Loaded Circular Loop Antenna

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Abstract **- This paper documents the design, construction, and verification process of a two-port loaded circular antenna. Theoretical calculations are carried out and the relevant parameters are shown in order to mold the radiation pattern into the desired cardioid shape. The cardioid single-lobed pattern is desirable for its ability to eliminate noise interference from backward reflecting waves in a strong signal environment. The antenna is then modeled and simulated in MATLAB and HFSS. The antenna is then constructed and characterized in the anechoic chamber to verify that it meets the specifications for gain, VSWR, and axial ratio.**

I. INTRODUCTION

The cardioid radiation pattern is unique to the loaded circular loop antenna and is desirable for commercial and industry use in many different applications. In heavily populated urban centers, the integrity of TV signals can be disrupted by ghost figures which are the result of backward reflecting waves in a strong signal environment [1]. The cardioid shape is desirable for this application because it readily receives signals directed towards it and rejects backward reflecting waves. Figure 1 shows the basic cardioid shape of the radiation pattern.

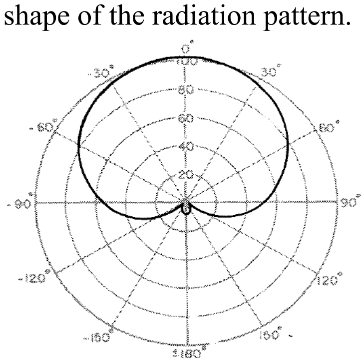

Figure 1. Cardioid Radiation Pattern [2]

Figure 2 shows the basic diagram for the loaded circular loop antenna. The radiation pattern is directed towards the front port and away from the load on the opposite end of the loop. The resistive termination yields a broadband impedance at the input port which is conducive to a low noise figure [2].

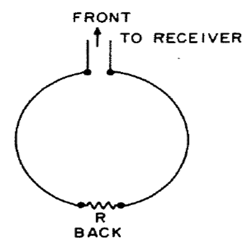

Figure 2. Two-Port Loaded Loop Antenna [2]

The goal is to eventually integrate this antenna with the Wireless Wildlife Tracking Senior Project. The antenna will be mounted on the RQ-20 fixed-wing glider, a small battery-powered unmanned aircraft produced by AeroVironment based in California [3]. The lightweight aircraft requires that the antenna weight not exceed 3.7 pounds and operate at a frequency of 165 MHz. The requirements for the aircraft are to locate any fisher pulsating a 165 MHz signal across the Sierra Nevadas. The characteristics of the two-port loaded circular loop antenna make this antenna the ideal design for this application.

This paper documents the design, simulation, construction, and characterization of this antenna. Section 2 explores previous work that has been done on this type of antenna. Section 3 explains the relevant design parameters and their relation to the design criterion. Sections 4 shows the simulation results of these design parameters. Both MATLAB and HFSS are used to verify that the design meets its criterion for VSWR, gain, and axial ratio. Section 5 details the required materials and construction process for the antenna. Section 6 outlines the characterization procedure which is carried out in an anechoic chamber. Finally, Section 7 contains some concluding remarks.

II. PREVIOUS WORK

Various designs have been attempted to achieve this cardioid shape in the radiation pattern. Figure 3 shows the typical radiation pattern of a plain loop antenna which contains two nulls that are 180º apart from one another. The bidirectional characteristic of the plain loop antenna is undesirable in environments with lots of backward reflecting waves and in situations where the true direction of the transmitting station needs to be known. The additional main lobe introduces ambiguity as to where the received signal is emanating from.

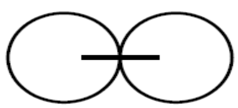

Figure 3. Loop Antenna Radiation Pattern [4]

The radiation pattern of the antenna can be molded into a cardioid shape with the addition of a second antenna element called the sensing antenna. It is called as such because it gives an added sense of direction to the radiation pattern. When the signals from the loop and the sensing antenna are combined with a 90º phase shift between each other, a cardioid pattern results [4]. Figure 4 shows the development of this pattern and figure 5 shows the circuit implementation of this method.

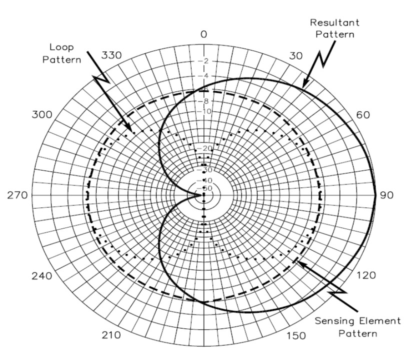

Figure 4. Combined Radiation Pattern of Loop Antenna and Sensing Antenna [4]

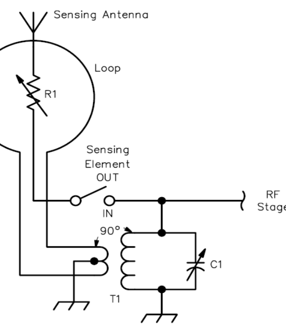

Figure 5. Circuit Implementation of Loop Antenna and Sensing Antenna [4]

Another design choice comes from a group of researchers in [1] who documented their design of a loaded circular loop antenna, which is what we base the design of our antenna off of. By putting a suitable load impedance at the symmetrical position to that of the feeding point, we can achieve the aim of controlling the phase and amplitude of the current on the loop [1].

The load impedance on the loop is set equal to the average characteristic impedance of the loop which is approximately

$$Z_a = 120 * \ln(b / a) \quad (1)$$

where a is the radius of the wire and b is the radius of the loop [1].

As far as the radiation pattern is concerned, the math is a little involved and the reader is invited to look to [1] for more details. However, what is of relevance to us is the design parameter βb which controls the shape of the radiation pattern. When the total length of the loop is less than a wavelength ($\beta b < 1$), the E-plane and H-plane patterns assume a cardioid shape. The smaller the βb, the sharper the half-power beamwidth [1]. When $\beta b > 1$, the maximum radiation direction will deviate from the feeding direction and eventually split of into two side lobes [1].

The βb term also allows us to control the gain of the antenna as is approximated by

$$\text{Gain} = 1.02 * 513 / Z_a * (\beta b)^4 \quad (2)$$

where Z_a is the average characteristic impedance of the loop [1]. Since we require $\beta b < 1$, this usually leads to a low gain which is one of the drawbacks for this design.

III. DESIGN

Figure 6 shows the diagram for our design and the relevant parameters which allow us to control the gain and radiation pattern of the antenna. Note that Z_L is the load impedance, a is the radius of the wire, and b is the radius of the loop.

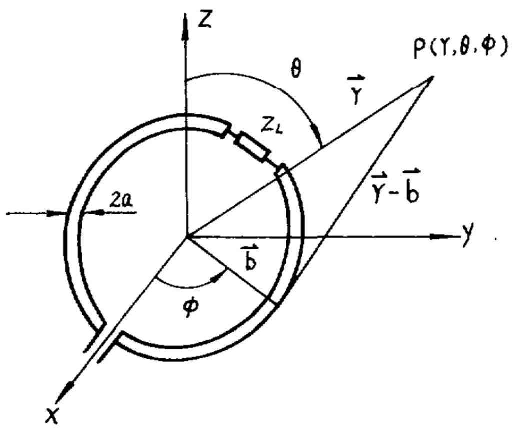

Figure 6. Loaded Circular Loop and its design parameters [1]

As mentioned earlier, we are designing this antenna to operate in the 165 MHz frequency band. The length of the loop has to be less than one wavelength (βb < 1) in order to achieve the desired cardioid shape. With this in mind, we purchased a copper loop from Home Depot where the radius of the loop comes out to be approximately 0.145 meters and the circumference 0.9 meters. This is equivalent to half a wavelength for 165 MHz and βb = ½, which meets the design criteria.

We also want our antenna to be lightweight, so the copper loop that we obtained has a wire radius of 6.4 millimeters. Using equation (1) we can now calculate the required load impedance for the loop which comes out to be approximately 450 ohms.

We can also use equation (2) to calculate the expected gain from this antenna which comes out to be approximately -22.77 dB. As mentioned before, this low gain is one of the drawbacks to this design. However, for the purposes of integrating this antenna in the wildlife tracking project, the resulting cardioid shape more than makes up for it.

We need not worry about meeting the required VSWR criteria for this project since the researchers in [1] proved that this configuration achieves a VSWR < 2. So long as the load impedance is set equal to the average characteristic impedance of the loop, this design criteria for VSWR is met. The reader is encouraged to read [1] for more details as the math is beyond the scope of this paper.

IV. SIMULATION

A. MATLAB

The antenna toolbox in Matlab has numerous predefined antenna structures which can be modeled and simulated in a separate GUI. Fortunately, the toolbox includes the structure for the circular loop antenna. The interface also allows the user to easily input the radius of the loop, the radius of the wire, the design frequency of the antenna, and the conductor type of the loop, which in our case is copper. We also have the option of inserting a load element whose position is symmetrical with that of the feed point. Figure 7 displays all the input parameters for the simulation.

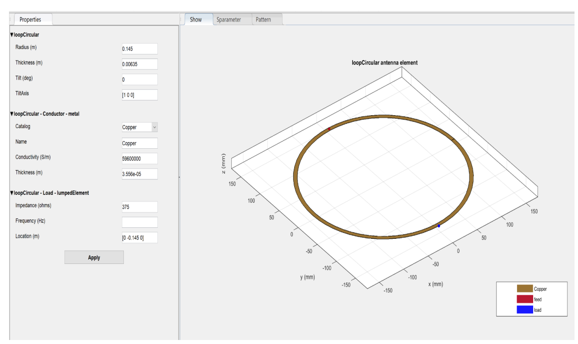

Figure 7. Matlab Model of Loaded Loop Antenna with Design Parameters

Figure 8 shows the simulated radiation pattern of the antenna. The pattern exhibits the desired cardioid shape with the main beam directed towards the feed point and the null towards the load impedance. The main beam has a gain of 3.98 dBi while the null has an attenuation of -12.5 dBi. The simulated gain does not agree with the predicted gain from equation (2). The Matlab model of the antenna might not be accurate enough.

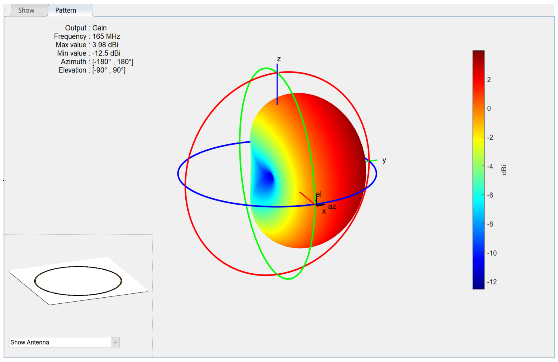

Figure 8. Simulation of Gain Plot at 165MHz

Figure 9 shows the $|S_{11}|$ parameter, or the reflection coefficient, for this antenna configuration. At our design frequency, the reflection coefficient has a value of -0.96 dB. This corresponds to a VSWR of just over 9 which is of course way over the specification. Also, this contradicts the findings in [1] where the VSWR was less than 2. Since the gain and VSWR simulations are a little spotty for Matlab, we will model the same antenna in HFSS and hopefully get more accurate results.

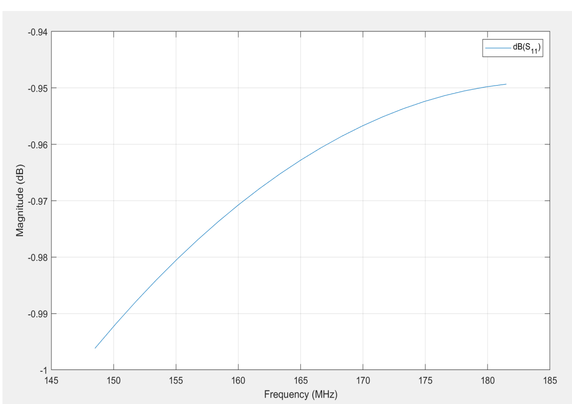

Figure 9: Simulation of $|S_{11}|$ vs. Freq.

B. HFSS

The loaded circular loop antenna modeled in HFSS is made from two semi-circular sections of a hollow copper tubing with a circumference of 0.909m, which is equivalent to $\lambda/2$ for 165MHz. The tubing has an inner radius of 0.0054m and an outer radius of 0.0064m. The orange element at the top of the model, shown in Figure 10, is a lumped element load resistor of R_L = 450Ω. The end of the loop opposite R_L is where lumped port excitation was assigned.

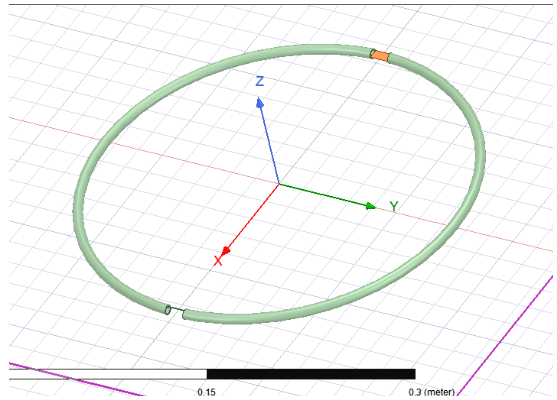

Figure 10. HFSS Model of Loaded Loop Antenna with Axis

Figure 11 & 12 show the $|S_{11}|$ and VSWR plots, respectively, against the frequency range {50 MHz, 500MHz}. At the desired 165MHz frequency, $|S_{11}|$ = -2.5 dB and VSWR = 7.5. The target parameters were $|S_{11}|$ < -10 dB and VSWR < 2, but from a loop antenna made of a conductive sheet, not a copper tube [1].

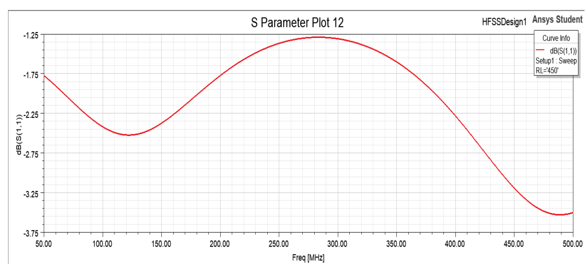

Figure 11. HFSS $|S_{11}|$ vs. Freq. Plot

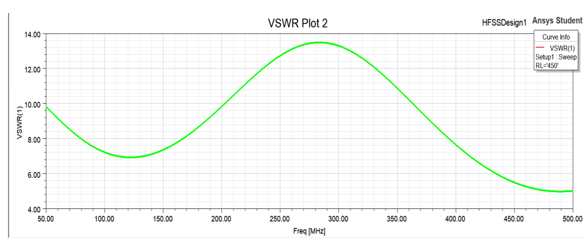

Figure 12. HFSS VSWR vs. Freq Plot

Figure 13 shows the HFSS-simulated radiation pattern. The radiation pattern ($\Theta = \pi/2$) has a cardioid shape and a more directive beam, with a maximum of -8.2 dB in the +x direction and a minimum of -28dB in the -x direction.

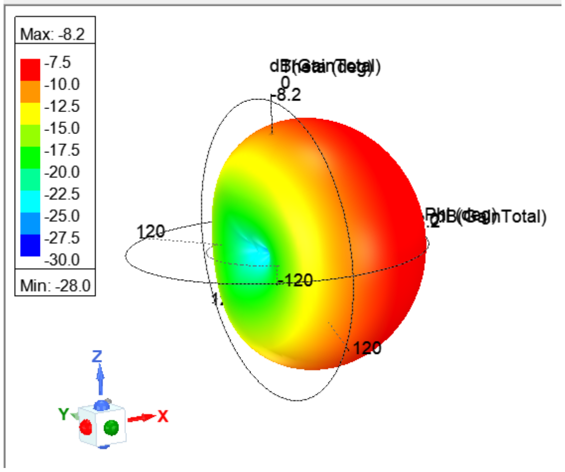

Figure 13. HFSS 3D Gain Plot at 165MHz

V. CONSTRUCTION

To construct the antenna, we purchased a few materials from Home Depot. We first needed a coax cable which contained an outer and center conductor. These conductors will be soldered to opposite terminals of the loop antenna to carry the received signals. Next, an edge-connect SMA female header pin needs to be soldered to the end of the coax cable which enables an SMA male connector to attach to and excite the conductors. For the loop wire, we chose to pick up 2 meters of copper wire. We also picked up a meter of PVC pipe to mount the loop antenna in place. Finally, we need the load impedance as calculated in the previous section. The closest standard resistance value to 450Ω is 470Ω so we would use that instead.

The final product is shown in Figure 14 above with the R_L resistance at the top of the figure and the feed network of a 50Ω coax cable at the bottom. According to HFSS, the input impedance of this antenna is 329.414 +j33.615. A shunt C, series L L-section matching network was constructed and implemented for this antenna, but they did not result in a cardioid radiation pattern and were therefore removed. No measurements in this paper incorporate a matching network of any kind.

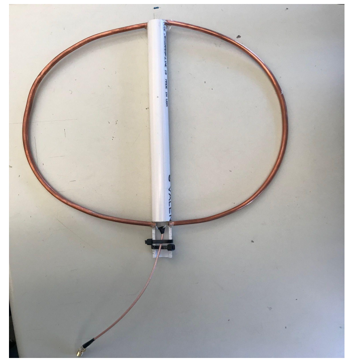

Figure 14: Loaded Loop Antenna Prototype

VI. CHARACTERIZATION

Using the anechoic chamber located in the microwave lab at Cal Poly SLO, the 2D radiation pattern of the antenna as oriented below ($\Theta = \pi/2$) was measured. There are no antennas in the lab that transmit at 165 MHz, and therefore a student-built 60° Vee-Dipole was used to transmit to the loaded loop antenna. The gain of this antenna was unspecified and therefore, the proceeding gain measurements are rough estimates. The test setup is shown in Figure 15 below.

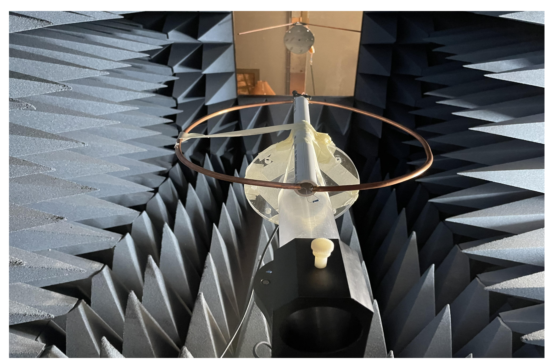

Figure 15: Anechoic Chamber Test Setup

The radiation pattern shown in Figure 16 is the result of the anechoic chamber tests. The E-plane ($\Theta = \pi/2$) radiation pattern for this xy-plane oriented loop antenna is more directive than that of a typical loop antenna [1] [2]. The main beam, with a gain of -42.68 dB is at ~45°, while the side opposite this has maximum gain of -50 dB. The nulls of this antenna are at ~150° and ~300°. These maximum and minimum beam directions are consistent with the MatLAB and HFSS simulations from *IV. SIMULATIONS*.

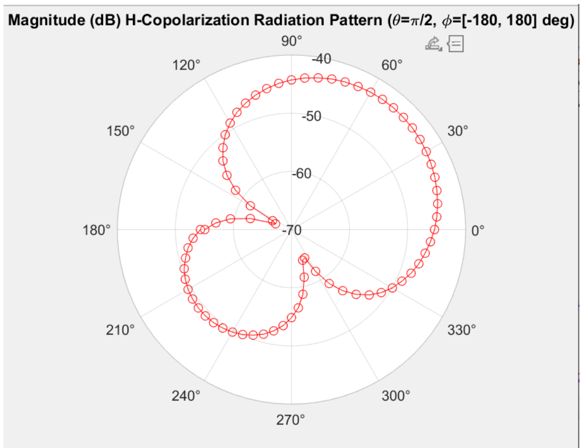

Figure 16: Loaded Loop Antenna E-Plane Radiation Pattern (dB) @ $\Theta = \pi/2$

Figure 17 shows the $|S_{11}|$ vs. frequency plot from 50 MHz to 300 MHz. The reflection coefficient has a value of -5.5 dB at the 165 MHz design frequency which corresponds to a VSWR of 1.78 which meets the design criteria.

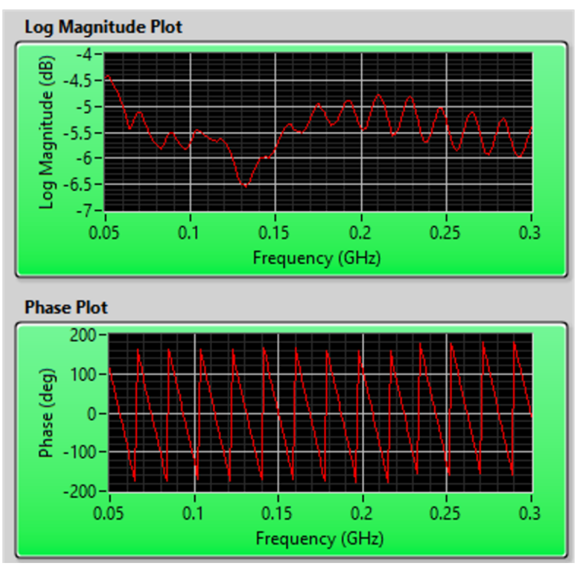

Figure 17: Loaded Loop Antenna $|S_{11}|$ vs. Freq.

VII. CONCLUSION

This Loaded Circular Loop Antenna design was a proof of concept for a method improving the directivity of a typical loop antenna by adding a load resistor [1] [2] [4]. The most common method of creating a directive loop antenna is with an additional "sense" loop that must be fed 90° out of phase to the main loop [2]. This alternative adds additional hardware and complexity, where the loaded loop antenna concept simply requires a resistor.

We expected the gain for the antenna to be quite low for this design and was predicted to be about -22.77 dB from [1]. However, we did not expect the gain to be as low as we had measured. Our gain came out to be roughly 20 dB below the [1 benchmark and 35 dB below the HFSS simulation. This was most likely due to our crude setup in the anechoic chamber since we were quite rushed for time. The VSWR results fortunately matched with the predictions given in [1] where the VSWR would be less than 2 which meets the design criteria. And although the gain was much lower than we expected, we did verify that this design produces our desired cardioid radiation pattern.

For future work, the performance of this antenna ($|S_{11}|$, VSWR, Gain) can certainly be improved. The $|S_{11}|$ can be improved with an optimum spacing of the feed point for frequency selection [1]. The VSWR can be improved with a conductive ribbon as the loop material [1]. According to design equation (2), the gain can also be improved by lengthening the radius of the loop at the cost of a less sharp cardioid radiation pattern [1].

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