

Fall 12-19-2016

Phased Helical Antenna Array for CubeSat Application

Kameron LaCalli

klacalli

Follow this and additional works at: http://digital.sandiego.edu/honors_theses

 Part of the [Electrical and Electronics Commons](#), [Space Vehicles Commons](#), and the [Systems Engineering Commons](#)

Digital USD Citation

LaCalli, Kameron, "Phased Helical Antenna Array for CubeSat Application" (2016). *Undergraduate Honors Theses*. 32.
http://digital.sandiego.edu/honors_theses/32

This Undergraduate Honors Thesis is brought to you for free and open access by the Theses and Dissertations at Digital USD. It has been accepted for inclusion in Undergraduate Honors Theses by an authorized administrator of Digital USD. For more information, please contact digital@sandiego.edu.

Phased Helical Antenna Array for CubeSat Application

A Thesis

Presented to

The Faculty and the Honors Program

Of the University of San Diego

By

Kameron James LaCalli

Electrical Engineering

2016

Preface

This design is presented as completion of the Honors Program at University of San Diego under advisorship of Dr. Kathleen Kramer and Dr. James Gilb. The work here, while done individually, is done as contribution to the University of San Diego CubeSat Team, established in 2016, in hopes of advancing CubeSat communications technology while still considering cost restraints.

The scope of this thesis only goes as far as a design, and due to time restrictions does not delve into hardware development or physical testing. Focus will also primarily be on the RF (radio frequency) elements of the phased array system, as there is much to be designed still constitute a fully functioning space-ready CubeSat design.

Contents

Introduction.....	4
Background.....	4
CubeSats	4
Phased Arrays	5
General Design.....	6
Limitations & Considerations	6
Primary Concept	7
Frequency & Protocol.....	8
Antenna.....	8
Part Selection & Description.....	9
CubeSat Parts	9
Ground Station Parts	10
Power Budget.....	10
RF Design	11
Link Budget	11
Losses.....	12
Gains	13
Summary	13
Antenna Design.....	14
Phased Array Modeling	16
Antenna Model.....	16
Array Model.....	18
Wilkinson Power Divider	20
Conclusion	24
Summary and Future Work.....	24
Thanks.....	25
Appendix.....	26
Supplementary Figures	26
References.....	28

List of Figures

Figure 1: Block Diagram of Overall Design.....	7
Figure 2: Physical Layout	8
Figure 3: Free Space Path Loss Illustration and Equation	12
Figure 4: Helical Antenna Design Equations and Physical Specifications.....	15
Figure 5: Scale Layout of Helical Antennas	15
Figure 6: 4NEC2 Antenna Specification Page.....	16
Figure 7: Polar Pattern from 4NEC2 Helical Antenna	17
Figure 8: 4NEC2 3D Model of Helical Antenna Radiation.....	17
Figure 9: Comparison of 4NEC2 Model and Matlab Immitation, Note Scale Differences.....	18
Figure 10: Array Factor Equation	19
Figure 11: Array Factor Value at Various Degree Shifts	20
Figure 12: Final Phased Model with -40, 0, and 40 Degree Shifts	20
Figure 13: Wilkinson Power Divider Design Specification	21
Figure 14: Lumped Element Divider Equivalent Schematic	22
Figure 15: 1 to 4 Wilkinson Microstrip ADS Design.....	22
Figure 16: S Paramters for Microstrip Design.....	23
Figure 17: Microstrip Design Board Layout.....	23
Figure 18:Example of Matlab Script for Phased Array Calculation.....	26
Figure 19:Lumped Element LC Design in ADS.....	26
Figure 20: S Parameters of LC Design	27

List of Tables

Table 1: Power Budget.....	11
Table 2: Link Budget at 1000km	13
Table 3: Link Budget at 200km	14

Introduction

Due to their size, CubeSats and other small satellites are severely limited in power and communication capabilities. Small, sometimes non deployable solar panels restrict potential transmission power, and physical layout limits space for higher gain antenna configurations, such as parabolic dishes, reflective arrays, and horn antennas. These restrictions have had the tendency to force CubeSat missions to have slower communications speeds, limiting the amount of data that can be transferred per overhead pass. So far this limitation hasn't been *severely* restraining on missions, as smaller CubeSats typically acquire a relatively small amount of data with only a few sensors. However, higher downlink speeds would allow for more data collection as sensors continue to be manufactured smaller and cheaper, squeezing more capability into the 1000 cm² CubeSat frame. A higher throughput standard for CubeSats would also allow for innovative approaches to satellite networking and beyond low earth orbit capabilities.

The purposes of this study are to investigate and design the RF components of a phased array antenna for 1U CubeSat application, to establish the feasibility of higher speed, lower power, low cost CubeSat communication capabilities.

Background

CubeSats

CubeSats, a standardized form factor for small satellites, are rapidly disrupting the satellite business. In the 1980's and 1990's, common research or surveillance satellites were large, heavy, and required long term projects that cost tens or even hundreds of millions of dollars. As such, designers ensured that these satellites would perform hundreds of tasks and have lifespans upwards of 10+ years. Recent technologies however are allowing governments, businesses, and universities to accomplish similar goals with cheap, lightweight, low power, electronics due

largely in part to the recent surge of smartphone components. With computing power similar to the processor found in a smartphone, small satellites can perform specific missions at a fraction of the cost and timeframe. They may not be *quite* as capable as older larger satellites, but they cost only tens or hundreds of thousands of dollars, and can be developed and launched exponentially faster.

In an effort to bring the smallsat cost down even further, the CubeSat specification was developed by a partnership between California Polytechnic University and Stanford University in 1999, with the first successful mission in 2003 [8]. This specification defines a physical standard for small satellites to adhere to, allowing companies to mass produce sub systems for the satellite that any payload can easily integrate to (otherwise, a “design from scratch” approach is required for all subsystems). This also simplifies the launch process, as anyone can design around the CubeSat standard and know with certainty that it will integrate into and deploy properly from the launch system, as previously, satellites required complicated custom integration.

Phased Arrays

The other primary technical field this thesis delves into is phased array antenna technology. First conceptualized in 1905 by Nobel laureate Karl Braun [6], phased array antenna radios use multiple antennas in conjunction, varying the phase of each antenna’s signal to get the propagation patterns of each to constructively interfere with each other in certain directions and destructively interfere in others [7]. This creates a stronger signal at specific angles to the antenna, allowing the radio to “target” where it sends the majority of its power, resulting in further, clearer, higher speed transmission. Commonly used in military and radar applications, phased arrays are seldom deployed in space applications, much less smallsats/CubeSats (though

designs exist, documentation on deployed phased antenna is scarce) [2]. The 2011 launched Messenger spacecraft is an early documented space-based application of a phased-array system. This field encompasses a large number of classified missions, as well, where there are a significant number of projects with documentation that is not publically available [12].

General Design

Limitations & Considerations

Being designed around a single unit CubeSat, space and power are severely limited. When designing a phased array, the number of elements is critical to its successful operation and beam forming capabilities. However, with only 1U there isn't much space for a large array. Deploying panels after launch and separation can increase effective area (and antenna aperture), though it quickly increases mechanical complexity as well. Power must also be considered, as typical CubeSat solar panel configurations only generate a few watts of power [1]. Other subsystems rely on this power as well, restricting the power available to the transmitter. For purposes of this design, the payload itself will be the phased array transmitter as a technology demonstration, allowing more in the power budget for the phased array.

Additionally, reaction wheels can consume considerable amounts of power orienting the satellite, though with the beam steering capabilities of a phased array physical orientation will be less critical for successful data connection. Lower power magnetorquers will provide sufficient earth facing orientation, with the beam steering handling the specific directionality of the high speed telemetry.

Link frequency must also be chosen carefully, as higher frequency can allow for higher throughput, though may also be inefficient for long range communication (due free space path

loss). As one of the primary benefits to a CubeSat is cost, availability of low cost/low volume parts at this specified frequency will be crucial for design feasibility. Apart from frequency choice though, lower cost for materials and general components will be important to keep with CubeSat convention.

Primary Concept

The phased design array consists of a 4 element array in a 2x2 helical antenna configuration arranged on one 10cm x 10cm face of a 1U CubeSat. The link will operate on the 2.4GHz band via the 802.11b standard protocol in CCK mode, for a downlink speed of 11 Mb/s. Transmission will be power intensive, so the array will avoid excessive power consumption by only transmitting when orbiting within line of site orbit from the ground station, allowing the battery to recharge before its next flyover. Figure 2 shows a physical representation of the 1U CubeSat with four helical antennas to scale, and figure 1 describes the general layout the system components.

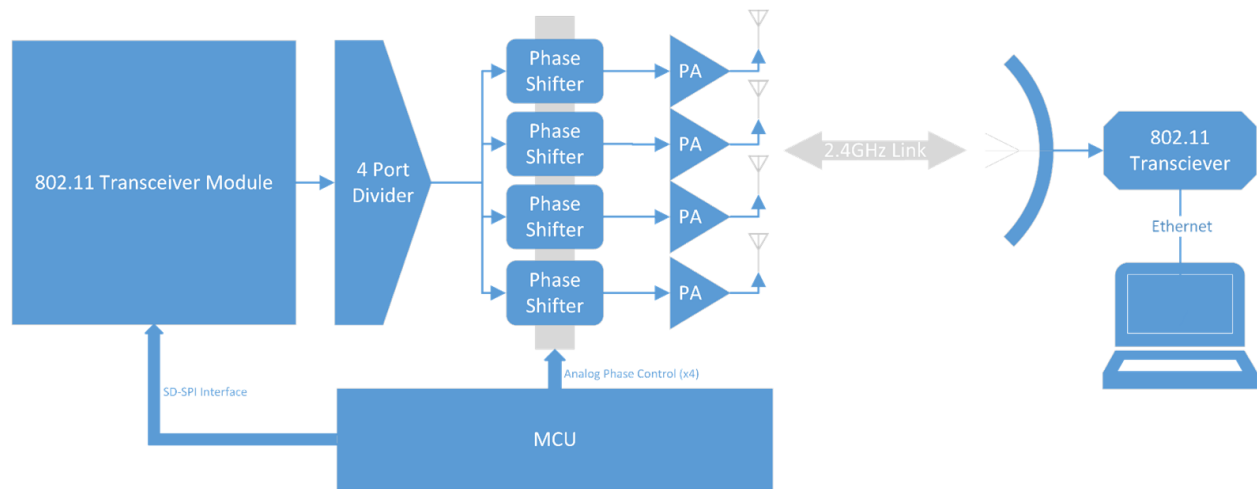


Figure 1: Block Diagram of Overall Design

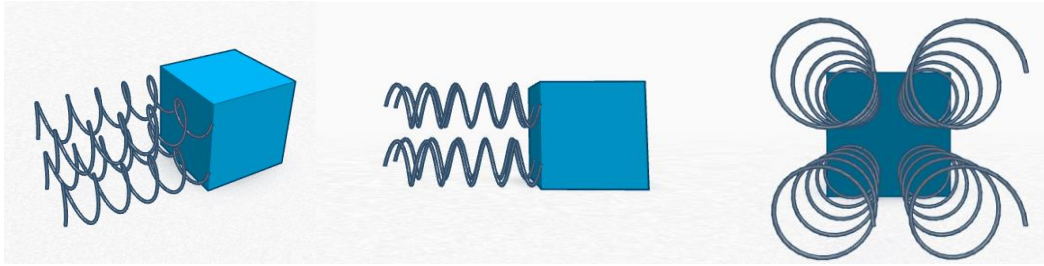


Figure 2: Physical Layout

Frequency & Protocol

Most CubeSat communication systems operate at 415MHz or 900MHz [8], with some running at 2.4GHz. For this design 2.4GHz is chosen, as the higher frequency allows for higher data rates, though not so high to undergo unrecoverable free space path losses from the sat to ground distance, ranging from 200km to 1000km. 2.4GHz also has a much smaller wavelength than typical CubeSat 415MHz/900MHz telemetry systems, allowing four helical antennas designed for 2.4GHz to fit nicely on one face. At 900MHz, the diameter for a single helical antenna would be 11.3cm, wider the entire 10cm x 10cm working space of a 1U CubeSat side. 2.4GHz also is a very common band, resulting in a plethora of cheaply available off the shelf parts. Being such a common band, interference and noise can be an issue, though with a ground station on top of a roof pointing directly to the sky, it will be less of a concern being isolated from other Wi-Fi, Bluetooth, and amateur networks.

802.11b as the system protocol works nicely, due to its networking capability and availability for quality components while operating CCK mode allows for 11MB/s, significantly higher than a large majority of CubeSat and small sat data links [8].

Antenna

Helical antennas are chosen here as the physical parameters at 2.4GHz operation fit nicely on a single side of a 1U. More importantly however, they typically offer higher gain than patch

antennas (commonly used in phased array configurations), ensuring a link connection with high data rates. Relatively simple in design and construction, they also offer a sort of “self-deploying” feature, in that the coil will have spring force capable of uncoiling itself [13]. Mechanical restriction before deployment may involve nichrome wire to control release of the helical antennas. More design will need to be done however to perfect the layout and deployment once in orbit.

Part Selection & Description

Primary active RF components for both the CubeSat and the ground station were chosen carefully with necessary requirements and power limitations in mind. Non-RF components (power, MCU, etc.) extend beyond the purposes of this design, as they are heavily dependent on other subsystems.

CubeSat Parts

Transceiver - The 802.11 capable transceiver needs to be low power and easily interfaced. High power output is not needed as signal amplification is done later in the path with the power amplifier, whereas there is actually an upper limit of signal power acceptable by the phase shifter, so adjustable gain is necessary. CCK mode capability (11Mb/s), though common on 802.11 transceivers is still a necessary trait. The Microchip RN171 LAN module with high speed SD-SPI interface, same interface used for writing to SD cards satisfies criteria nicely, with only 120mA current draw at 3.3V.

Phase Shifter - The Mini Circuits JSPHS phase shifter is actually one of very few small package, low power options available for the 2.4GHz band. Less than 2dB insertion loss is plenty low, and 320° phase shift capability is much more than needed.

Power Amp - For the power amplifier two viable options appear, one being lower power, the other having satisfactory low power requirements with much higher power output. The Skyworks SE2568U Wireless LAN PA is designed for the 802.11b standard, and provides up to 20 dBm output, while drawing 528 mW while amplifying. It also is relatively easy to use in only an 8-pin package. The Qorvo TQP9224 Small Cell PA pulls almost double the power, but is capable of putting out 24dBm and higher (nonlinear region) in a slightly more complicated 14 pin package. If power budget allows in conjunction with the rest of the CubeSat subsystems, this option will help ensure link budget completion with its higher gain.

Ground Station Parts

Antenna - The ground antenna on the receiving end of the link needs to have a high gain, and the L-Com 30dBi steel grid parabola provides just that. Being highly directional, it may require a mechanically steerable base to “follow” the CubeSat as it orbits across the sky, though the phased beam steering array on the CubeSat may be able to accommodate for that.

Receiver - Without power or size limitations on a ground station, a condensed and easy to use package with high sensitivity is the best option for the receiver. Marketed for the somewhat now-defunct “Wi-Max” venture, the Ubiquiti Bullet M provides a rugged weatherproof transceiver with Ethernet LAN connection for easy PC integration and highly sensitive -97dBm receive sensitivity. Software for easy control are included as well, and is available for approximately \$80.00 USD.

Power Budget

An in depth power budget is not needed for this study, as feasibility is the primary concern. As such, as long as typical 1U CubeSat power capabilities can be adhered to, the system will be

established as viable. With deployable solar panels in sun synchronous orbit, a 1U can generate a peak of 10W, while being able to charge batteries and/or capacitors to be discharged for the around twenty minutes of line of sight time over the ground station per orbit (number of orbits per day depends on the orbit angle and height). Table 1 establishes the transmitting power requirement with the 2x2 array to be under 3.5W, well under what a CubeSat would be able to supply for a substantial amount of time with fully charged batteries:

Table 1: Power Budget

Part	Voltage	Current - mA	Tx Power Draw - W	Total - W
802.11 Module	3.3	190	0.627	0.627
Phase Shifter (x4)	3.3	-	0.1	0.4
Power Amp (x4)	3.3	160	0.528	2.112
MCU	3.3	0.25	0.000825	0.0033
Total RF System Wattage:				3.1423

When not transmitting, and using a low power MCU (such as an MCU from the Texas Instruments MSP430 line), power draw would be on the order of microwatts, fully allowing batteries to charge (assuming no other data collection or sensor operation was to take place).

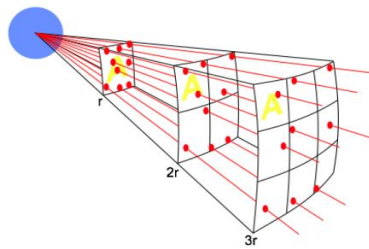
RF Design

Link Budget

The link budget calculates the feasibility of the wireless link by keeping track of the factors that degrade and boost the signal. With a margin for error, if the link budget totals to be at or over 0dB, the link should close in practice. If the budget is below the negative of the safety margin, then theoretically the wireless link physically cannot connect [11].

Losses

The largest and primary path loss by far associated with a long range point to point line of sight link is the free space path loss, which incurs simply from distance being between the transmitter and receiver, as the signal spreads out as it propagates. According to the free space path loss equation (sometimes also expressed as the “*Friis Equation*”), the value is also directly dependent on frequency, as shown by figure 3:



$$\text{FSPL(dB)} = 10 \log_{10} \left(\left(\frac{4\pi d f}{c} \right)^2 \right)$$

Figure 3: Free Space Path Loss Illustration and Equation

As the link is theoretically line of sight exclusively, with space to ground requiring no geographic interference and ignoring atmospheric absorption, the only other path loss to incur is that of the cabling and components, which is low with surface mount parts without long cables. The 2 dB insertion loss from the phase shifter and assumed 2dB cable losses result in only 4 dB more in loss, whereas the FSPL has at least a loss of 146 dB at a minimum 200km orbital height. The link margin, somewhat arbitrarily chosen depending on the system application (higher for more important mission critical systems) is also subtracted as a path loss, assuming worse than anticipated conditions. 10dB link margin is a value commonly chosen for space based applications [5].

Gains

On the other end, the antenna gains and both transceiver power and receiver sensitivity provide a gain in the link budget calculation. Values pulled from the data sheets and antenna design specs provide for easy summation. The receiver sensitivity is subtracted as a negative number, as the negative dBm value indicates how small a signal can be for the receiver to still reliably detect it, and is thus subtracted from the equation resulting in net a positive [4]. This receiver sensitivity at -97dBm provides the largest value of the link budget gains.

Summary

Table 2 and table 3 shows the summary of the link margin at both extremes of the wireless link distance, 200km when orbiting directly overhead, and 1000 km when crossing the horizon.

Table 2: Link Budget at 1000km

Operation	Factor	Value	Units
*+	Tx Power	24	dBm
*+	Tx Ant Gain	15	dBi
*+	Rx Ant Gain	30	dBi
*-	FSPL	160.05	dB
*-	Rx Sensitivity	-97	dBm
*-	Cable Losses	2	dB
*-	Phase Shift Insertion Loss	2	dB
*-	Link Margin	10	dB
*=	Surplus	-8.05	dB

Table 3: Link Budget at 200km

Operation	Factor	Value	Units
*+	Tx Power	24	dBm
*+	Tx Ant Gain	15	dBi
*+	Rx Ant Gain	30	dBi
*-	FSPL	146.07	dB
*-	Rx Sensitivity	-97	dBm
*-	Cable Losses	2	dB
*-	Phase Shift Insertion Loss	2	dB
*-	Link Margin	10	dB
*=	Surplus	5.93	dB

The surplus is negative at 1000 km, meaning that assuming worst case conditions the link will not close; although that is given the 10 dB link margin. Theoretically, the link could still complete at the farthest possible distance. In actuality, it will most likely be spotty until coming a little bit closer, unless more power is allocated for an even higher power amplifier, or an even more sensitive receiver is integrated.

Antenna Design

For helical antennas, a series of equations gives the physical design parameters needed for a given frequency, number of turns, and fraction of wavelength for turn spacing. Figure 4 shows the equations used, and figure 5 shows what parameters those physically refer to.

$$G = 10.8 + 10 \cdot \log_{10} \left(\left(\frac{C}{\lambda} \right)^2 \cdot N \cdot \left(\frac{S}{\lambda} \right) \right)$$

$$D = \frac{\lambda}{\pi} \quad R = 0.75 \cdot \lambda$$

Figure 4: Helical Antenna Design Equations Used

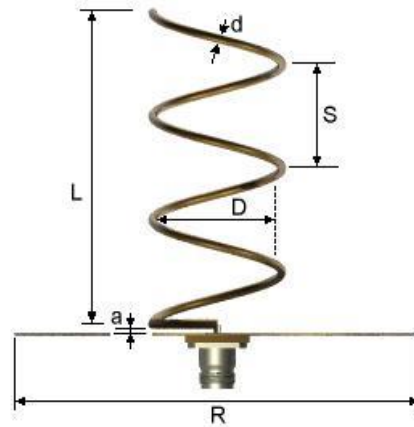


Figure 5: Helical Antenna Physical Parameters

For a 2.4 GHz antenna, with $N = 5$ turns at $\lambda/4$ spacing, the optimal helical antenna yields 11.8dBi gain with 153mm overall length, 39mm diameter, and 30mm spacing between coils.

While potentially a little optimistic by a few dB from actual real world antenna gain, the spacing and physical size fits nicely onto one 10cm x 10cm face of 1U CubeSat. Figure 6 shows a model to proportionate scale of what this configuration would look like:

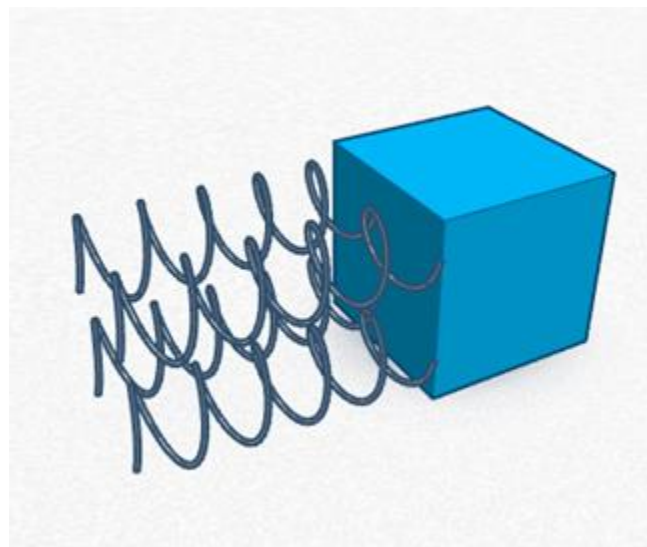


Figure 6: Scale Layout of Helical Antennas

Phased Array Modeling

Antenna Model

Before completing a model for the phased array, a model for the individual antenna element is needed. Initially, Matlab simulation was attempted following the “Antenna and EM Modelling with Matlab text” [10], though was abandoned due to complication and time consumption. Though powerful and deeply customizable, creating a full custom model within Matlab is beyond the scope of this project. However, using the freeware software program 4NEC2, based off of the NEC (Numerical Electromagnetics Code) simulation engine, a helical antenna of designed physical parameters can be easily constructed and simulated at any frequency and stimulus. The figures below depict the results, which at maximum gain of 9.9dBi, are only about 1dB off from the quick equation calculation, consistent with the findings from the Gunthard Kraus article [9]. Figure 7 shows the front page of 4NEC2 with parameters of the specific antenna design and figure 8 shows the resulting polar radiation plot simulation of that antenna. Figure 9 shows a nicely rendered 3D model of the same data.

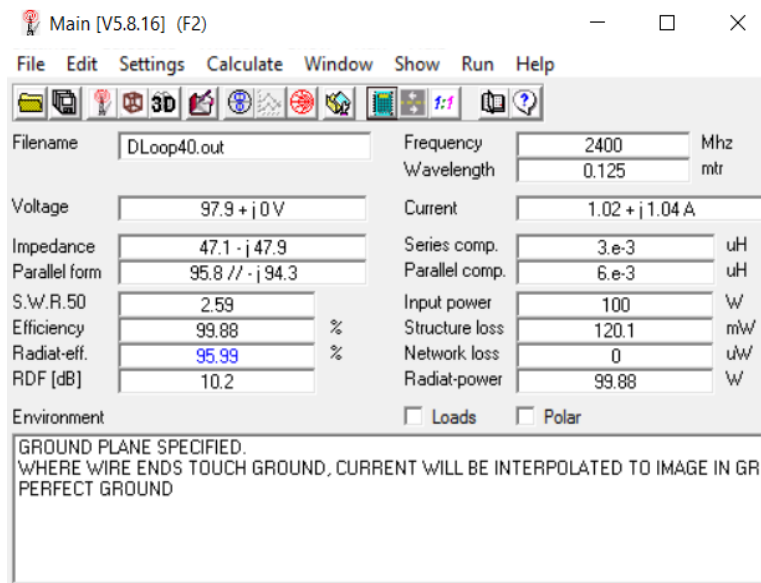


Figure 7: 4NEC2 Antenna Specification Page

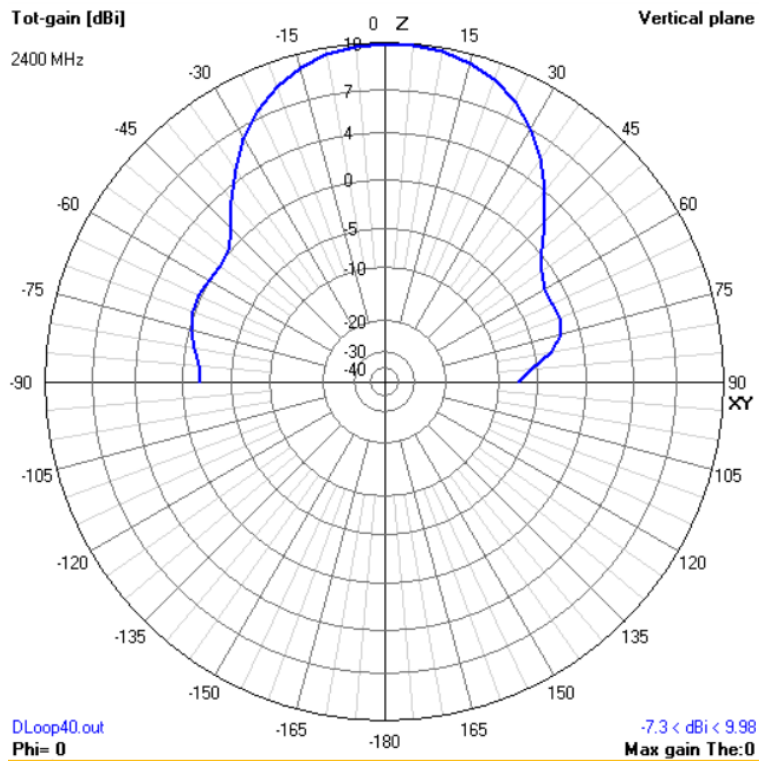


Figure 8: Polar Pattern from 4NEC2 Helical Antenna

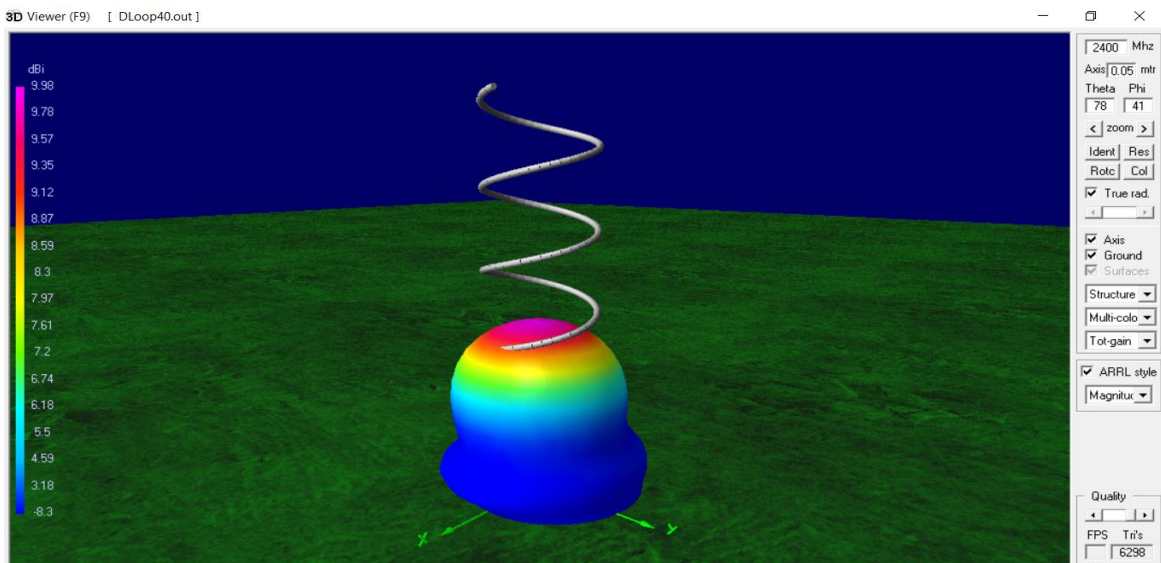


Figure 9: 4NEC2 3D Model of Helical Antenna Radiation

To create the phased array model however, a Matlab plot is needed to be able to mathematically operate on it. To quickly create this, a cubic spline function and twenty-four points of data from the simulation output are used to create a similar polar plot, now useful within the Matlab environment, as seen in figure 10.

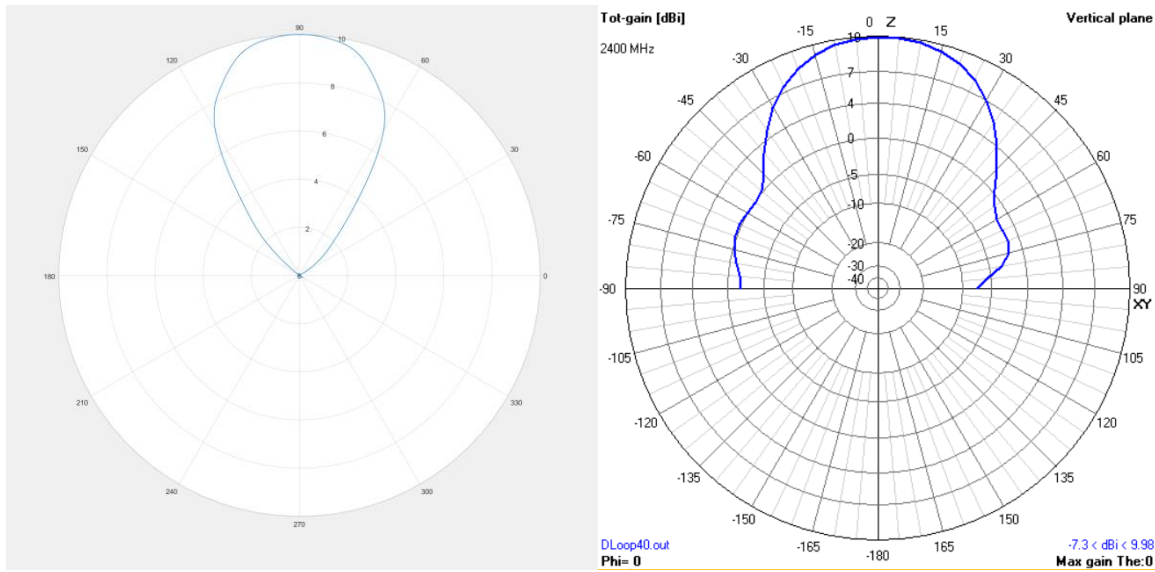


Figure 10: Comparison of 4NEC2 Model and Matlab Immitation, Note Scale Differences

As shown by figure 10, the cubic spline is capable of producing a very close match to the original function. The shape of the lobe isn't identical however, as the scales are different. The simulated model goes below 0 dBi, and the Matlab plot ends at 0 for practicality purposes (below 0 dBi the gain is negligible). Above 0 dBi however, the plot is plenty accurate for our purposes of simply trying to understand how the phased array will generally affect the radiation pattern, and to get beam width estimates and beam locations given different phase shifts.

Array Model

The phased array pattern is obtained by simply multiplying the propagation pattern of the individual antenna elements by the calculated array factor at a given phase shift. The array factor itself is dependent on the operation frequency, number of elements in the array, spacing between

the elements, and the phase shift between the elements. Refer to appendix for the actual equations used in Matlab code. The following figure 11 shows the derivation of the array factor equations used.

$$AF = \left(\frac{e^{-j3\pi \sin \theta \cos \phi / 2}}{e^{-j\pi \sin \theta \cos \phi / 2}} \right) \left(\frac{e^{-j3\pi \sin \theta \sin \phi / 2}}{e^{-j\pi \sin \theta \sin \phi / 2}} \right)^*$$

$$\left(\frac{\sin(3\pi \sin \theta \cos \phi / 2)}{\sin(\pi \sin \theta \cos \phi / 2)} \right) \left(\frac{\sin(3\pi \sin \theta \sin \phi / 2)}{\sin(\pi \sin \theta \sin \phi / 2)} \right)$$

$$|AF| = \left(\frac{\sin(3\pi \sin \theta \cos \phi / 2)}{\sin(\pi \sin \theta \cos \phi / 2)} \right) \left(\frac{\sin(3\pi \sin \theta \sin \phi / 2)}{\sin(\pi \sin \theta \sin \phi / 2)} \right)$$

Figure 11: Array Factor Equation

With equations and constants set, all that's left is to vary the phase shift between elements (Beta) and see how the beam is shifted in turn (note these phase shifts are constant between each phase shifter, i.e. phase control is "unweighted") [3]. Figure 12 shows the results of the plot of the array factor value as the phase changes, and figure 13 shows the result of different array factors multiplied with the original element pattern. This shows a phase shift range of +/-40 degrees, which yielded best results and a +/-30 degree beam shift pattern. Shifting higher than 40 degrees resulted in significant back/side lobes and notably less gain. Given the application and long distance of the link, a total 60 degree range for beam steering is plenty to ensure the maximum gain pointed directly at the ground station, regardless of satellite disorientation.

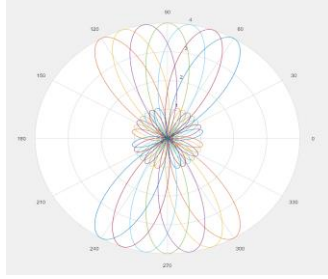


Figure 12: Array Factor Value at Various Degree Shifts

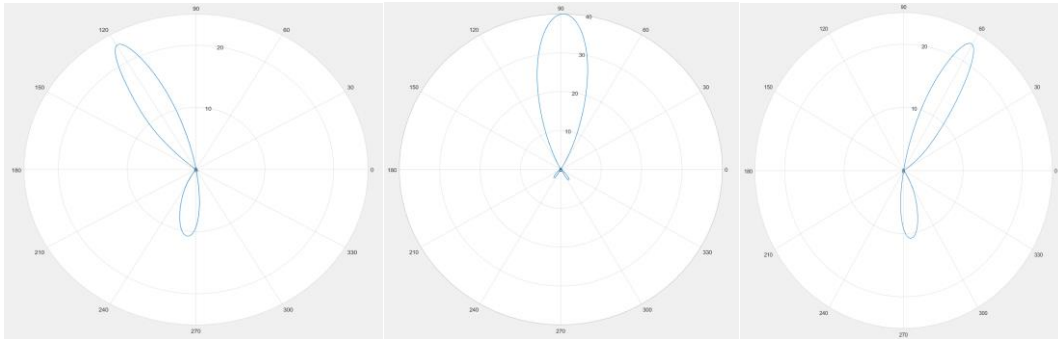


Figure 13: Final Phased Model with -40, 0, and 40 Degree Shifts

Wilkinson Power Divider

A power divider is required in order to split the RF power evenly between the four elements and the transceiver, the most straightforward method of which being through a Wilkinson power divider. A Wilkinson power divider simply splits a conductive microstrip trace into two and matches the impedance of the input while having a specific overall length for the given frequency, with a resistor in between the two outputs. For application, bends and curves must be added to the layout, which affect the RF response. The following diagram, figure 14, shows the relationships of the trace lengths and impedances needs for ideal power splitting.

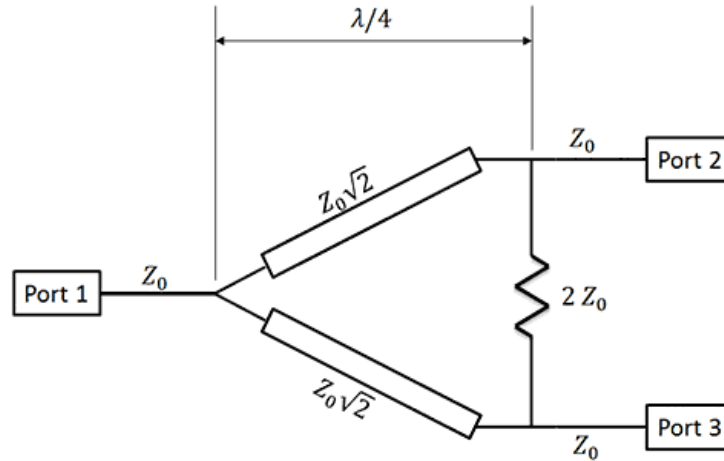


Figure 14: Wilkinson Power Divider Design Specification

Sometimes the required trace length can be rather long, resulting in a splitter that takes up significant space on a PCB, so an equivalent lumped element divider can be designed, replacing a line trace with two capacitors and an inductor in a pi configuration with equivalent impedance (parallel capacitors can be combined, requiring 4 capacitors and 3 inductors for each split, as shown in figure 15). This however does not easily take into account the added trace lengths and their added impedance on a board layout, making simple integration difficult, requiring tuning of numerous inductors and capacitors. A lumped element LC splitter without physical microstrip traces was quickly designed and simulated with positive results, although it was abandoned for the Wilkinson simplicity with regards ease of actual layout on a board.

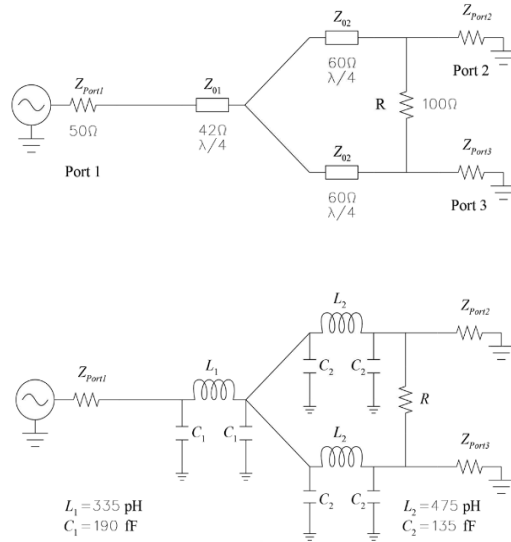


Figure 15: Lumped Element Divider Equivalent Schematic

Appendix figures 19 and 20 show the original design and S-parameters of the LC design, however the 2.4 GHz microstrip design was based off of a phased array design done by Allen Peters at California Polytechnic State University, San Luis Obispo [12]. Peters’ design was tweaked somewhat for layout purposes, as shown in figure 16, 17, and 18.

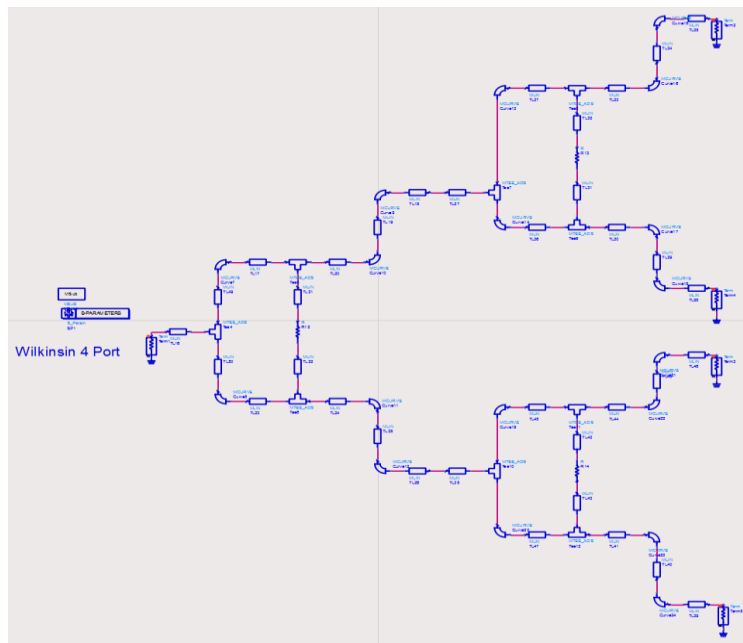


Figure 16: 1 to 4 Wilkinson Microstrip ADS Design

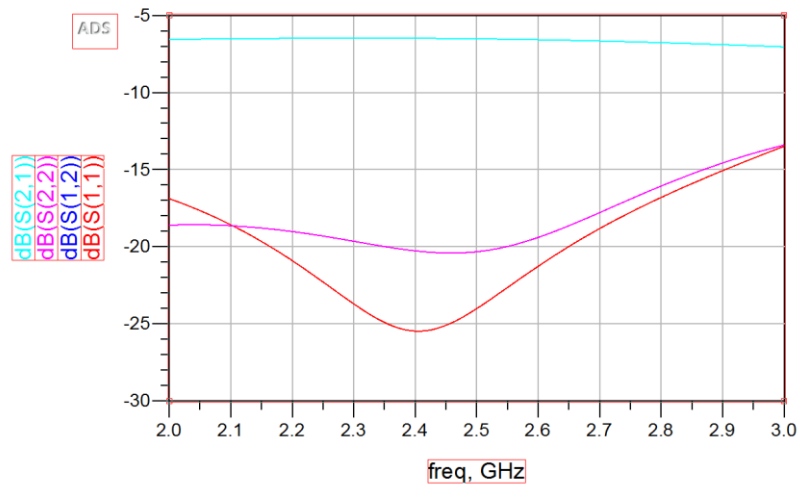


Figure 17: S Parameters for Microstrip Design

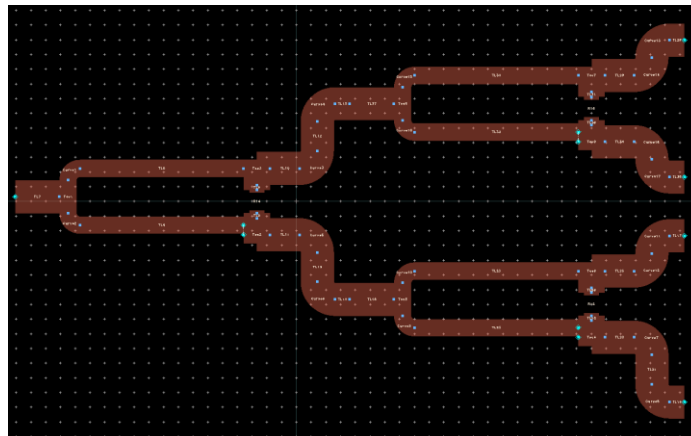


Figure 18: Microstrip Design Board Layout

From the S-parameters plot in figure 17, the gain [S(2,1), S(3,1), S(4,1) and S(5,1)] on each output is -6.3dB, only .3dB less than the ideal $\frac{1}{4}$ amount of input power at each output. The reflection S(1,1) has a spike downward at 2.4GHz as designed and goes below -25dB. These performance specs are plenty fine given the application.

Conclusion

Summary and Future Work

With the power budget totaling at just a few watts and link budget completion with low power COTS parts, feasibility of a 4 element phased array downlink communication system has been confirmed. The system theoretically is capable of sending downlink data faster than any successfully deployed CubeSat at 11Mb/s [8], and will be able to run on low enough power to provide power to other subsystems and sensors (though not much, provided there is ample charging time with deployable solar panels). Aside from the high data rate, phased array technology itself has not yet been successfully launched on a CubeSat (though there are designs and work towards it), and potentially may have never been done on a small sat in general, being that there is little documentation on space based phased arrays. Hopefully the work presented here contributes to that push forward in small satellite communications technology.

Being only a theoretical thesis design, physical hardware testing obviously still needs to take place to further confirm the feasibility of an 11Mb/s phased array CubeSat system. Even before that, is still design work to be done, as this study focused only on the RF components needed. With regards to the communication system, MCU control of the phase shifters, as well as MCU interfacing to the transceiver, though not overtly complex, still requires work. An entire schematic and board layout for all components selected is needed as well, with power supply power, to simply run a connection test. From there mechanical and electrical integration with an entire CubeSat bus will provide a fully working standalone system with the ground station.

Thanks

I would like to thank Dr. Kathleen Kramer and Dr. James Gilb in the Electrical Engineering Department at the University of San Diego for their help with this study, and for the extra time they put in to help my project along. I would also like to thank the Honors Department at USD, run by Dr. James Gump and Erin Prickett, for providing the Honors Thesis infrastructure, as well as organizing the wonderful Honors classes I have taken over the course of my undergraduate education.

Appendix

Supplementary Figures

```
1 %Set Constants
2 - N = 4; %number of elements
3 - f = 2.4*10^9; %Freq in Hz
4 - v = 3*10^8; %Speed of light
5 - l = v/f; %wave length
6 - k = (2*pi)/l; %wavenumber
7 - d = l/2; %element spacing
8 - g = 10; %Gain of single helical antenna in dBi
9
10 %360 Degree plot
11 - theta = [0:0.01:pi];
12
13 %Run for range of beta values (the phase difference between two elements)
14 - for beta_deg = [-30:10:30] %Running +/- 30 degrees
15 - beta = (-30*pi)/180;
16 - gamma = k*d*cos(theta + beta);
17
18 %Array Factor
19 - rho = (sin((N/2)*gamma))./(sin((1/2)*gamma)) ;
20
21 %Helical Model Match
22 - x = 0:.1309:pi;
23 - y = g*[0 0 0 0 0 .1 .2 .4 .7 .85 .95 .99 1 .99 .95 .85 .7 .4 .2 0 0 0 0 0];
24 - xx = 0:.01:pi;
25 - yy = spline(x,[0 y 0], xx);
26
27 %Phased Array Propagation
28 - array = yy.*rho;
29
30 - polarplot(theta, array);
31 - end
32 - hold off;
```

Figure 19: Example of Matlab Script for Phased Array Calculation

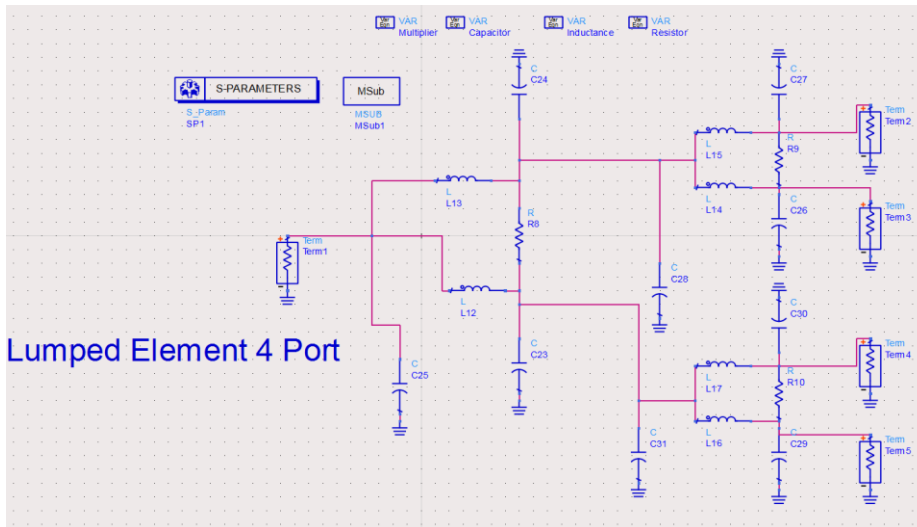


Figure 20: Lumped Element LC Design in ADS

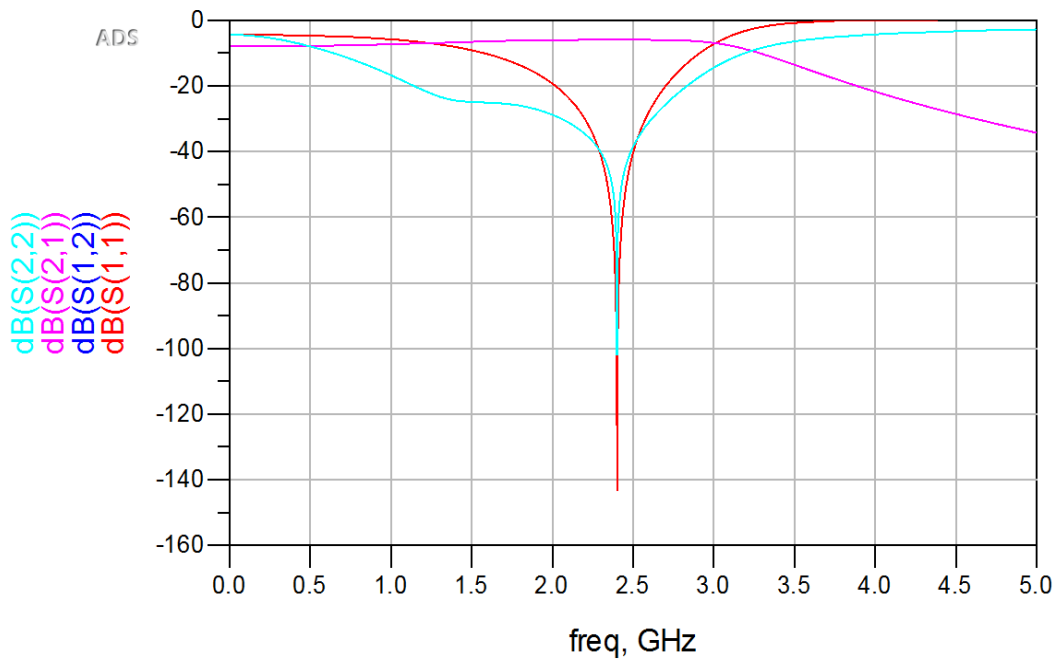


Figure 21: S Parameters of LC Design

References

- [1] Aragón, V., García, Á, Amaro, R., Martínez, C., & Sarmiento, F. (2011). *Researching a Robust Communication Link for CubeSats: OPTOS, a new Approach* (Unpublished master's thesis). National Institute of Aerospace Technology. Retrieved November 2, 2016, from https://www.thinkmind.org/index.php?view=article&articleid=spacomm_2011_3_20_30059
- [2] Balanis, C. A. (1997). *Antenna Theory: Analysis and Design* (2nd ed.). Hoboken, NJ: John Wiley & Sons.
- [3] Bevelacqua, P. J. (n.d.). Antenna Arrays. Retrieved October 5, 2016, from <http://www.antenna-theory.com/arrays/main.php>
- [4] Cantero Gómez, J. (2013). *Communication link design at 437.5 MHz for a nanosatellite* (Unpublished master's thesis). Aalto University. Retrieved November 2, 2016, from <https://aaltodoc.aalto.fi/handle/123456789/11119>
- [5] Capela, C. (2012). *Protocol of Communications for VORSAT Satellite - Link Budget* (Unpublished master's thesis). University of Porto. Retrieved September 15, 2016, from <http://paginas.fe.up.pt/~ee97054/Link%20Budget.pdf>
- [6] Dang, K. (2016). *Phased Array Antenna Investigation for CubeSat Size Satellites* (Unpublished master's thesis). Morehead State University. Retrieved September 15, 2016, from http://scholarworks.moreheadstate.edu/cgi/viewcontent.cgi?article=1003&context=msu_theses_dissertations
- [7] Klein, J., Hawkins, J., & Thorsen, D. (2014). *Improving CubeSat Downlink Capacity with Active Phased Array Antennas* (Master's thesis, University of Alaska, Fairbanks, 2014). IEEE.
- [8] Klofas, B. (n.d.). CubeSat Communication Systems: 2003-2016. Retrieved September 17, 2016, from <https://www.klofas.com/comm-table/table.pdf>
- [9] Kraus, G. (2010). Simulation and construction of a Helix antenna for 2.45GHz using 4NEC2. *VHF Communications*, (2). Retrieved December 10, 2016, from http://www.gunthard-kraus.de/Vortrag_Weinheim/4nec2_article.pdf
- [10] Makarov, S. N. (2002). *Antenna and EM modeling with Matlab*. New York, NY: John Wiley & Sons.
- [11] Langton, C. (n.d.). Link Budgets. Retrieved October 1, 2016, from <http://complextoreal.com/wp-content/uploads/2013/01/linkbud.pdf>

[12] Peters, A., & Arakaki, D. Y. (2010). *Phased array 802.11g antenna: a thesis* (Unpublished master's thesis). Retrieved September 15, 2016, from <http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1359&context=theses>

[13] Stilwell, R. K. (1991). Satellite Applications of the Bifilar Helix Antenna. *Johns Hopkins APL Technical Digest*, 12. Retrieved October 15, 2016, from http://www.jhuapl.edu/techdigest/views/pdfs/V12_N1_1991/V12_N1_1991_Stilwell.pdf