Wideband Circular-lens Utilizing Beamforming Electronics

High Level Design

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Table of Contents

1 Introduction

The student team IrishSat officially submitted a proposal for NASA's 2023 CubeSat Launch Initiative Opportunity. CLOVER-Sat, or the Circular Lenses Operating as a Variable Extendable Receiver Satellite mission, is a 2U CubeSat mission carrying a technology demonstration payload in collaboration with Dr. Jonathan Chisum. CLOVER-Sat aims to operate in low Earth orbit (LEO) with an inclination such that it regularly passes over the continental United States. The payload will be a low-power, low-cost millimeter wave phased-array fed gradient index lens antenna receiver operating in the K-band for Earth downlink communications and Earth science missions.

The technology relevant to this project pertains to Dr. Chisum's work, focusing on the novel development of millimeter wave phased-array fed lens (PAFL) antennas as a low power, low-cost and ultra-wideband solution for high gain electronically scanning capabilities in the MMW band. The PAFL antenna is a low power and low cost alternative to bulky mechanically scanning reflectors and costly and power hungry phased array antennas (PAA). The PAFL payload serves as a proof of concept for technology which aligns with NASA's strategic objectives in enabling future Earth and planetary science missions through potential use of GRIN lens antennas for scientific instrumentation, providing a low-cost, low-power solution that can make LEO satellite communications services more accessible, and enhancing the technology for NASA's future cislunar missions.

2 Problem Statement and Proposed Solution

Millimeter wave communication is of particular interest for achieving high-speed wireless data transmission in 5G base stations, satellite internet service in LEO, and data-intensive science missions such as Earth observation imaging. A high-performance communications solution requires an antenna that is wideband, operates in millimeter-wave bands, and requires beam-scanning capabilities (due to the need for a high-gain link).

Currently, traditional solutions for high-quality beam scanning utilize phased array antennas (PAA) which offer low scan loss over a wide field of view (FoV) with multi-beam functionality but suffer from limited bandwidth, vast amounts of power consumption, high costs, and cooling difficulties, especially on small platforms. Other current solutions utilize lens antennas which are naturally wideband and low-power but exhibit poor relative performance: they have fixed beam angles that create nulls in radiation patterns, making it difficult to examine a wide FoV as desired. The nature of the lens also requires a particular focal length to diameter ratio, which is difficult to implement on a small satellite such as a CubeSat.

This project aims to create a phased array fed lens (PAFL) that combines the beamforming advantage of phased arrays while minimizing power consumption, cost, and heat production of lens antennas. Additionally, a low-risk deployment mechanism will be used to collapse the focal depth and make lenses suitable for small space-based platforms. Dr. Jonathan Chisum's research group has developed a Particle Swarm Optimization algorithm which will be used to control the PAFLs. It determines the complex weighting (magnitude and phase angle) to feed each antenna array element, allowing for electronically controlled beamforming to steer the beam with maximized gain and minimized noise in the sidelobes.

A successful technology demonstration will provide a truly wideband, high-performance antenna at cost and power levels suitable for small sat missions. This represents a key enabling technology for future wideband, high-gain space-to-ground comm-links as well as a highly capable beam scanning aperture for wideband and multiband science missions.

3 System Requirements

3.1 - Computational Requirements

To successfully implement this system, Dr. Chisum's PSO algorithm will be implemented, feeding each antenna array element the calculated magnitude and phase that will yield optimal beams. The system must also be able to control the antenna array in multiple configurations so that the efficacy of the PSO algorithm can be demonstrated. For example, the system should be able to utilize some elements of the antenna array (one or multiple) and demonstrate its beamforming and detection capabilities when operating in this suboptimal state. Additionally, the system should be able to compensate for suboptimal operating conditions with regard to the focal length and diameter ratio, still producing beams with maximized gain even if the focal length to diameter ratio is non ideal.

3.2 - Operational Requirements

Since one of the main motivators for using PAFLs is the reduced power consumption, the system should monitor power consumption and feed this data back to the main flight computer.

3.3 - CLOVER-Sat Requirements

The W-CUBE system should follow requirements as set by the CLOVER-Sat team to ensure smooth integration into the CLOVER-Sat. This includes dimensional requirements, weight requirements, and electrical requirements for low earth orbit.

Power will be supplied by the CLOVER-Sat team, as they are responsible for creating a solar panel system that will provide 9V, 5V, and 3.3V.

3.4 - Demonstration Requirements

The PAFL controller system should be able to scan across a linear map and successfully receive transmission from one or more RF test sources. The system must display evidence of said reception, either using an isolated display or via communication with a computer. Additionally, power consumption data should be shown over the display.

4 System Block Diagram

4.1 - Overall System

Figure 1. W-CUBE System, Focusing on Antenna Control

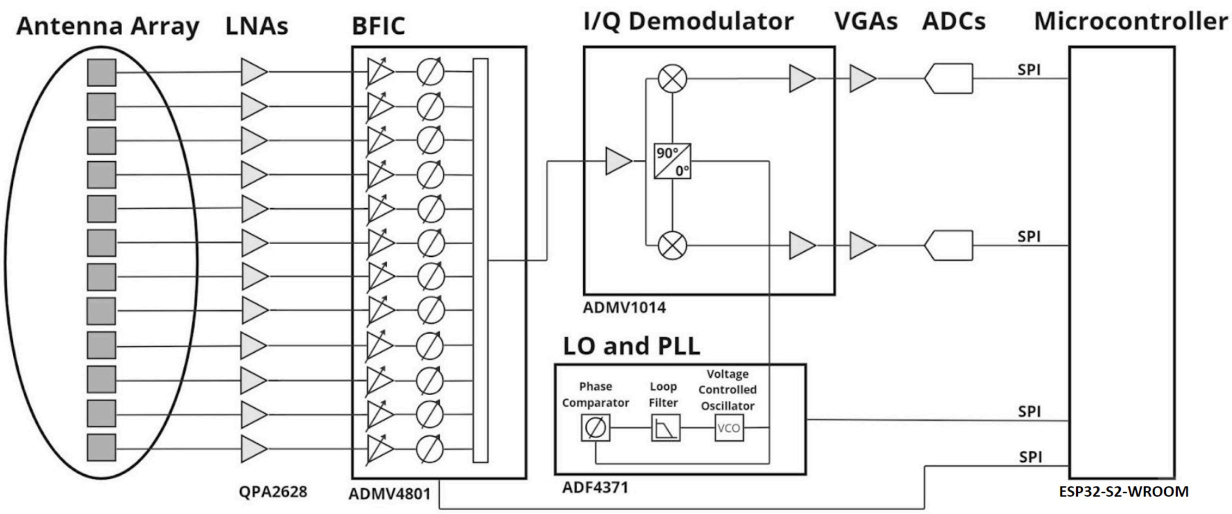
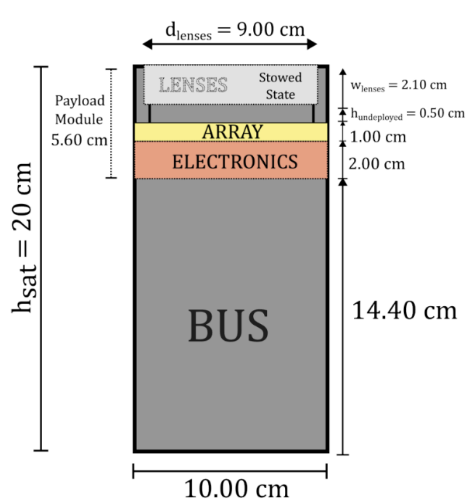


Figure 2. CLOVER-Sat System, with W-CUBE Components Integrated



4.2 - Power Subsystem

The power subsystem will regulate voltage and monitor power consumption of the W-CUBE. Since the CLOVER-Sat team has not yet determined what voltage(s) they are able to provide, the W-CUBE board must also be able to step up or step voltage down depending on the needs of the various hardware elements that are used. The power subsystem will also monitor power consumption of the overall system and send this data to the flight computer over either I2C or SPI.

4.3 - Antenna Control Subsystem

The Antenna Control subsystem is responsible for computing beamforming coefficients using the PSO algorithm and steering the antenna array via SPI or I2C communication with the beamformer. This subsystem will execute Dr. Chisum's PSO algorithm for the current system conditions, including which antennas will be turned on, the angle of the main lobe that the antenna array is steered toward, the focal length and diameter ratio of the PAFL, etc. This subsystem will also interpret and receive the incoming signals, so the software must be able to determine at what steering angle any signals were received at.

The hardware in this subsystem includes the MCU, antenna array, low noise antennas, beamformer integrated circuits, I/Q demodulator, phase locked loop, VGAs, and analog to digital converters. On the software side, Dr. Chisum's particle swarm algorithm is already written, but it must be edited for this implementation. Furthermore, the software must be developed to interpret the received signals from the test rig, determining the direction from which a transmission was received.

4.4 - Motor Control/Deployment Subsystem

The Motor Control/Deployment subsystem will be responsible for powering and controlling the servo motors connected to the lens for deployment onboard CLOVER-Sat. The CLOVER-Sat team will fully determine the mechanical deployment system and supply power lines. Motor control will then be native to the W-CUBE and will require 2 steps. First, this subsystem will be responsible for sending deployment signals to actuate the servo motors for the target rotation. Second, this subsystem will need to transmit the data of how far each motor deployed back to the onboard microcontroller, using either I2C or SPI, to be used for PSO solving.

4.5 - Display Interface Subsystem

The Display Interface software subsystem is intended to illustrate the results for beam scanning and power consumption. Said interface will not be a component of CLOVER-Sat when it is launched; however, it will serve a similar purpose to the ground station, for demonstration and development purposes. The display interface will likely be a computer that is connected to the W-CUBE board during testing and demonstration. This subsystem will configure science and power data received over SPI (or I2C) communication to a format that is intelligible for users. Then, it will display said data both graphically and numerically to confirm successful implementation of the technical requirements. Additionally, it could be extended to display other key metrics and information, such as computational results and inputs from the PSO algorithm or antenna gain values, that the team deems useful for demonstration purposes.

4.6 - Test Rig

On demo day, W-CUBE will need a testing setup to demonstrate its beam scanning capabilities, as described in Section 3.4 - Demonstration Requirements. Thus, it is necessary to have a testing rig with sources of millimeter wave frequency signals radiating such that the

W-CUBE can beam steer and detect the test sources. The test rig will consist of a handful of test sources (aka antennas) transmitting, arranged linearly, similar to the linear arrangement of the antennas on the W-CUBE. The transmitting antennas will turn on one by one in a somewhat random fashion, and the W-CUBE should be able to scan and determine which antenna is transmitting.

4.7 - Future Enhancement Requirements

The final, submitted version of this senior design project will likely not be the exact version of what is implemented by IrishSAT on the CLOVER-Sat mission, but it will effectively serve as the payload on the mission in 2026. Future changes will likely be necessary for the final implementation onto the actual CLOVER-Sat mission.

5 High Level Design Decisions

5.1 - Power Subsystem

The power subsystem is even more vital to this project's success than standard power subsystems on other projects. While most systems have their power coming from a known source, the WCUBE system will receive power from the greater CLOVERSat. This means that it must be designed with robust regulators ensuring the ability to step up or down voltages depending on the component needs and the input power conditions. The power system will also need to be low noise in order to not disrupt any antenna operation, creating an extra layer of design complexity. The exact specifications of the voltage amplifiers cannot be currently chosen as the IrishSat team has not disclosed the exact details of the provided power source.

5.2 - Antenna Control Subsystem

The antenna control system is headlined by the ESP32-S2 processor. The team has chosen this particular controller because the S series of ESP32 line provides increased computing power, something that will be very important in deploying the particle swarm algorithm. The microcontroller will perform this program, and in receiving outputs send information to the single polarization beamformer to make the necessary adjustments that will ensure proper antenna alignment. The other components that make up this subsystem are the antennas and their supporting parts, mainly the beamformer, wideband synthesizer, low noise amplifier, and wideband microwave downconverter.

5.3 - Motor Control/Deployment Subsystem

The motor, provided by the IrishSat team, will be driven by the Bipolar Motor Driver. This component has been chosen in anticipation of a stepper motor being utilized for the antenna deployment, a decision made due to the lens's low weight and ease of deployment. The motor control and deployment system will be communicated over UART from the ESP32. This subsystem will act as the deployment mechanism, actuating the antenna to the necessary position for proper receiving behavior given the operating conditions. Furthermore, this subsystem must communicate how far the motor was deployed so that the PSO algorithm can use that information to calculate what phases and magnitudes to feed the antennas.

5.4 - Test Rig

The test rig is made up of multiple transmitters arranged linearly. This setup allows for different transmission sources to be turned on intermittently, providing targets for the scanning antenna array. The test rig will have its signals configured to emulate those coming from Earth's surface, so when the project is tested it will be in a simulated environment close to the actual mission. The exact specifications of the transmitters will depend on the antennas provided by Dr. Chisum, a component that the group is still waiting to get more information on.

6 Open Questions

- What is the exact allotted space that this team is given on the CLOVERSat?
- What are the specifications of the provided power source? Will this be enough for all of the project's components to run?
- What are the details of the provided antennas, and how will they be implemented on the team designed PCB?
- Can the particle swarm algorithm be optimized enough to run on the ESP32-S2?
- What are the exact operating conditions of the antenna lens?

7 Major Component Costs

Due to the need for space-grade components, the cost for major components is inflated in comparison to parts typically used in senior design projects. The team is readily aware of the $500 budget allotted to them, however they have received confirmation from Dr. Chisum that he will cover the difference between the budget and the component costs. An outline of the parts is below in Table 1.

Table 1. Necessary Component Descriptions

Part Number	Part Description	Manufacturer	Cost
QPA2628	22 - 31.5 GHz GaAs Low Noise Amplifier	Qorvo	$101.87
ADMV4801	24 GHz to 29.5 GHz Transmitter/Receiver, Single Polarization Beamformer	Analog Devices	Quote Needed
ADF4371	Microwave Wideband Synthesizer with Integrated VCO	Analog Devices	$308.84
ADMV1014	24 GHz to 44 GHz, Wideband, Microwave Downconverter	Analog Devices	$167.93
To Be Determined	Patch Antenna	N/A	Provided by Chisum
ESP32-S2-WROOM-N4	WiFi 802.11b/g/n Transceiver Module 2.4GHz	Espressif	$2.05
TMC2300-LA	Bipolar Motor Driver Power MOSFET Step/Direction	Analog Devices	$3.60

7 Conclusions

By highlighting the low-power, low-cost, wideband, electronic beam scanning millimeter wave capabilities of PAFL, CLOVER-Sat's research payload serves as a proof-of-concept for technology with applications in planetary science, radio astronomy, and satellite communications. This project enables such research by developing and providing the necessary electronics to power and control the beamforming elements of the novel PAFL. The onboard PAFL antennas, along with the constructed controller, will optimize millimeter wave communication technologies through increased antenna spacing and beam weighting so as to decrease power consumption, improve cooling, and decrease overall cost.

References

W. Wang, N. Estes, N. C. Garcia, M. Roddy, A. K. Bolstad and J. D. Chisum, "Beamforming Phased-Array-Fed Lenses With >0.5λ-Spaced Elements," in *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 3, pp. 2208-2223, March 2023, doi: 10.1109/TAP.2023.3240085.