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# Design, Verification, and Validation of the Communication System of an Undergraduate CubeSat Mission

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**Abstract**

This paper outlines the design, verification, and validation of the communications system of the Carleton University CubeSat project. The CubeSat project is an opportunity for final-year undergraduate students to partake in the design, verification, and validation of systems on a 3U CubeSat. As an undergraduate capstone project, there is an increased emphasis on implementing as many in-house solutions as possible. The communications system is comprised of ground and spacecraft-based elements, in order to deliver spacecraft telemetry and payload data consisting of locations of detected ongoing forest fires in Canada. In addition, the satellite operator uses the system to transmit telecommands to the spacecraft.

The ground station is designed, built, and tested in house and consists of four subsystems: Structure, Tracking, Radio Frequency (RF), and Digital Processing. The ground station consists of commercial-off-the-shelf, in-house manufactured and additive manufactured parts. Ground station software is a combination of open-source software, in-house written firmware, and GNU Radio flowgraphs. The spacecraft element is categorized in three main subsystems: Antenna, Antenna Feed Network (AFN), and Transceiver. The antenna and antenna feed network are designed in-house using ANSYS High Frequency Structure Simulator (HFSS), and Keysight Advanced Design System (ADS). The communications system uses a single antenna on the spacecraft, operating in half-duplex, transmitting a circularly polarized signal at Ultra High Frequency (UHF) while the ground station supports two redundant UHF antennas. Software on a space-proven transceiver is configured through testing to satisfy link budget requirements.

Verification and validation can vary based on the subsystem of interest. The system link budget is verified through analysis, and subsystems are tested individually to ensure they can deliver the required operational performance. The AFN and antennas undergo Vector Network Analyzer (VNA) testing at the component and subsystem level to quantify gain, losses, and other performance parameters of the subsystem. The transceiver is configured through testing to select the optimal settings such as modulation and coding. Ground station subsystems are validated by communicating with on-orbit satellites that have similar communications architectures. Spacecraft validation involves end-to-end tests in a simulated environment to accurately test the functionality using predicted losses from the link budget and empirical data from subsystem tests.

**Keywords: CubeSat, Satellite Communications, Undergraduate Project**

**Acronyms/Abbreviations**

Advanced Design System (ADS)
Antenna Feed Network (AFN)
Continuous Wave (CW)
Device Under Test (DUT)
Gaussian Minimum Shift Keying (GMSK)
Half Power Beamwidth (HPBW)
High Frequency Structure Simulator (HFSS)
Left-Hand Circular Polarization (LHCP)
Low Noise Amplifier (LNA)
Radio Frequency (RF)
Receive (RX)
Right-Hand Circular Polarization (RHCP)
Software Defined Radio (SDR)

Transmit (TX)
Two Line Elements (TLEs)
Ultra High Frequency (UHF)
Vector Network Analyzer (VNA)

## 1. Introduction

The CuSAT is a CubeSat being designed by undergraduate students at Carleton University in accordance with the Canadian CubeSat Competition. CuSAT's mission is to identify and transmit coordinates of forest fires in Canada's Boreal Forest. The satellite must be capable of imaging the entirety of the Canadian Boreal Forest and provide its daily payload data to a ground station in a single pass.

The CuSAT project is organized as one of twelve Carleton University's capstone engineering projects; the mission has been ongoing since 2015. Engineering students in their final year of studies may partake in the project and gain hands on experience in the design, assembly, and testing of a CubeSat. The students are divided into eight sub-teams: Structures, Payload, Communications, Attitude Determination and Control, Power, Thermal, Command & Data Handling, and Systems. Each of the sub-teams is led by a lead engineer who has either industry experience or a strong academic background relevant to that subsystem. This paper discusses the current state of the Communications subsystem which is responsible for communications between the operator of the spacecraft and the spacecraft itself including payload data, housekeeping data, and spacecraft commands. The onboard transceiver selection and commission, design of the onboard antenna, the ground station development, and the end-to-end link budget analysis are the main tasks of the Communications sub-team in the last academic year.

## 2. Transceiver

The transceiver selected and purchased for the CuSAT mission is GomSpace NanoCom AX100U. A trade-off study was performed before the Covid-19 shutdown in 2019 to select and purchase the NanoCom AX100U. This transceiver nominally uses GMSK modulation and has several framing modes. A challenge faced during testing was the fact that the transceiver can only connect to other I2C devices as the master device, and the On-Board Computer (OBC) also must be connected to the I2C network as the master. I2C dual-master testing was not completed successfully. A Software Defined Radio (SDR) transceiver and GNU Radio software were used to create a simulated ground station for RF physical layer testing.

### *2.1. Design*

In the current design of the CuSAT, the NanoCom AX100U will be connected to the On-Board Computer (OBC) via I2c. For testing purposes, a laptop running an Ubuntu Linux operating system communicated with the NanoCom AX100U via a serial debugger. Minicom software was used to send command and receive housekeeping data to/from NanoCom AX100U through the serial debugger.

Two types of testing were performed on the AX100U, the first being to verify changes to settings in the memory of the transceiver. The second was to verify the transmission and reception capability of the transceiver. Transceiver settings was modified using a serial debugging probe, and a laptop computer running the Ubuntu 20.04 Linux distribution. Transmission and reception testing included a separate laptop connected to either an Airspy Mini or HackRF One Software Defined Radio (SDR) dongle equiped with a monopole antenna in addition to the components required for the first test.

### *2.2. Verification*

The test setup for validation of transceiver transmission was placed in a well-insulated room within a large building to reduce the amount of RF interference to the public generated by the testing. The command to transmit a Continuous Wave (CW) at 436.5 MHz was given to the NanoCom AX100U, with the AirSpy Mini tuned to listen at the same frequency This test successfully resulted in the SDR software showing a spike at 436.5 MHz. Next, a bandwidth test was performed. Setting the NanoCom AX100U to transmit a series of random bytes at a baud rate of 9,600 bps using Gaussian Minimum Shift Keying (GMSK) modulation resulted in the reception of a 15,000 Hz wide signal. In addition to the bandwidth, a constellation plot of the received signal was created to verify that GMSK modulation was being used.

Reception testing for the transceiver was performed with a similar test setupto the transmission testing. The NanoCom AX100U was set to output the RF power received at the operating frequency of 436.5 MHz, and a HackRF SDR transmitted 15 mW CW signal at the same frequency. While the HackRF was transmitting, the NanoCom AX100U detected a 20 dB increase in the received RF power.

### *2.3. Validation*

Validation of the transceiver will be completed by sending a test data packet from the on-board computer through the transceiver to a simulated ground station. The test data packet will be decoded on the ground station side to ensure data integrity, and then send back to the onboard computer. Once received by the onboard computer, the packet will again be analysed for error detection. This process will be completed several times to validate the robustness of the communication setup under different link budget scenarios.

## 3. Antenna

The CuSAT antenna is designed to have a near-omnidirectional gain pattern that transmits a left hand circularly polarized signal from the nadir face of the spacecraft to allow for communication with the ground station. Omnidirectional performance is desired so that direct pointing to the ground station is not required. When the spacecraft is in nadir-pointing mode and within line of sight of the ground station, the spacecraft shall be capable of transmitting telemetry and payload data or receiving commands from the ground. Furthermore, in the event of a loss of attitude control, a near-omnidirectional antenna pattern maximizes attitudes wherein the spacecraft can continue to receive transmissions from the ground.

### *3.1. Design*

The current antenna design as modelled in Fig. 1 is based on the GomSpace NanoCom ANT430 Antenna [1]. The antenna design is comprised of four 163 mm length deployable monopole elements that make a 30-degree angle with the nadir face of CuSAT. Monopoles are located near each corner of the AFN and are connected to the transceiver through the AFN.

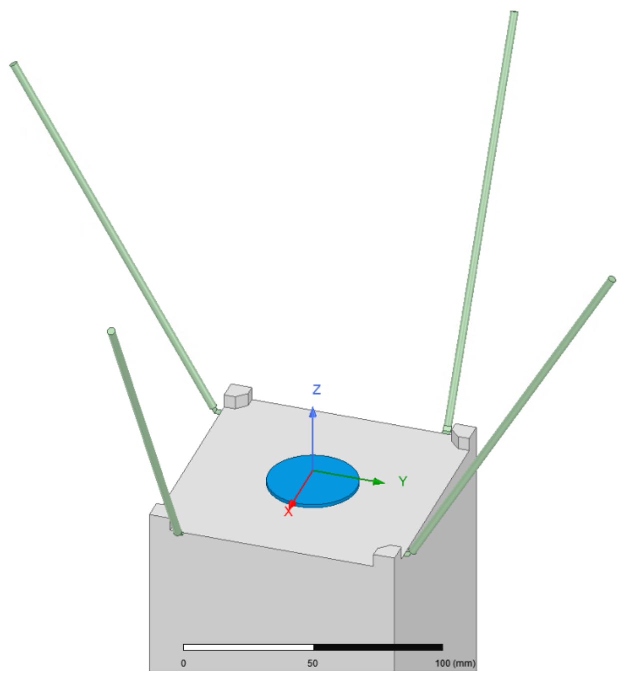


Fig. 1:Antenna Configuration in HFSS

### *3.2. Verification*

Preliminary verification tests of the antenna are done using EZNEC+ v.6.0 (EZNEC) and Ansys High Frequency Structure Simulator (HFSS) simulation software. Simulations show a maximum predicted LHCP gain of 0.9 dBi with a 3dB beamwidth of 193.6 degrees. Antenna verification testing is suitable for both the CuSAT antenna as well as ground station antennas. RF testing of antennas has included testing antennas first in the lab and then outdoors. Initial lab tests use a VNA to measure impedance and VSWR. It should be noted that indoor testing is not as accurate as outdoor testing, however the setup process is simpler, and testing can be done independent of outdoor weather conditions. Outdoor testing is similar to indoor testing with the exception that the antenna is attached to the ground station to resemble real-world performance as much as possible. Furthermore, in outdoor testing it is significantly easier to distance the antenna from any obstacles and therefore obtain more accurate results.

For improved antenna characterization, an outdoor testing of antenna gain pattern is proposed. First the antenna directivity (i.e., maximum gain) can be tested using a VNA and a modified test configuration. The test will require two dipole antennas resonant at the same frequency as the antenna undergoing testing, henceforth referred to as the device under test (DUT). The two dipoles should be set up on tripods at least 1.5 m above the ground to mitigate ground plane effects and placed in each other's far field. Then the antennas would be connected to the two ports of the VNA, and the VNA should be calibrated and configured to measure S21 parameter. The receive dipole should then be replaced by the DUT, where the DUT faces the transmitting dipole with the DUT elements parallel to the dipole elements. Taking the same measurements and comparing the results can provide the difference in gain. Since the gain of a dipole antenna is known (2.15 dBi), the gain of the DUT can be determined.

To determine the antenna pattern, the same process as the maximum gain determination can be used, however the process is repeated with several orientations of the DUT. In each test, the DUT is rotated more and more from the original orientation until sufficient points to plot the pattern are obtained. The axis of rotation is shown in Fig. 2. Once the antenna has been rotated ±180 degrees in 10-degree steps from the original orientation, the antenna should be returned to the initial orientation. Then, the dipole and DUT should be rotated 90 degrees about the axis of the boom and the test process repeated. This will provide a three-dimensional measurement for the gain pattern that can be compared to the simulated patterns from HFSS or EZNEC.

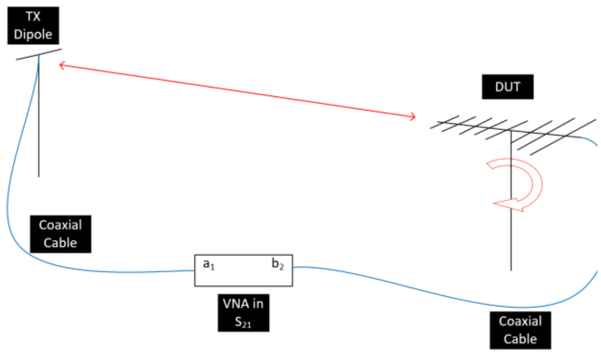


Fig. 2: Planned testing configuration for DUT

*3.3. Validation*

Validation tests of the antenna will take place when the antenna is integrated into the entire communications subsystem to perform end-to-end testing. These tests will require the completion of the AFN.

## 4. Antenna Feed Network

The purpose of the Antenna Feed Network (AFN) for the CuSAT is to provide a phasing interface between the transceiver and the circularly polarized antenna array. The AFN achieves this by using three hybrid-couplers and an additional quarter-wavelength of transmission line. Additionally, the AFN matches the 50 Ohm impedance of the transceiver to the impedance of the monopole elements using an LC or Pi matching circuit.

*4.1. Design*

Fig. 3 provides a block diagram of the AFN's phasing circuit and its connections. Starting from the right-side of the diagram where the transceiver is located, a linearly polarized signal is sent through a coaxial cable and connected to the AFN through an MCX connector. The signal then passes over the first transmission line which connects to the first hybrid-coupler, a Mini-Circuits QBA-07+. The QBA-07+ was selected due to its relatively low cost and high performance which met the requirements for the CuSAT mission. The signal is then split into two half-power signals, with one signal keeping its initial phase and the other phasing 90°. The 90° phased signal travels an additional quarter-wavelength which adds another 90° phase difference relative to the 0° phased signal. Both signals pass through a hybrid-coupler and then all the resulting split signals travel on equal length transmission lines to the matching circuit which will match the antenna and AFN impedance to minimize losses. Each of the signals will then travel to their respective monopole elements through U. FL connectors. The phasing circuit finally results in each of the monopole elements of the antenna array having a 90° phase shift from each other, creating a circularly polarized antenna array.

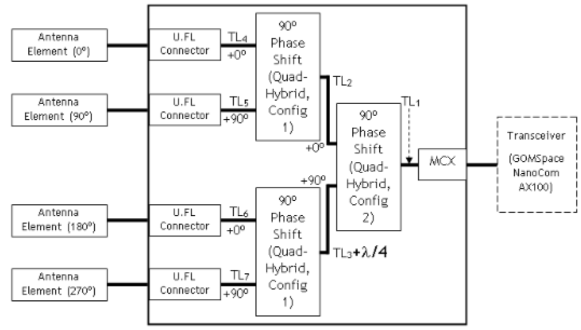


Fig. 3 Phasing circuit design of AFN

The AFN board is designed using FR4 substrate material with a permittivity of 4.5 To minimize the mass of the AFN the substrate thickness was selected to be 0.762 mm, or 30 mils. The AFN microstrip width and thickness are determined as 1.46 mm and 0.01524 mm, respectively. With the substrate and microstrip values the effective permittivity of the design is calculated to be 3.32 F/m which resulted in a quarter-wavelength of 9.1 cm at the operating frequency.

The matching of the phasing circuit (50 Ohms) and monopole elements (52.7 – j6.3 Ohms) is done with a lumped circuit to use of minimal space on the printed circuit board. The lumped circuit designs investigated were the LC circuit and Pi circuit. The LC circuit uses a single capacitor and inductor in series while the Pi circuit uses two capacitors and an inductor. An example of a LC matching circuit is provided by Fig. 4.


Fig. 4 Example of a LC matching circuit [2]

It is found that the addition of a LC circuit would not provide any return loss improvement. Preliminary simulations of an implemented Pi circuit show the possibility of improving the current return loss, but further investigation is required as the resonant frequency band is extremely narrow and could lead to drastically worse performance if implemented improperly (i.e. capacitance and inductance values are not perfectly matched for the operating frequency of the AFN).

The phasing circuit prototype board designed in ADS software is shown in Fig. 5. The components soldered to the board are the MCX connector, hybrid-couplers, 50 Ohm resistors, and SMA female edge-mount connectors. Additionally, U.FL connectors were added to the design to allow for the validation of the performance of the designed antenna elements. It should be noted that the mounting holes and holes for the wiring of other subsystem components are missing from the design of this board.

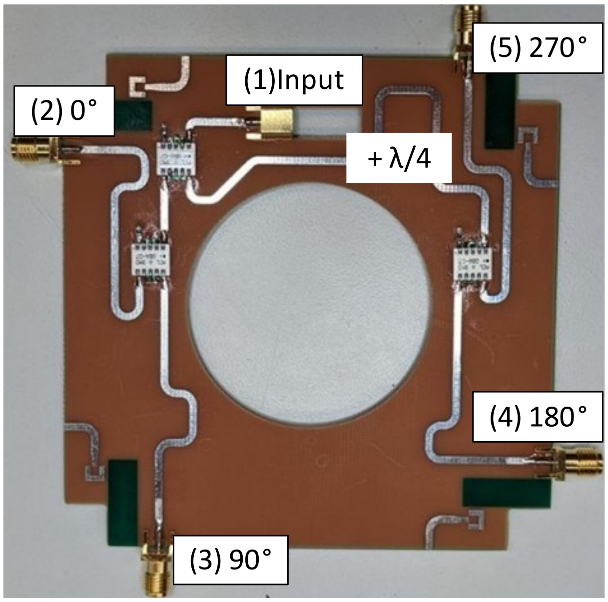

Fig. 5 Assembled AFN Phasing Prototype

For the design of the flight board there are additional considerations and design decisions to be made. For instance, one consideration for the AFN is protection of the RF components and traces against the harsh space environment (e.g., atomic oxygen). Research must be conducted to find the best options such as an RF shield or a protective finish on the AFN.

### *4.2. Verification & Validation*

The performance of the AFN's phasing design was verified using ADS circuit simulation. To create the simulation the blocks used were the microstrip, SnP (representing the hybrid-coupler), and terminals which can be used to measure the performance of the design. For the SnP block, a. s2p file from the manufacturer's website is used to import the recorded testing data and simulate the hybrid-coupler in ADS. The design of the AFN phasing circuit in ADS is provided in Fig. 6.

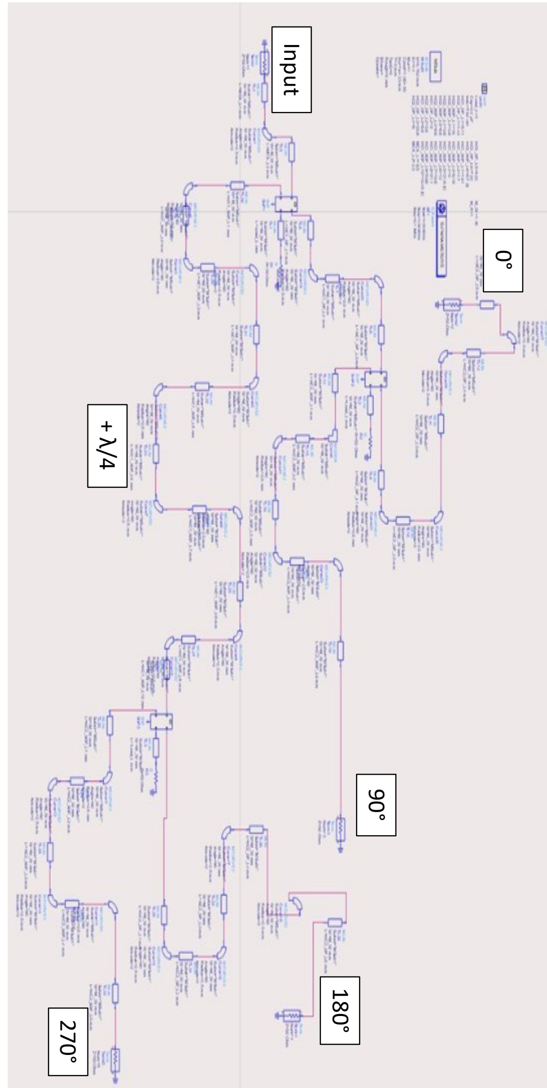

Fig. 6 Preliminary phasing design in ADS

The validation of the AFN phasing circuit was done by manufacturing, assembling, and testing a physical prototype designed in the PCB layout design in ADS.

Each port of the AFN was tested using two-port VNA with respect to the input to the board while other ports were terminated by 50 Ohm loads. Table 1 provides the comparison of the results from the simulation and testing of the AFN phasing prototype.

Table 1. Comparison of verification and validation results

| *Terminal* | *Measured Return Loss (dB)* | *Simulated Return Loss (dB)* | *Measured Phase Difference* | *Simulated Phase Difference* | *Measured Amplitude (dB)* | *Simulated Amplitude (dB)* | *Measured Insertion Loss (dB)* | *Simulated Insertion Loss (dB)* |
|---|---|---|---|---|---|---|---|---|
| 2 | -26.8 | -26.9 | 88.8 | 90.4 | -8.2 | -6.2 | | |
| 3 | -28.5 | -26.8 | 88.8 | 90.0 | -7.0 | -6.8 | | |
| 4 | -27.0 | -35.5 | 91.7 | 90.4 | -7.1 | -6.9 | 1.0 | 0.8 |
| 5 | -27.6 | -23.4 | 90.4 | 89.2 | -6.2 | -7.5 | | |
| 1 (Input) | -27.7 | -20.0 | N/A | N/A | N/A | N/A | | |

The testing of the AFN phasing prototype validated its design as its performance is similar to the circuit simulation. Notably, the measured return loss for the AFN phasing circuit is -27.7 dB, a -7.7 dB improvement over the simulation. Additionally, the measured insertion loss of 1.0 dB is comparable to the simulation's 0.8 dB which did not include the losses from the MCX and SMA connections. The measured insertion loss is then added to the link budget, accounting for the losses of the phasing circuit.

## 5. Ground Station

To communicate with CuSAT in orbit, a satellite ground station is required. The ground station is required to be capable of pointing high-gain antennas at CuSAT during a pass to transmit commands, as well as receive telemetry and payload data. Furthermore, the ground station shall be capable of the required modulation/demodulation and encoding/decoding required to connect CuSAT and ground support equipment. The current design of the ground station is based on previous ground station work conducted to receive LEO weather satellite transmissions [3]. The current configuration of the ground station is shown in Fig. 7.

Fig. 7: Current ground station configured for UHF (TX/RX) and L-Band (RX)

### *5.1. Design*

The ground station is controlled by a single command computer that provides time-dependent azimuth and elevation values generated by software called GPredict using Two Line Elements (TLEs) of a target spacecraft [4]. Hamlib, a collection of middleware connects the rotator controller and sends target azimuth and elevation values to the Arduino Mega on board the ground station. The Arduino converts commands into motor step commands which are sent to motor drivers and re-orient the ground station. The current system is open-loop through there is expandability for motor shaft encoders and magnetometer-gyroscope acceleration boards which may be implemented in the future. On the RF side of the ground station, the command computer is connected to the antennas through software defined radios (SDRs) which pass signals to and from (de)modulation and (de)coding software. A block diagram of the ground station configuration can be seen in Fig. 8.

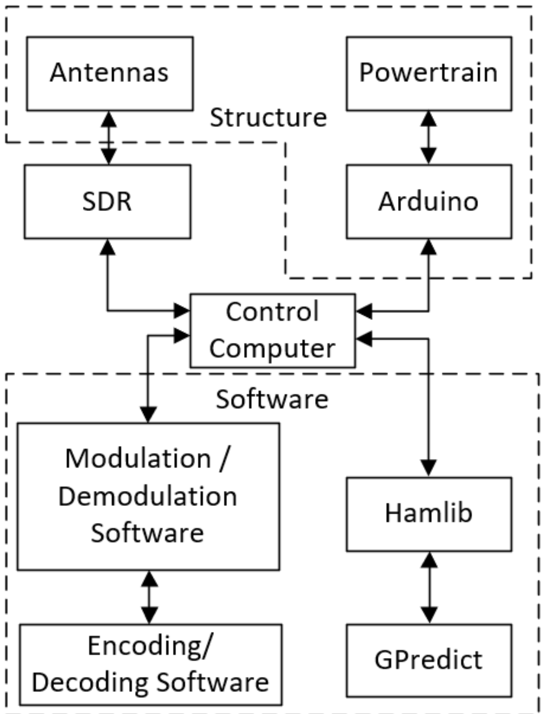


Fig. 8: Block diagram of ground station configuration

The structure of the ground station comprises the physical components that serve to support the RF and pointing subsystems [3]. Many structural components were manufactured with FDM 3D printing to support rapid prototyping and custom sized components [3]. The current structural design allows for the ground station to be reconfigured modularly [3]. The total mass of the ground station is approximately 9 kilograms excluding antennas [3]. A render of the main ground station rotator structure can be seen in Fig. 9.

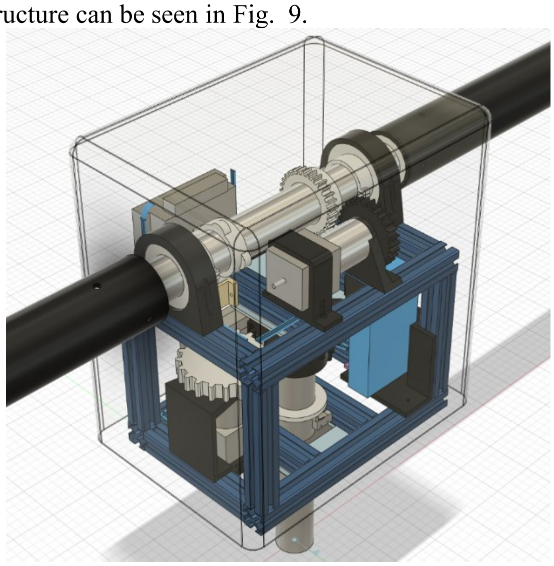

Fig. 9: Structure of ground station rotator mechanism

The main modifications of the ground station include adding two UHF Yagi antennas, adding extra RF components, and modifying tracking software. Among the two new Yagi antennas, one is a commercially available solution and the other is designed and built in-house.

*5.1.1. In-House Antenna Design*

After several preliminary design iterations for the in-house antenna using EZNEC+ v.6.0 (EZNEC), AutoEZ, and HFSS simulation tools, an 8-element, linearly polarized Yagi antenna is selected for detail design, manufacturing, and testing. Simulation results show that the minimum SWR of 1.12 occurs at 436.5 MHz. Furthermore, the maximum gain is 12 dBi, with a half power beamwidth (HPBW) of 49 degrees. The prototype antenna can be seen in Fig. 10.

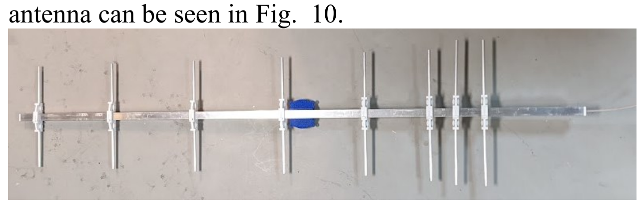

Fig. 10: Prototype in-house antenna design

*5.1.2. Commercial Antenna Selection*

To compare the in-house antenna design, a commercially available option, the 436CP16 from M2 Antenna Systems Inc. is selected. The 436CP16 has a minimum measured SWR of 1.04 at 436.5 MHz with a maximum gain of 13.3 dBi [5].

*5.1.3. RF Component Selection*

Non-antenna RF ground station components presently include a low noise amplifier (LNA), coaxial cable, and SDRs. The impedance of the RF subsystem is 50 Ohms, therefore, antennas must either have an impedance of 50 Ohms or appropriate impedance matching to minimize reflections. SDRs tested include the Nooelec NESDR SMArt XTR, Nooelec NESDR SMArTee v2, Airspy Mini, and the HackRF One. Note that of the SDRs tested, only the HackRF One is capable of transmission [6]. For UHF (i.e., the configuration required for CuSAT), Airspy Mini and HackRF One are selected as the ground station receiver and transmitter, respectively.

To close the uplink communication, the HackRF One transmitter requires an amplifier [7]. The selected amplifier is P8X, which is suitable for 420-450 MHz [8]. The P8X can provide up to 10 W of output power from 20 mW input, even though only 1 W of transmit power is currently required to close the uplink [9]. The P8X amplifier can be seen in Fig. 11.


Fig. 11: P8X Power amplifier

Low noise amplifiers (LNAs) for reception have also been tested. The Nooelec SAWbird+ NOAA is used for VHF and Nooelec SAWbird+ GOES for L-band. For general use, the Nooelec LaNA low noise amplifier is selected as the lack of bandpass filter allows for compatibility with the 430 – 440 MHz band [10]. When installed in the ground station, a suitable bandpass filter must be chosen. The LNA is expected to provide 24 dBi of gain at the CuSAT frequency and can be powered either by bias tee or external USB power [10]. The Nooelec LaNA has typical supply current and noise temperature of 85 mA and 67 K, respectively [11].

*5.1.4. Ground Station Software*

The control computer uses Gpredict and NeedleGUI, which are both open-source software for use in the ground station [3]. NeedleGUI is a new software written by Carleton University students to replace Hamlib and provide additional tracking capabilities. Gpredict connects via TCP/IP to NeedleGUI. NeedleGUI is written in Python and uses the serial library to communicate with the ground station. The front-end of NeedleGUI has been built in Qt. Within the program, not only can users connect the ground station to Gpredict, but one can also manually control the ground station. This is commonly employed when searching for geostationary satellites. As well, NeedleGUI has a spiral search component which allows users to move the ground station in a spiral motion to search for satellites. From the Arduino Nano, a connection is made to the ground station's Arduino Mega via Serial Peripheral Interface (SPI) communication. This is accomplished through two transceiver modules, one connected to each board.

*5.2. Verification and Validation*

Ground station verification tests involve the integration and testing of all ground station subsystems. These tests confirm that the components and subsystems are functioning properly and meets the requirement. For example, the tracking software, hardware, and part of structure subsystem were tested by running a mock tracking and replacing antenna with laser pointer to verify pointing and temporal accuracies. Major remaining verification parameters include the power level of transmitting signal, and bit-error-rate of software-based (de)modulation and (de)coding. Ground station validation will occur once all ground station verification tests are completed to a satisfactory degree.

The validation tests are performed on the integrated ground station, and they can be broadly categorized into two main categories: reception, and transmission. Ground station reception tests can further be broken down into two further categories: hardware validation, and an integrated reception validation. The hardware verification has been completed for the current design. This test is accomplished by tracking NOAA 15, 18, or 19 spacecraft and receiving signals transmitted by the on-board VHF and/or L-band antennas as described in a Winter 2022 directed study on ground station RF equipment [14]. The next step will be to perform an integrated reception validation by adding the demodulation/decoding software and tracking spacecraft in the same frequency band and modulation theme as CuSAT. The reception system should demodulate and decode the received signals from the spacecraft.

For transmission system verification, closing a communication link between the ground station and an amateur radio spacecraft (such as AMSAT Fox-1) equipped with a UHF/VHF or UHF/UHF transponder. The spacecraft will automatically relay back the data it receives using the on-board transponder. The successful reception and decoding of the relayed signal would indicate that the ground station can successfully code, modulate and transmit the intended signal. Note the spacecraft will have different uplink and downlink frequency bands. Therefore, another antenna, capable of communication at the correct frequency may be required. The final proposed validation test is to collaborate with another university with a spacecraft on-orbit operating at the same frequency band. For the 2021-2022 year, the communications team has communicated with Concordia University who plans to launch their 3U CubeSat operating at a near-CuSAT frequency in December of 2022. Note that licencing and legal regulations would likely prohibit transmission, although reception may remain a possibility.

## 6. Conclusion

Table 2 provides a summarization of the link budget analysis conducted on the designed communications subsystem. More in depth information on the calculation behind the values of the link budget can be obtained by contacting the authors. The calculated margins in Table 2 verifies the link budget requirement of higher than 3 dB in the critical design phase.

Table 2 Link budget summary

| ***Parameter*** | ***Downlink*** | ***Uplink*** |
|---|---|---|
| Transmit Power | 1.0 W | 1.0 W |
| EIRP | -0.4 dBW | 9.4 dBW |
| Spacecraft Antenna Pointing Loss | 2.1 dB | 2.1 dB |
| Path Loss | 152.6 dB | 152.6 dB |
| Atmospheric Loss | 0.45 dB | 0.45 dB |
| Ionospheric Loss | 0.4 dB | 0.4 dB |
| Rain Loss | 0.15 dB | 0.15 dB |
| Isotropic Signal Level | -156.1 dBW | -147.4 dBW |
| Figure of Merit (G/T) | -15.5 dB/K | -24.6 dB/K |
| Signal-to Noise Power Density (S/N0) | 56.7 dBHz | 54.5 dBHz |
| System Desired Data Rate | 9600 bps | 1200 bps |
| Telemetry System Eb/N0 | 15.1 dB | 22.0 dB |
| Eb/N0 Threshold | 9.6 dB | 11.3 dB |
| System Link Margin | 5.5 dB | 10.7 dB |

During the project, students gained experience with design, developing, verification, and validation of the various spacecraft communications system components as well as with the ground station subsystems. Their experience during the project has continued to advance the design as well as prepare the project for the next year's group of students.

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