A PLANAR ANTENNA AND MODULAR SUBSYSTEM DESIGN FOR CUBESATS

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ABSTRACT

Previous University of Hawaii CubeSats constantly used new designs for each succeeding project. Having to redesign the three major subsystems (TTC, PGD, CDH) to accommodate a particular payload resulted in long development times and a steep learning curve for new members. To avoid these problems a modular subsystem design was researched and implemented. The utilization of standard connectors with all subsystem boards, and the independence of payloads in the design of subsystems were adopted to create a modularized CubeSat platform that could be used in future projects without modification. Two different types of planar antennas were also researched and designed to address shortcomings of previous CubeSat antennas.

INTRODUCTION

The University of Hawaii has produced several successful CubeSat designs since 2001, with varying missions spanning retrodirective crosslinks to global imaging. With each new mission the CubeSat group would design each subsystem (Tracking, Telemetry, and Control, Power Generation and Distribution, Command and Data Handling, Payload) using a few components that worked well in the past, but mostly starting from scratch with new components and PCB designs. This mantra catered mostly towards each specific mission and payload, but left future groups having to change designs to fit their own specifications. Therefore, to facilitate future CubeSat designs, a standardized interface approach was adopted. Each subsystem would be designed independently from any particular payload and instead be able to provide all the basic functionality previous subsystems offered, while also being reusable (without redesign) in the future in a "plug- and-play" fashion. The design of a standardized Tracking, Telemetry, and Control (TTC) subsystem is explained in this paper.

Along with the modular subsystem design, several planar antennas were examined for their feasibility in a CubeSat platform. The planar aspect of the antenna would seek to address the need to simplify CubeSats in order to reduce risk related mission failures and to bolster overall system robustness. Two designs were chosen and studied further to the point of design and simulation, with one being fabricated and tested. The methods for the design and testing of the antennas are described in this paper.

TTC SUBSYSTEM REQUIREMENTS

The Tracking, Telemetry, and Control subsystem is in charge of all inter-satellite (satellite-to-satellite) and satellite-to-ground communications. When data needs to be relayed between nodes in a CubeSat network constellation, the TTC subsystem is in charge of establishing communication links between the correct satellites to transfer the data that is needed.

When the ground station wants to retrieve this information, or simply give instructions to the satellite network, a reliable link must be created between satellite and ground station that is sufficient for ranges of about 500 km or low earth orbit (LEO).

Also, a low-power satellite beacon was proposed as a way of identifying the satellite. When satellites pass overhead, they usually broadcast a simple Morse code message that functions as an identifier. Using a separate, low-power beacon would free up the primary transceiver to focus on its data transmission priorities, and allow for constant beacon identification, which was not possible with the relatively high power consumption of the primary transceiver.

With this in mind, communication components were selected with the following requirements:

- The primary transceiver must be capable of communicating through line of sight with another node in the network, as well as a ground station that is around 500 km away.
- The frequency of the transceiver should be in one of the amateur radio bands, allocated for amateur satellite use.
- The antenna for the transceiver should be low profile and non-deployable, resonate at the correct frequency, and must have enough gain with omnidirectionality to communicate with a ground station as well as adjacent satellites in orbit.
- The primary transceiver must be capable of transmitting a complete data stream in an allotted time. This is necessary because satellite passes are very short (5-15 minutes long), and incomplete data transmissions are useless.
- With the goal of CubeSat constellations in mind, the subsystem must be able to configure itself into a complete network capable of file sharing, as well as being able to reconfigure the network in case of node failures.
- The TTC beacon should be a simple Morse code message (duration of less than 30 seconds) that consists of an identifying call sign and some simple satellite health telemetry data. The data must be transmitted with a low-power transmitter that can be on at all times if necessary.

These communication requirements were verified with a link budget analysis using the Jan King excel spreadsheet[1].

COMPONENT RESEARCH AND SELECTION

TTC Inter-Satellite and Satellite-to-Ground Communications

Several Hawaii CubeSats used the MHX 2400 radio for its main satellite communications[2]. While the radio met many of the subsystem requirements mentioned above, it was quite difficult to establish a network configuration in a space based application setting. For this reason, the Xtend radio module was chosen as the new TTC main satellite communications radio. The Xtend radio transmits at 900MHz, for which there is a dedicated band for amateur radio use[3]. The Xtend matches or exceeds the critical features of the MHX 2400, including 1W transmit power, 115kbps throughput, and most importantly, better networking capabilities. While the MHX required a master/slave relationship between nodes in a network (which posed the problem of figuring out which satellite is the master while all others were slaves), the Xtend radio maneuvered around that by implementing peer-to-peer networking which allows radios to communicate with whichever node it can establish a link to. The Xtend radio can easily be configured on a computer using a terminal and AT command line.

Figure 1: Xtend 900MHz RF module.

TTC Beacon

The TTC beacon was designed to be low powered, while still being able to function as a secondary communications system in case the Xtend radio failed. The beacon was implemented with a simple microcontroller and a low-power transmitter. The microcontroller chosen was the PICAXE 28-X1 which was selected because of its ease of use and because it satisfied the requirements of being a low-power controller for the satellite beacon (20mW). The PICAXE also supported I2C which was being implemented as part of the modular subsystem design. The TWS-434 transmitter was chosen because of its frequency of operation (433MHz), low-power design (230mW), and modulation scheme (AM). The microcontroller and transmitter formed the basis of the satellite's beacon system.

DESIGN

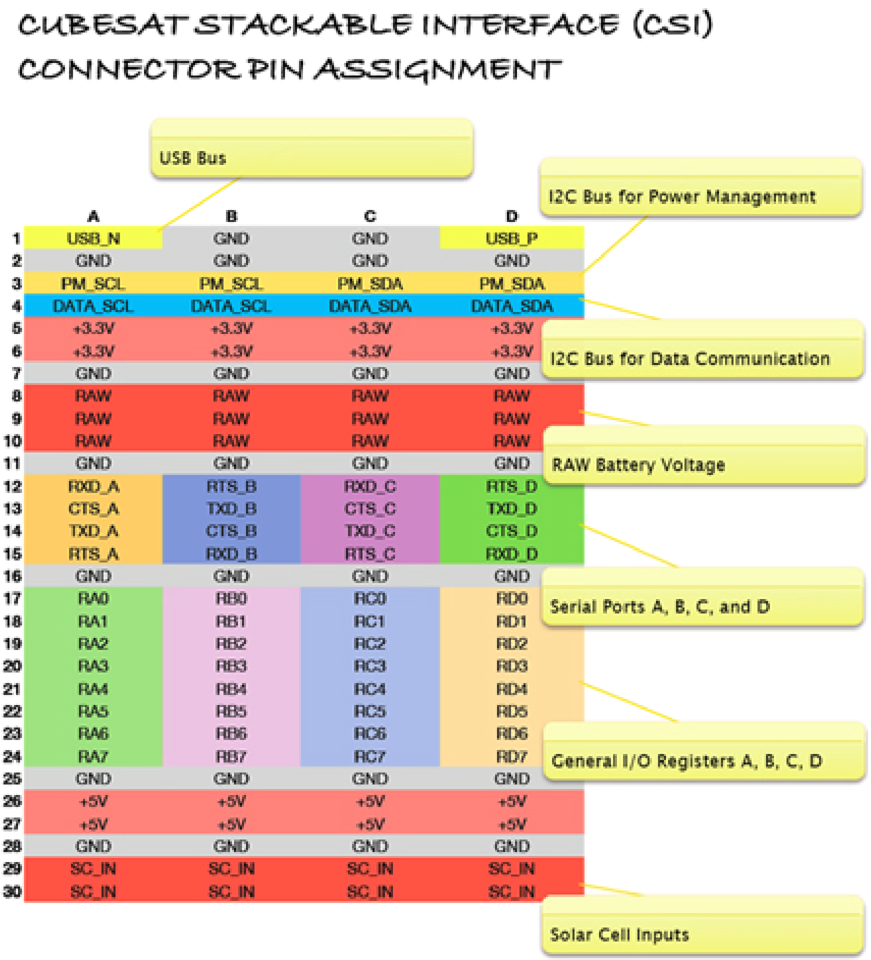
Modularity Through the CubeSat Stackable Interface (CSI)

A major facet of designing a modular subsystem is the interface between the different parts of the satellite. A stackable connector that is used for all the boards in a CubeSat bus would provide the necessary data and power connections, and facilitate a standardized design. By stacking the various subsystem boards on top of each other, different modules could be added or subtracted from the system without changing the basic design foundation of the satellite bus. This fit the requirement of developing a baseline CubeSat platform which future projects could base their design off of.

The PC-104 connector fit the requirements of the design and was chosen because of its presence in the technology and small satellite industry. The PC-104 standard is a 120-pin connector that contains a 4x30 pin configuration in a sturdy package[4]. This stackable connector was highly standardized with parameters for PCB placement and mounting hole placements. When stacked with subsystem boards, the PC-104 connector would provide a strong physical connection between all CubeSat systems that would aid in the system integration phase of satellite development.

Along with the standard PC-104 connector, there is also a standard pin assignment that is usually used. Since many of the pins were not necessary in the CubeSat design, a proprietary pin assignment was developed which maximized the pin resources for the different subsystems, and allowed for future payloads to be connected to the bus. Designing for an arbitrary payload involved including an I2C bus, general input and outputs to the microprocessor, as well as standard power lines (5V, 3.3V), solar cell inputs, and raw power lines. The use of the PC-104 connector and the proprietary pin layout is called the CubeSat Stackable Interface (CSI)

Common signals were located near each other and often times included several rows of identical signals. This was implemented for signal integrity as more and more devices are connected to the bus. Also, to shield signals from possible interference, power lines were separated from data carrying lines by ground signals. Digital signals were never placed adjacent to each other (as can be seen by the altering of pin assignment order in the serial port block) to further limit the possibility of signal interference. Four serial ports are available as well as four general purpose inputs and outputs to allow for future payloads to be able to communicate with the CDH microprocessor. Finally, two I2C busses were implemented on the CSI, one for data between master and slave devices, the other for dynamic power management purposes. A pin assignment diagram for the CSI is shown below.



CUBESAT STACKABLE INTERFACE (CSI)
CONNECTOR PIN ASSIGNMENT

	A	B	C	D
1	USB_N	GND	GND	USB_P
2	GND	GND	GND	GND
3	PM_SCL	PM_SCL	PM_SDA	PM_SDA
4	DATA_SCL	DATA_SCL	DATA_SDA	DATA_SDA
5	+3.3V	+3.3V	+3.3V	+3.3V
6	+3.3V	+3.3V	+3.3V	+3.3V
7	GND	GND	GND	GND
8	RAW	RAW	RAW	RAW
9	RAW	RAW	RAW	RAW
10	RAW	RAW	RAW	RAW
11	GND	GND	GND	GND
12	RXD_A	RTS_B	RXD_C	RTS_D
13	CTS_A	TXD_B	CTS_C	TXD_D
14	TXD_A	CTS_B	TXD_C	CTS_D
15	RTS_A	RXD_B	RTS_C	RXD_D
16	GND	GND	GND	GND
17	RA0	RB0	RC0	RD0
18	RA1	RB1	RC1	RD1
19	RA2	RB2	RC2	RD2
20	RA3	RB3	RC3	RD3
21	RA4	RB4	RC4	RD4
22	RA5	RB5	RC5	RD5
23	RA6	RB6	RC6	RD6
24	RA7	RB7	RC7	RD7
25	GND	GND	GND	GND
26	+5V	+5V	+5V	+5V
27	+5V	+5V	+5V	+5V
28	GND	GND	GND	GND
29	SC_IN	SC_IN	SC_IN	SC_IN
30	SC_IN	SC_IN	SC_IN	SC_IN

USB Bus

I2C Bus for Power Management

I2C Bus for Data Communication

RAW Battery Voltage

Serial Ports A, B, C, and D

General I/O Registers A, B, C, D

Solar Cell Inputs

Figure 2: CubeSat Stackable Interface (CSI) pin assignments.

PICAXE Beacon

The main goals for the beacon subsystem are to function as an identification beacon for the satellite, as well as a source of simple telemetry data. The identification beacon would function as the satellite's call sign transmitted in Morse code. The beacon also would function as a secondary communication system in case our primary communication system failed. The identification beacon would be transmitted in Morse code, and would be audible to any amateur radio operators outfitted with the necessary equipment. The telemetry data is transmitted serially using Amplitude Shift Keying (ASK) modulation. This allows for reliable transmission of serial data, which consists of a series of zeroes and ones, with the satellite's low-power transmitter.

The data that will be transmitted is simple telemetry numbers from the satellite. These numbers include: battery voltage and current levels, current being drawn from the solar panels, transmit power, etc. The amount of telemetry data being sent is not large because the entire beacon message, including the identification beacon, should be less than 30 seconds long. This is an important time constraint as LEO orbits have communication windows of about 15 minutes long at best, so to ensure reliable data transmission, the message must be looped several times within the satellite pass window.

The PICAXE microcontroller and the TWS-434 transmitter function together as the satellite's beacon. The PICAXE is hardcoded with the Morse code version of the satellite's call sign, and also handles the data from the CDH subsystem and prepares it for serial data transmission. The PICAXE then outputs the Morse code and telemetry data to the TWS-434 transmitter for transmission down to Earth.

Planar Antenna: PIFA

Previous CubeSats have implemented various types of antennas for their transceivers, ranging from whip antennas to patch antennas. Whip antennas are simple and have an omnidirectional radiation pattern, but they require deployment and that can be complicated in a space environment where there is little physical control of the satellite. Patch antennas are hailed for their low profile (does not require deployment) and beam-like directionality, but on a satellite where little to no attitude control is utilized, this advantage can easily be a strong disadvantage (since the patch antenna could be pointed away from Earth, with nothing going towards the ground station).

PIFAs are used in mobile communications because of their low profile and omnidirectional radiation patterns[5]. One could say the PIFA provides the advantages of the whip (omnidirectionality) and patch antenna (does not require deployment), without the disadvantages. A planar inverted F antenna (PIFA) was researched, designed, fabricated, and tested to see if integration on a CubeSat structure would be possible. The basic physical form of the PIFA is shown below, including the patch, ground plane, substrate, and pin locations.

Graduate student Brandon Takase assisted in the design, fabrication, and testing of a 900MHz PIFA to be used with the Xtend RF module. The PIFA antenna dimensions are scalable, and a report done by Anpeter Nguyen[6] was referenced to find the appropriate dimensions of all components based on the radio's operating frequency. The measurements depend on wavelength, which is related to operating frequency in free space by c, the speed of light. Below are calculated values for 900MHz operation with a physical size of 6.8cm x 14.7cm x 1.47 cm (perfect for the long side of a 1.5U CubeSat which measures 10cm x 10cm x 15cm).

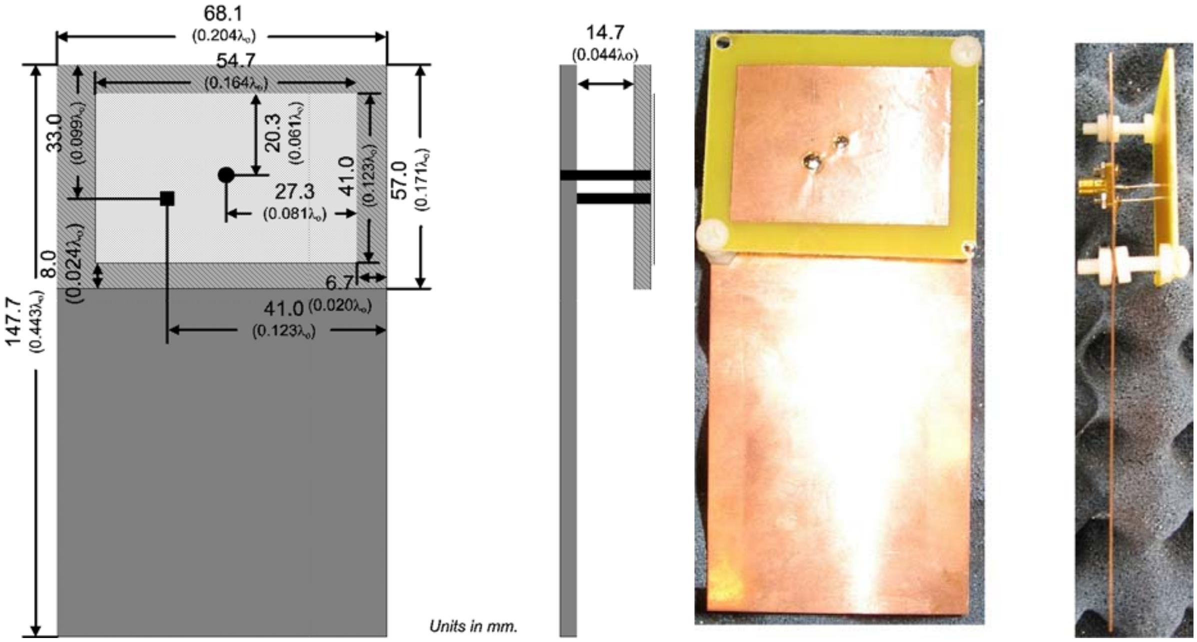


Figure 3: PIFA physical dimensions drawing alongside the fabricated PIFA.

PIFA Testing and Measurement

Following the PIFA fabrication, standard antenna parameters were measured to quantify the antenna's performance and verify the fulfillment of design requirements. The measurements were done with the assistance of Brandon Takase in a microwave engineering lab at the University of Hawaii at Manoa.

The first measurement taken was the return loss of the antenna; this is known as the S11 scattering parameter. By looking at the return loss, one can determine at which frequencies the antenna will resonate and therefore output propagating waves (with an ideal return loss of -∞ dB which indicates zero return loss). When the PIFA was hooked up by itself to port 1 of the network analyzer, the return loss as a function of frequency as seen below was obtained. The highest return loss of -37.2 dB occurs at 937MHz, while a frequency range of 775MHz to 1025MHz satisfies the 2:1 VSWR (at -10 dB) threshold. This wide frequency range is more than enough to encompass the Xtend radio frequency hopping spectrum of 902-928MHz. This measurement verified that the antenna operates at the desired 900MHz frequency.

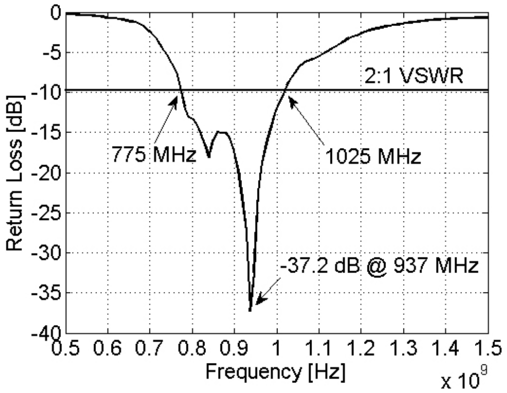


Figure 4: PIFA Return Loss vs. Frequency.

The second measurement taken was the PIFA's radiation pattern. A transmitting horn was fixed at a position and the PIFA was rotated around 360° with the receive power plotted as a function of rotation. Different polarizations of the transmitting horn and orientations of the PIFA were used. The radiation pattern received at the PIFA is shown below. From the results, the PIFA is omnidirectional in the *x*-*z* plane when the horn in oriented in co-polarization position. This was as expected, and a good sign that this antenna radiates omnidirectionally at the designed frequency of 900MHz.

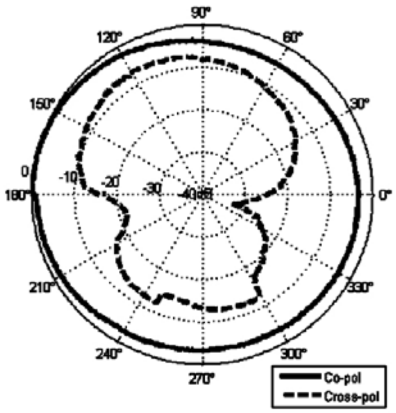


Figure 5: Radiation pattern of PIFA in x-z plane.

The preliminary results obtained for the PIFA were very good. The antenna functioned at the correct frequency and was omnidirectional in the *x*-*z* plane. Brandon Takase recommended that a more accurate measurement would be to mount the antenna onto a satellite structure. I obtained a sample 1.5U aluminum CubeSat structure and mounted the antenna on, and simulated a complete structure with copper plating on all sides. This measurement yielded poor results compared to the original measurements. This degradation of performance led to an exploration of a new antenna type.

Planar Antenna: Printed Dipole with Integrated Balun

Another approach studied for the satellite's antenna was the printed dipole with integrated balun. A dipole antenna is one of the most basic antenna types, and it exhibits the omnidirectional characteristic of the satellite subsystem requirements. A basic dipole antenna uses two elements which length is a function of operating frequency, and for the resonant type antenna this length is $\lambda/2$. The printed dipole antenna implements a basic dipole on a dielectric substrate, like FR-4 or PCB material. This printed dipole could be mounted flush on the side of a CubeSat and thus reduce the complexities of a deployable antenna. This antenna type was chosen because it fit all of the design specifications set out for the satellite antenna, namely being omnidirectional and planar.

Because the printed dipole was to be fabricated on a substrate using microstrip line and SMA connectors, a balun was needed to convert from an unbalanced feed (microstrip line) to a balanced feed (two feed points of the printed dipole). This was a complex step which was solved by including a top microstrip patch which served to fulfill the balun requirement. The balun requirement involves feeding the two elements of the dipole at a 180° phase difference of current. By using an integrated balun, the performance of the antenna (radiation pattern, operating frequency) would approach predicted antenna theory.

Advanced Design Systems (ADS) software from Agilent was used to design the antenna and simulate its performance. Referring to the IEEE journal paper by Chuang and Kuo[7] which designed a similar antenna for a different frequency, a prototype antenna was designed which operated at the 900MHz frequency range of the Xtend radio. The antenna layout can be seen in the figure below. At 900MHz, the longest dimension of the antenna is about 12cm, which will fit nicely in a 1.5U CubeSat structure.

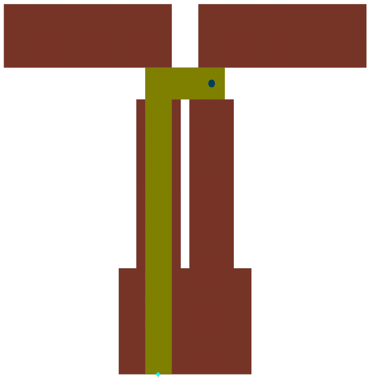


Figure 6: Prototype layout for 900MHz printed dipole antenna.

The simulated return loss shows good performance at our radio's frequency range of 902-928MHz. The plot below shows the S11 or return loss plot, with the red line representing the antenna's usable frequency bandwidth (frequencies below the red line represent the frequency bandwidth). The two markers point out the low and high end of the radio's frequency range, verifying that the antenna matches nicely with the radio.

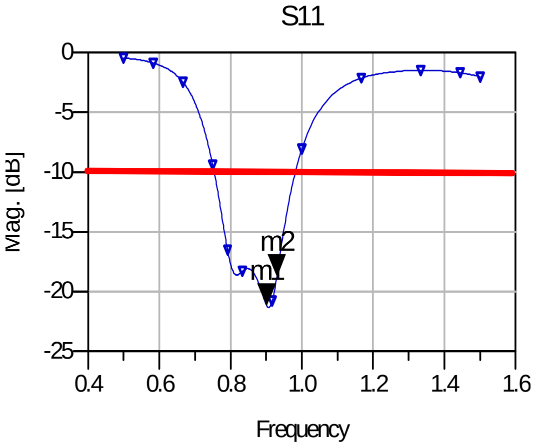


Figure 7: S11 Return Loss plot of 900MHz printed dipole antenna.

The 3D simulated radiation pattern is shown in the figure below. Notice how the pattern is omnidirectional in one plane (plane perpendicular to the plane of the paper). This is very close to the ideal case of a basic dipole antenna, with only slight differences due to the inefficiencies of using a dielectric substrate. The omnidirectional pattern of the antenna fulfills the requirement for omnidirectionality in at least one plane.

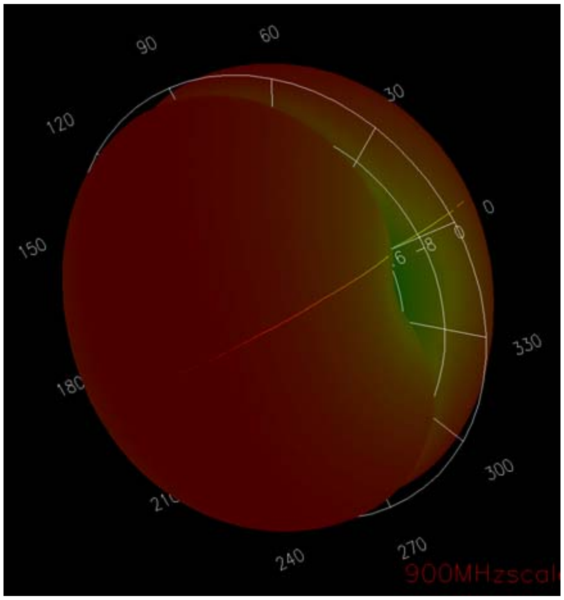


Figure 8: 3D radiation pattern for 900MHz printed dipole antenna.

The successful implementation of the integrated balun is illustrated in the figure below. The arrows in the figure depict the surface current vectors of the antenna at a given instant in time. The arrows represent both phase and magnitude (direction of arrow, size of arrow). As one can see, the current vectors at both feed points show arrows of equal magnitude in 180^o phase shift (arrows are pointed in opposite directions). This result verifies that the integrated balun successfully implements the balun requirement.

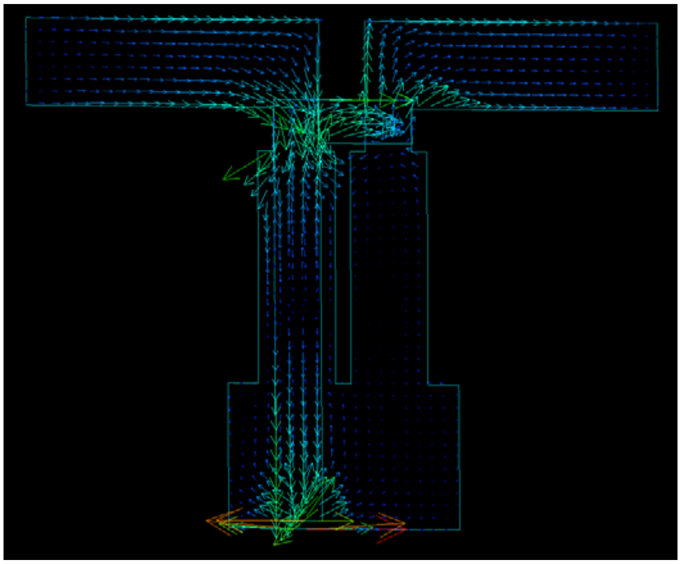


Figure 9: 2D plot of surface current vectors of 900MHz printed dipole antenna.

FUTURE WORK

For future work, the printed dipole design will be exported to be fabricated and tested in the same fashion as the PIFA (radiation pattern, return loss). If the design is verified with measurements to meet the design specifications, a cross dipole configuration based on this antenna will be studied to implement circular polarization. Circular polarization is an additional requirement that will serve to increase the satellite's link margin. Based on these results, the best antenna design (PIFA, printed dipole, cross dipole) will be chosen to be used in the standardized modular subsystem design.

CONCLUSION

A modular subsystem design for the TTC subsystem was described in detail in this paper. The motivation for this standardized design and the methods of implementing such a design, from choosing components to creating an interface for all subsystems to communicate, were discussed. The modular design that was examined will serve as a platform for future CubeSats to use to facilitate more streamlined production and allow for increasingly complex payloads and more sophisticated missions. Two antenna designs were explored and will be further compared to legacy antennas to determine which type will best suit the future of the University of Hawaii's CubeSat platform.

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