_dBm = -20;                          % transmitted power (20 dBm)
nFreqBlocks = 3;                       % number of frequency blocks
freqs_GHz = [2.00, 0.446, 0.29];       % frequency values in GHz
dists_m = [0.12, 0.7472, 1.2192];      % fixed distances for angular sweep
normalize = true;                      % true -> max = 0 dB

%% Import data
opts = detectImportOptions(dataFile);
opts.DataLines = [3 Inf];              % skip header rows
T = readtable(dataFile, opts);
A = table2array(T);

%% Create tiled layout (3 rows    2 columns)
figure;
tiledlayout(3,2,"TileSpacing","compact","Padding","compact");

%% Loop over frequency blocks
for blk = 1:nFreqBlocks
    c0 = (blk-1)*4 + 1;

    % Extract distance and angular sweep data
    distance_m         = A(:,c0);
    distance_power_dBm= A(:,c0+1);
    angle_deg          = A(:,c0+2);
    angle_power_dBm    = A(:,c0+3);

```

```matlab
    %% Distance vs Power Plot
    % Plot
    nexttile;
    plot(distance_m, distance_power_dBm, 'o-','LineWidth',1.5);
    xlabel('Distance (m)');
    ylabel('Power (dBm)');
    hold on;
    grid on;
    title(sprintf('%.3f GHz: Distance Sweep', freqs_GHz(blk)));

    % Mark  3  dB line relative to peak
    thr3dB = max(distance_power_dBm) - 3;
    yline(thr3dB,'r--','LineWidth',1.5);

    % Find  3  dB line crossings
    crossings = find((distance_power_dBm(1:end-1) > thr3dB & distance_power_dBm(2:end) <= thr3dB) | ...
                     (distance_power_dBm(1:end-1) < thr3dB & distance_power_dBm(2:end) >= thr3dB));

    dist_cross_vals = [];
    for k = 1:length(crossings)
        i1 = crossings(k);
        i2 = i1 + 1;
        t = (thr3dB - distance_power_dBm(i1)) / (distance_power_dBm(i2) - distance_power_dBm(i1));
        x_cross = distance_m(i1) + t*(distance_m(i2)-distance_m(i1));
        dist_cross_vals(end+1) = x_cross; %#ok<SAGROW>
        plot(x_cross, thr3dB, 'ro','MarkerFaceColor','r','MarkerSize',6);
    end
    if isempty(dist_cross_vals)
        fprintf('%.3f GHz distance sweep: No -3 dB crossing found.\n', freqs_GHz(blk));
    else
        fprintf('%.3f GHz distance sweep -3 dB crossing at distances (m): %s\n', freqs_GHz(blk), num2str(dist_cross_vals));
    end

    %% Azimuth Plot
    P = angle_power_dBm;
    if normalize
        P = P - max(P);                 % normalize so peak = 0 dB
    end

    % Convert angle to radians for polarplot
```

```
    theta = deg2rad(angle_deg);

    % Plot
    nexttile;
    polarplot(theta, P, 'LineWidth', 2);
    hold on;
    rticks([-30 -20 -10 0]);              % customize radial ticks
    rlim([-30 0]);                        % dB scale from -30 to 0
    title(sprintf('%.3f GHz: Azimuth Pattern (dist = %.3f m)', freqs_GHz(blk), dists_m(blk)))

    % Add   3   dB reference circle
    polarplot(linspace(0,2*pi,360), -3*ones(1,360), 'r--','LineWidth',1.2);

    % Find azimuth crossings
    crossings = find((P(1:end-1) > -3 & P(2:end) <= -3) | (P(1:end-1) < -3 & P(2:end) >= -3));
    angle_cross_vals = [];
    for k = 1:length(crossings)
        i1 = crossings(k); i2 = i1+1;
        t = (-3 - P(i1)) / (P(i2)-P(i1));
        theta_cross = theta(i1) + t*(theta(i2)-theta(i1));
        angle_cross_vals(end+1) = rad2deg(theta_cross); %#ok<SAGROW>

        % Mark crossing
        polarplot(theta_cross, -3, 'ro', 'MarkerFaceColor','r', 'MarkerSize',6);
        polarplot([theta_cross theta_cross], [0 -30], 'r-', 'LineWidth',1.5);
    end

    if isempty(angle_cross_vals)
        fprintf('%.3f GHz azimuth pattern: No -3 dB crossing found.\n', freqs_GHz(blk));
    else
        fprintf('%.3f GHz azimuth pattern -3 dB crossing at angles (deg): %s\n', freqs_GHz(blk), num2str(angle_cross_vals));
    end
end

%% Overlay Plots for All Frequencies

% Distance sweeps overlay
figure;
hold on; grid on;
for blk = 1:nFreqBlocks
```

```
    c0 = (blk-1)*4 + 1;
    distance_m         = A(:,c0);
    distance_power_dBm= A(:,c0+1);

    plot(distance_m, distance_power_dBm, 'LineWidth',1.5, ...
        'DisplayName', sprintf('%.3f GHz', freqs_GHz(blk)));
end
xlabel('Distance (m)');
ylabel('Power (dBm)');
title('Overlay of Distance Sweeps');
legend('show','Location','best');
hold off;

% Azimuth patterns overlay
figure;
pax = polaraxes;   % create polar axes explicitly
hold(pax,'on');
for blk = 1:nFreqBlocks
    c0 = (blk-1)*4 + 1;
    angle_deg       = A(:,c0+2);
    angle_power_dBm = A(:,c0+3);

    P = angle_power_dBm;
    if normalize
        P = P - max(P);   % normalize so peak = 0 dB
    end
    theta = deg2rad(angle_deg);

    polarplot(pax, theta, P, 'LineWidth', 1.8, ...
        'DisplayName', sprintf('%.3f GHz', freqs_GHz(blk)));

    % Add  3  dB reference circle
    polarplot(linspace(0,2*pi,360), -3*ones(1,360), 'r--','LineWidth',1.2, 'HandleVisibility','off');

    % Find azimuth crossings
    crossings = find((P(1:end-1) > -3 & P(2:end) <= -3) | (P(1:end-1) < -3 & P(2:end) >= -3));
    angle_cross_vals = [];
    for k = 1:length(crossings)
        i1 = crossings(k); i2 = i1+1;
        t = (-3 - P(i1)) / (P(i2)-P(i1));
        theta_cross = theta(i1) + t*(theta(i2)-theta(i1));
        angle_cross_vals(end+1) = rad2deg(theta_cross); %#ok<SAGROW>

        % Mark crossing
```

```
        polarplot(theta_cross, -3, 'ro', 'MarkerFaceColor','r', 'MarkerSize',6);
        polarplot([theta_cross theta_cross], [0 -30], 'r-', 'LineWidth',1.5, 'HandleVisibility','off');
    end
end
rlim(pax,[-30 0]);
rticks(pax,[-30 -20 -10 0]);
title(pax,'Overlay of Azimuth Patterns');
legend(pax,'show','Location','bestoutside');
```

Listing 11.1: MATLAB code used for raw data plotting.

```
clc; clear all; close all;

c = 299792458; %speed of light m/s
e_a = 1.006; %relative permittivity of air
elements = 15;

%Frequencies of LPDA elements in MHz
f = [13, 13.978, 15.031, 16.162, 17.378, 18.687, 20.093, 21.605, 23.232, 24.980, 26.860, 28.882, 31.056, 33.394, 35.907];

%Convert to feet
L_f = [37.8297, 35.1816, 32.7189, 30.4285, 28.2986, 26.3177, 24.4754, 22.7621, 21.1688, 19.6870, 18.3089, 17.0273, 15.8354, 14.7269, 13.6960];

%Convert to feet
P_f = [0, 3.5182, 6.7900, 9.8329, 12.6628, 15.2945, 17.7421, 20.0183, 22.1352, 24.1039, 25.9347, 27.6375, 29.2210, 30.6937, 32.0633];
for n=1:elements
    P_f(n) = P_f(elements)-P_f(n);
end

%Find wavelength
lambda = c./(f.*1e6.*sqrt(e_a));
lambda_f = (lambda.*100)./(12.*2.54);

alpha = 30; %angle of boom in degree
beta = 20; %angle of wires in degrees

%z positions
z_start = P_f.*sind(beta)+10;
z_end = z_start - ((L_f./2).*sind(alpha));

%y positions
```

```
y_start = P_f.*cosd(beta);
y_end = y_start;

%x posistions
x_end = (L_f./2).*cosd(alpha);

%print statements for wire coordinates
n=1;
while n <= elements
    if (mod(n,2)==0)
        fprintf("Start wire %1.0f: 0, %0.2f, %0.2f\n",n, y_start(n), z_start(n)-0.2);
        fprintf("Start wire %1.0f: %0.2f, %0.2f, %0.2f\n",n, x_end(n), y_end(n), z_end(n)-0.2);
        fprintf("End wire %1.0f: 0, %0.2f, %0.2f\n",n, y_start(n), z_start(n));
        fprintf("End wire %1.0f: -%0.2f, %0.2f, %0.2f\n",n, x_end(n), y_end(n), z_end(n));
    else
        fprintf("Start wire %1.0f: 0, %0.2f, %0.2f\n",n, y_start(n), z_start(n)-0.2);
        fprintf("Start wire %1.0f: -%0.2f, %0.2f, %0.2f\n",n, x_end(n), y_end(n), z_end(n)-0.2);
        fprintf("End wire %1.0f: 0, %0.2f, %0.2f\n",n, y_start(n), z_start(n));
        fprintf("End wire %1.0f: %0.2f, %0.2f, %0.2f\n",n, x_end(n), y_end(n), z_end(n));
    end
    n = n + 1;
end
```

Listing 11.2: MATLAB code used to calculate coordinates for EZNEC simulations.

```
clc; clear all; close all;

f_max = 35e6;
f_min = 13e6;
T = 0.93;
s = 0.05;
c = 299792458;

%find number of elements
N = 1 + ceil(log(f_max/f_min)/log(1/T));
fprintf("Number of elements --> %d\n",N);

L(1:N) = 0;
S(1:N) = 0;

```

```
L(1) = c/(2*f_min)*100/2.54/12;
%calculate lengths
for n=2:N
    L(n) = (L(1)*T^(n-1));
    S(n) = (2*s*L(n))+S(n-1);
end

fprintf("Element length:");
disp(L(1:N));
fprintf("Element spacing:");
disp(S(1:N));

%calculate frequencies of elements
f(1:N)=0;
for n=1:N
    f(n) = c/(2*(L(n)/100*2.54*12));
end
fprintf("Element frequencies:");
disp(f(1:N));
```

Listing 11.3: MATLAB code used to element lengths and frequencies for EZNEC simulations.

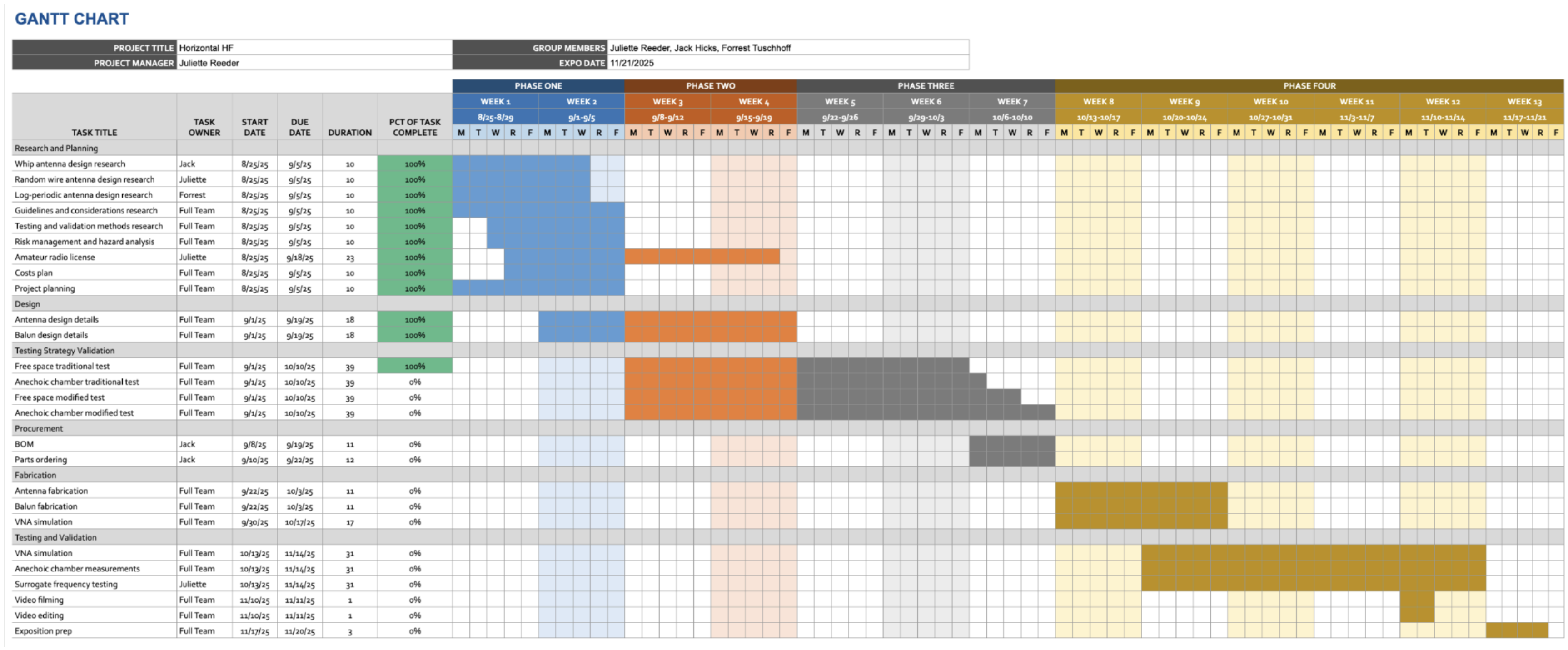

Figure 11.1: Gantt Chart