# Announcement of Partnership Opportunity
# CubeSat Launch Initiative

# CLOVER-Sat

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# CLOVER-Sat

## Circular Lenses Operating as a Variable Extendable Receiver Satellite Mission

| CubeSat Mission Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CubeSat Mission Name | Mass | Cube Size | | Desired Orbit | Acceptable Orbit Range | Is an ISS deployment acceptable ( 400 km @ 51.6 degree incl.)? (Y/N) | Ready for Dispenser Integration Date | Desired Mission Life |
| CLOVER-Sat | 3.5kg | 2U | Altitude | 500 km | 300-800 km | Yes | June 1, 2026 | 6 months |
| | | | Inclination | 45 degrees | 20 - 70 degrees | | | |

| CubeSat Project Details | | | | | |
|---|---|---|---|---|---|
| Focus Area(s) | NASA Funding | | Sponsoring Organization(s) | Collaborating Organization(s) | |
| | Y/N? | Organization | | List | International (Y/N?) |
| ☑ Education<br>☐ Workforce Dev.<br>☐ Science<br>☑ Technology | No | N/A | Boeing, General Electric Foundation | Cheshir Industries, Fortify | No |

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# Contents

# Abstract

CLOVER-Sat, the Circular Lenses Operating as a Variable Extendable Receiver satellite mission, is a 2U CubeSat undertaking research on millimeter wave gradient-index (GRIN) lens antennas for wideband small-satellite ground links and wideband/multiband Earth observation missions in the 8-50 GHz band. The mission payload is in collaboration with Professor of Electrical Engineering Dr. Jonathan Chisum for its mission payload. CLOVER-Sat shall be undertaken by the University of Notre Dame's undergraduate satellite design team IrishSat as, primarily, an educational project for undergraduates and, secondarily, a technology demonstration mission of the GRIN lens antenna as a receiver taking noise power measurements of the Earth at the K-band water absorption band.

As an educational project, CLOVER-Sat shall educate students in satellite mission design, development, testing, verification, and operations, thus fulfilling NASA's educational goals detailed in Strategic Objective 4.3 of the NASA Strategic Plan and the NASA Strategy for STEM Engagement. CLOVER-Sat is building Notre Dame's next generation of space enterprise engineers by engaging students through every step of the engineering process. To facilitate meaningful student experience and leadership, the satellite bus subsystems shall be designed and developed by undergraduates, full stack from component to system level. In addition, CLOVER-Sat mission operations shall be supported by IrishSat's ground station team, and the testing infrastructure and procedures shall be supported by IrishSat's instrumentation lab team.

The technology demonstration showcases the research of Dr. Chisum, 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 (1.1, 1.2), providing a low-cost, low-power solution that can make low Earth orbit satellite communications services more accessible (2.4), and enhancing the technology for NASA's future cislunar missions (3.1).

The mission's merit and feasibility were examined by the IrishSat team through an extensive internal review process, with the findings presented to external merit and feasibility review panels. Both merit panels and feasibility panels were made up of a diverse group of experienced space industry contacts. Panel feedback affirmed the educational and technological merit of the mission as well as its high probability of success in light of IrishSat's years of experience and successes recognized through prototype CubeSat development, a functional permanent ground station, instrumentation lab infrastructure, and a NASA FLOATing DRAGON finalist high-altitude balloon node guidance system.

# 1 Mission

## 1.1 Mission Introduction

The student team IrishSat proposes the CLOVER-Sat mission as a collaborator for NASA's 2023 CubeSat Launch Initiative (CSLI) opportunity. IrishSat is the University of Notre Dame's first and only student run satellite and space systems engineering team. Founded during the 2020-2021 academic year, the team has developed a ground station for satellite communications and an instrumentation lab for testing. The team has experience in high-altitude balloon missions and the development of prototype FlatSats in preparation for a future CubeSat mission.

CLOVER-Sat, or the **C**ircular **L**enses **O**perating as a **V**ariable **E**xtendable **R**eceiver **Sat**ellite mission, is a 2U CubeSat mission carrying a technology demonstration payload in collaboration with Dr. Jonathan Chisum in the Department of Electrical Engineering at the University of Notre Dame. CLOVER-Sat aims to operate in low Earth orbit (LEO) with an inclination such that it regularly passes over the continental United States, as shown in Appendix A, Figure 1. **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.** This payload is ensured to meet the Launch Services Program requirements.

## 1.2 Objectives

As an undergraduate-led organization, the primary objective of CLOVER-Sat is educational. CLOVER-Sat will provide undergraduate students the opportunity to participate in a CubeSat mission from design through development and testing to operations in LEO. In this educational approach, CLOVER-Sat aligns itself with the NASA Strategy for STEM Engagement as well as Strategic Objective 4.3 of the NASA Strategic Plan 2022: "*Build the next generation of explorers*" [1]. By engaging a diverse, interdisciplinary array of undergraduate students, CLOVER-Sat will prepare the next generation of engineers to join the space enterprise. Further detail on how CLOVER-Sat fulfills these goals are covered in Section 3 covering the merit review.

The secondary objective of CLOVER-Sat is to perform a technological demonstration of the lens antenna receiver research payload. Dr. Chisum's research on novel millimeter wave GRIN lens antennas boasts a low-cost, low-power, wide-band solution in comparison to existing conventional millimeter wave technology used in satellite communications. CLOVER-Sat will seek to demonstrate these capabilities in a small space-based platform. In order to display these capabilities, the lens antenna payload will be implemented as a radiometer. It will measure noise power on the Earth, observing changes in received power as it electronically scans from land through the ocean to the edge of the atmosphere. A diagram demonstrating this mission concept in more detail can be seen in Appendix B, Figure 2.

**By highlighting its low-power, low-cost, wideband, electronic beamscanning millimeter wave capabilities, CLOVER-Sat's research payload serves as a proof-of-concept for technology with applications in planetary science, radio astronomy, and satellite communications.** This aligns with objectives listed in the NASA Strategic Plan 2022, namely: Strategic Objective 1.1 - "Understand the Earth system and its climate", Strategic Objective 1.2 - "Understand the Sun, solar system, and universe", Strategic Objective 2.4 - "Enhance space access and services", and Strategic Objective 3.1 - "Innovate and advance transformational space technologies". As with the primary focus area, the way in which the technological demonstration aligns itself with these stated NASA objectives is detailed further in Section 3.

# 2 Project Plan

CLOVER-Sat's proposed timeline seeks a launch opportunity in the Summer of 2026. This section will thus detail IrishSat's organizational structure and how it will facilitate the design, development, and execution of CLOVER-Sat, as well as a proposed schedule and budget.

## 2.1 Organizational Structure

With previous experience in establishing space systems infrastructure and carrying out educational FlatSat and high-altitude balloon projects, IrishSat has established a comprehensive organizational structure. This structure will be utilized to carry out the CLOVER-Sat mission. IrishSat is a project-based organization split up into 4 main project teams: CubeSat, Ground Station, Instrumentation Lab, and High-Altitude Balloon (HAB). Each project team is led by a Project Manager who carries out managerial tasks and a Chief Engineer who guides technical problem-solving. IrishSat members have the ability to decide which project(s) they join. Beyond the project divisions, the IrishSat organization also has five technical leads specializing in the following areas: Communications, Computing, Power, STOC (Structures, Thermal, Orientations, and Control), and Machining. Each technical lead acts as the point of expertise for their area and heads subsystem teams within project teams. A diagram visualizing overall organizational structure as well as reporting hierarchy can be seen in Appendix C, Figure 5.

### 2.1.1 Project Teams

The CubeSat project is IrishSat's central project and interfaces with the other projects throughout its development and operations. They have worked on educational prototype CubeSats in the past. The CubeSat project team will develop the bus for CLOVER-Sat, using the knowledge and existing infrastructure from prototypes to reach flight readiness. A payload subteam within CubeSat will work with Dr. Chisum to design and integrate the payload into the bus.

The Instrumentation Lab project team develops testing capabilities to aid the CubeSat team's development and ensure meets NASA CubeSat requirements are met. They have developed a Helmholtz cage and plaster air-bearing for attitude estimation and control testing - conducting successful controls tests in 2022. To aid CLOVER-Sat's progress and to verify success in a simulated environment, this team will continue developing testing protocols with existing instruments and develop new instruments such as a vibration table.

The Ground Station project team maintains and operates IrishSat's ground station, a now permanent fixture atop a campus building. Design and construction of this structure began in 2021 and completed in 2023. This team will carry out CLOVER-Sat's mission operations once in orbit.

The High-Altitude Balloon (HAB) project team designs, constructs, and launches technologies aboard high-altitude balloons. They have found success through the NASA FLOATing/ICE DRAGON challenge. This team will be the least involved in CLOVER-Sat operations, although it will help in development and testing processes, providing a reusable launch platform to test CLOVER-Sat components and ground station capabilities.

#### 2.1.2 Technical Leads

The Communications lead specializes in wireless communications theory and implementation. They work within both the Ground Station and CubeSat projects to lead the team's effort to build an end-to-end communications system to transmit and receive data to and from orbit. The Computing lead specializes in developing algorithms and software, especially attitude determination and control algorithms and overall flight software. They assemble the software critical for the CLOVER-Sat's operation in orbit. The Power lead specializes in designing power systems, especially generating and storing power from solar panels. They design the system responsible for CLOVER-Sat's power generation, distribution, and management. The Structures, Thermal, Orientation, and Controls (STOC) lead specializes in the development and creation of general structural designs across all projects as well as thermal considerations that must be accounted for. The Machining lead specializes in working with and teaching the use of manufacturing tools as well as verifying the viability of design for manufacturing and assembly.

#### 2.1.3 Club Officers

Leads report to an executive board of club officers, consisting of the President, Chief Technology Officer (CTO), and Director of Research and Development (Director of R&D). The President heads all of IrishSat operations, the CTO acts as the source of technical expertise, and the Director of R&D leads the team's pursuit of future projects. Together, the three executive officers manage all teams and technical groups while being invested in technical work. Additionally, the organization has a fourth executive officer, the Director of Business Operations, who heads IrishSat's business division. This division manages the team's fundraising, accounting, marketing, corporate outreach, and community outreach functions. Further, a Safety lead directly reports to the executive board. The safety lead handles the write-up and management of safety and operating procedures throughout the organization.

For transfer of power, the club officers are elected every year during March through a team-wide election. The newly elected club officers appoint the project and technical leads during the summer for the upcoming academic year.

### 2.2 Schedule

IrishSat plans for a launch opportunity in 2026, as seen in the Gantt chart timeline in Appendix D, Figure 7. The CLOVER-Sat mission shall span from August 2023 to December 2026. Key milestones include completion of a Preliminary Design Review by May 2024 and a subsequent Critical Design Review by November 2024. CubeSat hardware fabrication, integration, and testing will be completed by December 2025, and a proposed launch in Summer 2026.

### 2.3 Budget

The estimated material cost for CLOVER-Sat is $88,340. A detailed breakdown of these costs is in Appendix E. Values were obtained from CubeSat part vendor quotes and estimated in-house manufacturing costs. There will also be added costs for 3rd party verification testing.

## 3 Merit Review

To assess the merit level of CLOVER-Sat's mission, the team conducted a comprehensive review of the benefits that are born from being an educational undergraduate-led project as well as executing a demonstration of novel millimeter-wave technology.

### 3.1 Review Process

For the educational focus area, the team sought to answer the following prompt from this year's CSLI Announcement of Partnership Opportunity (AoPO): *Does the proposal describe a project with clear, meaningful student leadership in conducting management, design, analysis, development, construction, and operation?*

To analyze how team leadership can facilitate meaningful student engagement, the executive officers reflected upon IrishSat's organizational structure. To analyze educational benefits, the project and technical leads detailed the educational benefits of involvement with CubeSat development in their respective area. These leads laid out necessary tasks for successful completion of the CLOVER-Sat mission as well as the skills learned along the way. To align CLOVER-Sat with NASA's educational goals, the team also referred to Strategic Objective 4.3 of the NASA Strategic Plan 2022 and the three goals of the NASA Strategy for STEM Engagement:

**Strategic Objective 4.3**: "Build the next generation of explorers. Engage students to build a diverse future STEM workforce."

**NASA Strategy for STEM Engagement [2]**:

1. Create unique opportunities for students to contribute to NASA's work in exploration and discovery
2. Build a diverse, future STEM workforce through authentic learning experiences
3. Attract diverse groups of students to STEM

To analyze the mission's secondary technological focus area, the payload team, working with Dr. Chisum, developed a value proposition for the payload technology and defined a suitable payload measurement metric. This statement was crafted with special consideration toward Strategic Objectives 1.1, 1.2, 2.4, and 4.1 of the NASA Strategic Plan.

The CLOVER-Sat internal merit review findings were documented and compiled into a slide deck and associated review document. These findings were then presented to a panel of qualified reviewers as the officers and leads conducted sessions that included presenting the slide deck. Feedback was received both as verbal comments during the presentation and as written feedback afterward.

## 3.2 Review Findings

The primary findings from the merit review are split into two areas:

1. Educational: CLOVER-Sat will effectively meet the stated NASA educational objectives by providing students opportunities to lead and work on the various facets of satellite development manifested through different projects and technical groups
2. Technological Demonstration: the CLOVER-Sat mission will meet the stated NASA objectives by demonstrating technology with potential uses for future planetary science experiments *and* satellite communication infrastructure.

### 3.2.1 Educational Focus Area

**Organizational Structure**
CLOVER-Sat's mission is split across three projects: the CubeSat team, designing and developing the bus and payload, the Instrumentation Lab team, testing and verifying the CubeSat team's work, and the Ground Station team, responsible for mission operations. The technical leads will be heavily involved in CLOVER-Sat's progression, directing the subsystem teams within projects. The team makeup of IrishSat, shown in Figure 6 in Appendix C, reflects a diverse student workforce across every engineering discipline as well as non-engineering disciplines such as physics and finance. Thus, members of IrishSat learn how to effectively communicate and collaborate across interdisciplinary and inter-team lines.

**Project: CubeSat Team**
IrishSat's CubeSat project, responsible for the completion of the CLOVER-Sat bus, is the central team in the pursuit of the CLOVER-Sat mission. The CubeSat team is divided into seven subteams, allowing for delegation and specialization of targeted tasks. These subteams include structures, power, computing, communications, thermal, attitude determination and control system (ADCS), payload, and payload integration[1]. These subteams are involved in the whole engineering design process from mission design to flight hardware implementation.

Through the subteams, members develop skills that align with their interests. The communications subteam will learn how to design a robust bidirectional uplink-downlink system. The power subteam will learn how to optimally generate, manage, and distribute power harvested from solar panels. The structures subteam learns how to identify structural requirements and defines a design to meet them. The ADCS subteam learns how to devise a sensor and actuator suite. The computing subteam works on flight software, especially the algorithms driving the ADCS[2]. The thermal subteam learns how to mitigate risks posed by LEO conditions. Finally, the payload integration subteam learns how to implement low-risk deployment schemes for the payload. As each subteam develops subsystems from individual parts (instead of purchasing an integrated turn-key subsystem), they are learning the fundamental principles necessary to succeed as engineers in the future. The dependencies between these subsystems foster interdisciplinary cohesion, educating members on how to work and communicate across disciplines.

[1] Of these subteams, the power, computing, and communications subteams are led by the corresponding technical lead.

[2] The computing and ADCS subteams work together closely.

Additionally, a few members of the CubeSat team make up the payload subteam and work with Dr. Chisum to design and develop the payload. This endeavor to construct and test the antenna will be completed by undergraduate students under faculty advisement. Through this subteam, members gain experience in undergraduate research, specifically in RF engineering, and learn how to derive engineering requirements from the payload's mission specifications.

A group of senior electrical engineering students is working in tandem with the CubeSat team to design and test the payload's prototype microcontroller which will be used in the creation of a final flight-ready CLOVER-Sat system. This process includes incorporating all electronic payload-relevant components on a PCB with documentation for future reference.

**Project: Instrumentation Lab Team**
IrishSat's Instrumentation Lab team is responsible for the production and operation of low-cost, in-house satellite testing instrumentation. The team has developed its own orbital dynamics software for orbital modeling, a Helmholtz Cage for geomagnetic modeling, and a spherical plaster air bearing for attitude control testing [3]. To assess CLOVER-Sat's flight readiness, this team is constructing a vibration table and gyroscope test rig for fully integrated ADCS testing. This project team provides IrishSat in-house testing, saving expenses due to 3rd-party testing, and allowing for an iterative design process. The Instrumentation Lab also reflects an industry environment, treating the CubeSat team as a customer.

**Project: Ground Station Team**
The Ground Station team offers students a unique opportunity to delve into the intricacies of satellite mission operations. Engaging in this project empowers team members with a comprehensive understanding of HAM radio operations and working with the FCC, culminating in the attainment of their HAM radio technician licenses. Furthermore, the project teaches members about antenna design and the utilization of software-defined radios (SDR). Beyond these foundational skills, team members gain hands-on experience in satellite tracking using two-line elements and conduct orbit determination exercises. The Ground Station project serves as a transformative platform, shaping individuals into satellite mission operations engineers.

**Project: IRIS High Altitude Balloon**
The HAB project, also referred to as IRIS, is not a central component of CLOVER-Sat but it plays a crucial role as an educational project for new members and a developmental platform for CubeSat components. Annually, the team embarks on the development and launch of a new HAB-deployed node system. Through monitoring, testing, and retrieval facilitated by autonomously guided flight aboard the compact, reusable, and reliable IRIS node, the new system will act as a launch vehicle for CubeSat tests. The upcoming launch is slated to support an industry-research cross-venture by conducting thermal and pressure climb monitoring and testing on a payload comprised of CubeSat 3D-printed, space-grade alumina lens materials and components - innovative technology specially manufactured by a startup that is donating them for Prof. Chisum's research development. IRIS functions as a valuable, cost-effective learning opportunity, particularly for underclassmen. Due to its low-stakes and low-cost nature, the project provides students with hands-on experience in iterative engineering processes for near-space missions and the acquired skills are transferable to CLOVER-Sat.

**Technical Group: Communications**
The key educational benefits that the communications technical group provides to members center around designing for constraints related to hardware, software, regulations, and standards. Members working under the guidance of the communications lead learn fundamental communications engineering skills and techniques, such as convolutional encoding and pulse shaping, used to create a robust communications link. Lastly, members learn how to work with development environments and cross-compiling to integrate into embedded systems.

**Technical Group: Computing**
The computing technical group works on the flight software required for CLOVER-Sat, including state estimation and attitude control. Members engage in collaborative work through GitHub version control, learning how to work alongside and resolve conflicts with others. Work sessions prompt insightful discussions of the benefits and drawbacks of certain approaches and how they impact the future functionality of the software system. The computing team, mostly made up of computer science majors, learns to work alongside engineering and physics majors.

**Technical Group: Power**
The power technical group gives student engineers an education in power systems engineering through hands-on experience in developing complex circuitry to support space missions. Communication between the power lead and project leads is necessary for updating each project's power needs considering things such as orbital assumptions, component power draw, and power management logic. Power group members learn to responsibly specify components like solar panels, batteries, and core power management architecture.

**Technical Group: STOC and Machining**
The STOC technical group is involved in Structures, Thermal, Orientation, and Controls topics and serves as a strong knowledge base providing project support. The STOC lead hosts tutorials in subjects such as computer-aided design and finite element analysis, emphasizing the ways these skills are used to tackle real engineering problems. The machining lead educates new members in manufacturing skills through tutorials conducted which incorporate hands-on practicing while learning in Notre Dame's Engineering Innovation Hub (EIH). This on-campus machine shop provides the team with valuable machining experience, promoting design mindful of manufacturing considerations.

These project teams and technical leads work together, utilizing IrishSat's matrix structure, as project requirements are communicated throughout the matrix.

### 3.2.2 Technology Focus Area

**Value Proposition**
The technology payload will consist of a phased array fed lens (PAFL) antenna operating as a receiver in the millimeter wave K-band. A block diagram of the payload at a component level can be seen in Appendix B, Figure 3. 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). Similarly, Earth science missions often require scanning radiometers and radar.

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. Alternatively, lens antennas are naturally wideband and low-power but exhibit poor relative performance. They have fixed beam angles that create nulls in radiation patterns and static beam shapes make minimizing side lobe levels over a large FoV difficult. The lens also requires a focal depth that is not suitable for small satellites. **This technology demonstration is intended to demonstrate a phased array fed lens (PAFL) that combines the beamforming advantage of phased arrays with the decreased 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. 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.**

The PAFL design will be inherently low risk when compared to other deployable antenna systems. The deployment system will consist of a linear screw actuator that will translate the lens to a desired focal length to yield a F/D of 0.5. A redundant actuator will be present to limit single-point failures. By leveraging the multiobjective optimization of antenna elements, a total deployment failure will still result in a minimum viable beam by activating all elements. The lens will be constructed from alumina, a low-loss material that can withstand extreme temperatures of up to 1500°C [4, 5]. The result is a low-risk, efficient, lower-cost phased array communication system that can operate as satellite-to-satellite and satellite-to-ground systems. A LEO mission would achieve space lineage for PAFL antennas to validate the use of low-risk parts.

This technology has ample opportunity for orbital communications as the demand for cislunar and LEO satellite communication grows. Traditionally, phased array antenna (PAA) elements must maintain a $< 0.5\lambda$ spacing to avoid grading lobes and maintain performance. This is problematic for two main reasons: cost and power. Small spacing requires an increased number of elements at an increased cost while compounding problems of heat distribution. The latter challenge may require downtime to radiate heat away from the antenna. The addition of a gradient index throughout the lens volume offers more degrees of freedom than reflectors, resulting in better beams, wider bandwidths, and a lower overall mass/volume ratio [6].

CLOVER-Sat works to improve both of these problems of phased arrays by spacing elements to $0.7\lambda$ spacing to reduce the number of elements and optimization algorithms to limit the impact of grading lobes while maintaining a suitable gain. A complex weight is applied to each antenna element to control the magnitude and phase. A few elements will be activated using specified weights with their fields collimated by the lens to produce a suitable beam at an arbitrary angle. Multiple active elements cancel out side lobes that result from increased element spacing. This iteration of PAFL will consist of a receive-only, one-dimensional array of 12 elements that implement a multiobjective optimization method using particle swarm optimization to calculate optimal weights. The result will be a suitable phased array communications device that uses $(0.5/0.7)^2 \approx 50\%$ less ICs. In the one-dimensional case, $\sim 30\%$. Experimental data has shown a PAA has an average power dissipation of $2.4\text{W/cm}^2$ compared to only $0.3\text{W/cm}^2$ for a PAFL.

**Relevance to NASA Objectives**
Strategic Objective 1.1 of the NASA Strategic Plan 2022 expresses NASA's desire to better understand the Earth and its climate as a system, especially through Earth-observing measurements and missions. Strategic Objective 1.2 expresses interest in new ways to answer questions in the fields of astrophysics, heliophysics, space weather, and planetary science, especially by laying the foundation for space-based missions and innovating new space-based observing capabilities. Conducting a merit review revealed that the CLOVER-Sat payload targets these NASA objectives. A successful demonstration of the technology's capabilities will provide a foundation for future missions integrating the lens antennas into more complex instrumentation capable of science-rich data. Due to its low power and low cost, the technology is an alternative to existing millimeter wave solutions, interesting to Earth scientists as water and other molecules in the atmosphere display spectra in these ranges.

These low-power, low-cost capabilities are promising for satellite communications infrastructure. This technology may provide a future solution for accessible, low-cast LEO satellite communications, superseding conventional millimeter wave solutions, and thus fulfilling Strategic Objective 2.4. This technology could additionally provide a transformational solution for cislunar communications, enhancing future cislunar (and possibly beyond) NASA missions, thus aligning with Strategic Objective 3.1.

## 3.3 Panel Findings

The internal merit review findings were presented to a panel of space industry project engineers, managers, and scientists[3]. This panel responded to the findings regarding CLOVER-Sat's educational and technological merits.

With regard to the educational benefits, the panel noted a strong point of merit in IrishSat's emphasis on knowledge transfer. As mentioned in Sec. 3.2, knowledge transfer is a team priority, and leadership frequently engages in tutorials and year-round mentoring. Panel discussions revealed that these aspects were key in developing CLOVER-Sat as an educational project and panelists encouraged continuing efforts of knowledge transfer as a core everyday goal.

Panel members raised a question regarding what external resources the team could consult for technical guidance. Potential resources were not included in the original merit considerations, and panel members noted critical nature for both CLOVER-Sat's success *and* educational quality. To integrate this feedback, it should be noted there exist established mentor relationships with professors at the university as well as industry contacts whom the team has previously consulted and intends to maintain relationships with. A notable example is the CubeSat team's communication with Dr. Javier Romualdez of StarSpec Technologies for guidance on developing robust satellite ADCS. Through developing and maintaining such connections, CLOVER-Sat allows students to learn from their peers and experienced industry and academic mentors.

[3] A breakdown of member qualifications can be seen in Appendix F.

A panel member expressed concern regarding the absence of identified, standardized documentation methods for CLOVER-Sat. This aspect was missing from the original analysis and presentation, and to address this feedback, the team plans to engage in documentation across all CLOVER-Sat relevant work. Milestones to be accompanied by sizable documentation include the completion of a Preliminary Design Review during Spring 2024, a Critical Design Review during Spring 2025, and an internal Flight Readiness Review during Fall 2026. Accomplishing these documentation goals will help to educate members on technical documentation and further systems engineering skills.

With regard to the merit of CLOVER-Sat's technological demonstration, panel members emphasized the importance of including the projected and quantified benefits of the lens antenna payload. Within the original merit analysis, the team asserted that the proposed payload promises low-power and low-cost capabilities when compared to conventional millimeter wave technology, but did not provide quantified figures to support this claim. The team addressed this feedback by working with Dr. Chisum to quantify the stated benefits included in the value proposition of Sec 3.2.2. Further, the panel identified the absence of performance metrics definitions. The result was ambiguity regarding the measurement of the technological benefits over conventional solutions. To address this issue, the team identified several metrics to quantify success. To assess the improvements for PAFL power-efficiency, power consumption will be tracked and these values will be compared to values of an analogous PAA system. Additionally, in comparing PAFL with conventional lens antennas, emissivity measurements detecting the noise power of water over the ocean vs the land will be taken with the PAFL in a variety of its programmable configurations. To simulate static beam antenna behavior for comparison purposes, the antenna will only activate single feeds instead of utilizing complex weights for multiple elements. Also, creating the capability to vary the F/D ratio would showcase the ability for PAFL to utilize multiple beams to create a minimum viable superimposed beam. Comparing the resolution of emissivity maps with simulations will quantify the effectiveness of PAFL as a receiver.

# 4 Feasibility Review

To assess the readiness level and CLOVER-Sat's probability of success, the team conducted a comprehensive feasibility review with respect to both the mission and IrishSat organization.

## 4.1 Review Process

The contributing feasibility factors examined throughout this review are divided into four main categories: (1) organizational structure, (2) past experience and expertise with satellite development and adjacent projects, (3) current level of critical technology development, and (4) financial feasibility given the team's budget and fundraising. Category 1 and 4 factors were examined by the club officers. Category 2 factors were examined by members previously involved with projects, including former and current leads. Category 3 factors were examined by current project and technical leads. Feasibility review findings were documented and compiled into a slide deck and associated review document. These findings were then presented to a panel of qualified reviewers. Feedback was received both as verbal comments during the presentation and as written feedback afterward.

## 4.2 Review Findings

The following section details the findings of the CLOVER-Sat internal feasibility review.

### 4.2.1 Organizational Structure

As mentioned earlier, the IrishSat's project teams not only tackle CubeSat bus and payload design and development but also testing through the instrumentation lab team and operations through the ground station team. Further, The technical groups ensure that members, principally the technical lead, carry expertise in their respective fields. By emphasizing the technical lead's responsibility to facilitate learning amongst new members through tutorials, knowledge transfer occurs as an essential part of IrishSat's operations. This institutionalized knowledge transfer addresses the issue of turnover in a student design team as senior members graduate. Further, having multiple executive officers overseeing the projects aids in dividing the task of organizational management among three knowledgeable and heavily involved individuals, ensuring that executive oversight is not reliant on one person.

### 4.2.2 Experience and Expertise

IrishSat has developed the experience and infrastructure needed for CLOVER-Sat's success through the work done to produce successful projects during the 2020-2023 academic years.

**Past Project: ProtoSat**
Throughout the 2021-2023 academic years, the ProtoSat team developed a prototype CubeSat to create a knowledge base for future development and test core functionalities. This project designed and constructed important 1U CubeSat subsystems in a cost-effective manner to prepare for working with true flight hardware. The main focus areas were attitude control, flight software, and power management. The attitude control subsystem utilized PID tuning scripts to control three reaction wheels. To desaturate the reaction wheels, magnetorquers were constructed and tested in a Helmholtz cage. The body of the ProtoSat was suspended on a plaster air bearing in the instrumentation lab to allow for near frictionless movement to test reaction wheels. An unscented Kalman Filter performed IMU sensor fusion for orientation estimation [7]. Solar panels utilize a Maximum Power Point Tracking (MPPT) charging circuit to provide power to a LiPo battery, microcontroller, and reaction wheels. A power budget determined a viable payload operating time before requiring recharge. Solar panel deployment was incorporated using a burn wire.

ProtoSat involved aspects of systems engineering by incorporating engineering requirements and promoting undergraduate work in diverse technical backgrounds. ProtoSat documentation continues to function as a referenced knowledge base. The project successfully produced a realistic testbed that demonstrated IrishSat's ability to engineer complicated subsystems and integrate them into a functional system as well as the capability to educate a team on satellite fundamentals and conduct effective knowledge transfer.

**Infrastructure: Instrumentation Lab**
The instrumentation lab team has developed technology to perform in-house attitude control and orbital simulation testing. This team has constructed a low-cost spherical plastic air-

bearing, which has been successfully used to test prototype attitude control systems. Through this project, the team developed expertise in methods for attitude control testing. Additionally, to complete orbital simulation testing, the team constructed a Helmholtz cage. Together with custom orbital dynamics software, the cage simulates the magnetic field experienced by a satellite in LEO to test magnetometer readings and magnetorquer control. This project has taught the team valuable skills in mechatronics integration and power supply design. This existing infrastructure will be critical for CLOVER-Sat's testing phase in the future.

**Infrastructure: Ground Station**

Ground Station's main goal is to command, control, and track the satellite. The team designed two Yagi Uda directional antennas with a 144 Mhz VHF uplink antenna and a 438 Mhz UHF downlink which are currently functional on an on-campus building's roof. The 144 Mhz antenna will later be replaced with a 2x2 patch antenna array tuned to 2.2 GHz for downlinking from the satellite. For mission communications, the team will use a USRP software-defined radio which would allow for easily adjustable, modular radio design. For the ground station's proof of concept, HAM radio deluxe was used for satellite tracking and a hardware-based transceiver for signal processing. Moving toward the final ground station design, the team has switched to Gpredict which takes in a satellite's two line elements set and runs algorithms over it in order to predict when communications are possible [8].

**Past Project: IRIS High Altitude Balloon**

IrishSat's involvement with its HAB project, IRIS, provides valuable experience and learned lessons that will translate to CLOVER-Sat's success. Namely, the IRIS team has found success in its participation in the NASA FLOATing/ICE DRAGON competition where they worked within competition guidelines and requirements. To support IRIS's mission, the payload autonomously guides itself from its deployment point (at 120,000 ft) toward an optimally selected safe waypoint on the ground, doing so using the Model Predictive [9]/Free [10] Control algorithms to control a servo-steered parafoil [11] - technology notably developed at the University of Notre Dame [12]. The design, test, and operations experience of a HAB mission will translate into successful mission coordination for CLOVER-Sat. The technical competencies learned by members through producing a successful aerospace product with IRIS, including autonomous guidance systems, flight software, avionics, thermal control, power management, structural design and analysis, and integrated embedded systems, add to the needed knowledge base of flight software and hardware development. The engagement in flight operations, launch procedures, risk mitigation, payload integration, and more add to the experience level of IrishSat.

### 4.2.3 Critical Technology Development

**CLOVER-Sat Overview**

As detailed in the merit review, the CubeSat project team divides the development of CLOVER-Sat's 2U bus into to seven subsystems: attitude determination and control system (ADCS), communications, computing, power, structures, thermal, and payload integration. This division allows for members of the CubeSat team to specialize. It is recognized that this modularity poses potential risks with regard to eventual systems integration. Thus, the CubeSat project manager and chief engineer will work with the CTO and technical leads to ensure proper communication of needs and system requirements between subteams.

The following findings report the current state of critical technology development and subsequent plans to prepare for flight readiness of the critical CubeSat team subsystems.

**ADCS Subsystem**

The current attitude determination and control system (ADCS) is a culmination of past research and implementation. Past prototypes utilized three reaction wheels for attitude control. For CLOVER-Sat, a fourth reaction wheel will introduce redundancy, thus reducing the severity posed by a reaction wheel failure event. The CLOVER-Sat ADCS will incorporate three magnetorquers (one for each axis), to allow for successful detumble and the desaturation of reaction wheels [13]. The reaction wheels and magnetorquers are driven by proportional-integral-derivative (PID) controllers, which compare a current estimated attitude with a goal setpoint. The sensor suite for attitude estimation consists of a 9-DOF IMU and a GPS module. The GPS's measurements combined with the IMU gyroscope's and magnetometer's readings will provide the observation model needed to estimate orientation at a given time. These sensors are integrated into an Unscented Kalman Filter, which has been written by the computing team. To mitigate drifting sensor bias, a pinhole sun sensor for calibration shall be implemented.

**Flight Software Subsystem**

The computing subteam leads software development and integration between all subsystems. Up to this point, the team's primary focus has been on developing the ADCS software, as it is a demanding computational task for flight readiness. For attitude estimation, this subteam has successfully written an Unscented Kalman Filter (UKF) integrating an attitude dynamics model with an observation model as defined by the ADCS sensor suite. The subteam is currently implementing PID controllers for attitude control and defining the critical operational modes for ADCS. These modes include a charging mode where the solar panels are angled toward the sun, a payload mode which prioritizes the payload's measurements, and a communications mode which prioritizes downlinking data. To reach flight readiness for ADCS software, the subteam has defined an attitude estimation to attitude determination software loop. To ensure speed in computation, the subteam rigorously tests and optimizes their software to minimize runtime. Unit and integrated testing will ensure both functional modular scripts as well as cohesive connections between software modules. To receive technical guidance and review, they plan to continue consulting academic and industry contacts as done in the past.

**Communications Subsystem**

The communications subsystem defines both transmit and receive capabilities to enable complementary downlink of data and reception of commands for general payload and bus control, independent of the payload receiver. The transmission system will begin with a digital data stream into the onboard Software Defined Radio (SDR), which will generate a digital baseband waveform, modulate and encode the waveform, and transmit the signal using the S-band patch antenna to the ground station. The reception system will detect commands using a UHF tape measure antenna, filter and amplify the signal, and push it to the SDR for command processing and actuation [14, 15]. To avoid transmit and receive overlap, the system will have a transmission schedule so the SDR can be put into transmit or receive mode accordingly. Frequency and phase correction algorithms shall be implemented to avoid errors during transmission between the ground station and CLOVER-Sat.

**Power Subsystem**
The power subsystem seeks to accomplish an autonomous and intelligent electrical architecture. This subteam has taken steps toward defining and developing CLOVER-Sat's fundamental electrical generation and storage systems and has created multiple printed circuit boards for power management including an MPPT board for solar charging and intelligent battery and load management [16]. This subteam is working with a supplier to secure the space-rated solar panels required for such a mission. Testing and verification risks shall be mitigated by focusing on diligently designing components one at a time to ensure that the subteam maintains technical perspective of the project as a whole when considering sequential integrations.

**Instrumentation Lab Testing**
The instrumentation lab is currently working on four different projects for satellite testing: the Helmholtz cage, plaster air bearing, vibration table, and 2U gyroscope ADCS test rig. The team is improving the power supply of the Helmholtz cage by consolidating the design to an Arudino Leo and PCB filter that will output a constant analog DC voltage to the cage for current control. The plaster air bearing has been completed and the team is now carrying out a viscous drag analysis to characterize the air resistance experienced on the testing platform. This will allow the team to perform reaction motor unit testing. The team is currently constructing a vibration table to simulate the shocks and forces CLOVER-Sat will experience during launch. The team has referred to NASA's Payload Vibroacoustic Test Criteria for its necessary engineering specifications. The last milestone for the project is the development of a 2U gyroscope ADCS test rig. The rig will be constructed inside the Helmholtz cage to allow for simultaneous magnetorquer testing. By providing access to such testing capabilities, these instruments will reduce the developmental risks for the CLOVER-Sat bus, especially the ADCS subsystem.

**Mission Operations**
The Communications and Ground Station leads have defined a system overview of operations, as seen in Appendix B, Figure 3, for CLOVER-Sat to ensure mission success. The ground station will be used for UHF command transmission to control the satellite's operational mode. Ground station commands can control which mode CLOVER-Sat enters once a communications link is present. The UHF antenna on the satellite will constantly detect commands from the ground station and react accordingly when commands are received. Transmission to the ground station will occur during a window based on CloverSat's orbital trajectory. To mitigate ineffective communications due to satellite orientation, commands can be sent to the omnidirectional radiation UHF antenna to orientate the higher gain S-Band patch antenna towards the ground station.

#### 4.2.4 Financial Feasibility

A detailed breakdown of IrishSat's sources of funding is provided in Appendix E. IrishSat expects additional corporate donations beyond the total indicated on the basis of verbal intent from company representatives. Current sponsors include Boeing and General Electric. Notre Dame Club funding for 2024 is based on 2023 allocations. After summing sources one through four (totaling $36,000), Notre Dame's Research Department will cover the remaining expenses to bring the total funding in line with the estimated budget. This funding is supported by a Letter of Intent from Dr. Jeffrey Rhoads, Vice President of Notre Dame Research in Appendix G.

## 4.3 Panel Findings

The feasibility review findings were presented to a panel of space industry project engineers, managers, and scientists, many of whom were also panel members for the merit review [4]. The panel gave feedback on CLOVER-Sat's probability of success in light of the presented findings.

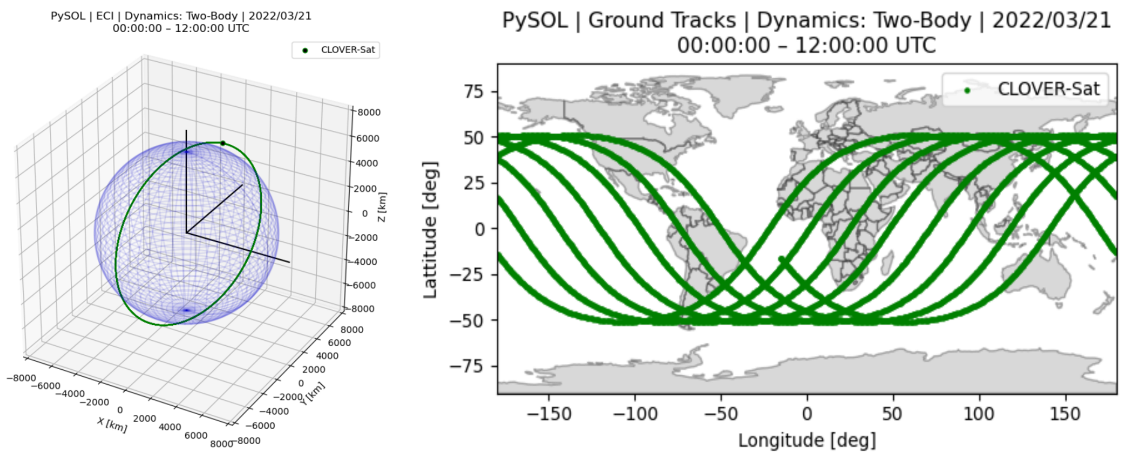
One concern raised by panel members is the (seemingly unnecessary) devotion of time and effort toward solving technical problems that could be solved by purchasing commercially available products. By designing and constructing most components in-house, CLOVER-Sat becomes a deeply educational project, but this low-level engineering approach also poses a potentially critical risk to mission success. At the panel's suggestion, the team plans to consult faculty, communicate with industry specialists, and undergo more internal design reviews to ensure that decisions to develop such parts are well-guided and reasonably supported.

Another suggestion revolved around the implementation of proper systems engineering processes that could mitigate developmental risks associated with subsystem integration. This input was highly valuable, as the team's primary efforts have been on developing independent subsystem technologies while waiting on integration. The team is addressing this by creating plans for the development of a real-time operating system to control the employed embedded systems as well as incorporating integration scheduling into CLOVER-Sat's developmental timeline. One such test targets the ADCS system within flight software while utilizing the developed power system, bringing together technologies to test integrated performance. Another planned test includes validating the in-house-developed ground station's capabilities by uplinking and downlinking data between the IRIS system to practice and prepare for CLOVER-Sat operations. Further, the team plans for the creation of a systems engineering group to be led by the CTO. This group shall work to facilitate inter-team communication and ensure that the various subsystems interface seamlessly. This includes defining and assuring physical constraints, verifying atomicity and data safety in concurrent software operations where i/o is shared between sensors, actuators, and processors, developing adequate testing procedures with the instrumentation lab team, and ensuring that all mission requirements are effectively met through adequate redundancy measures. This work minimizes the risks associated with integration in the developmental cycle of CLOVER-Sat, and promotes a successful mission.

The final concern raised by the panel was the team's recognition, understanding, and mitigation of various risks associated with the design process. These risks include insufficient technical skills necessary for critical technology development, lack of redundancies in subsystems, and running out of funding for various subsystems. The team has plans to combat these risks primarily by writing a comprehensive Preliminary Design Review. This document shall combine all pertinent mission knowledge to provide a stable, documented base of design requirements, engineering specifications, proposed solutions, and explored avenues to continue development on pertinent tasks. This document will lay the groundwork for the future of CLOVER-Sat development and serve as a comprehensive overview guiding members.

[4] A full breakdown of the feasibility review panel members' qualifications can be seen in Appendix F.

# A Target Orbit




(a) (b)

**Figure 1.** Target CLOVER-Sat orbit, propagated for 12 hours and visualized using the team's custom orbital software, PySOL. The above figure depicts the orbit in (a) an Earth-centered inertial reference frame and (b) Earth-centered, Earth-fixed ground tracks, with the following orbital elements: eccentricity $e = 0.0001$, inclination $i = 51$ degrees, semimajor axis $a = 6,800$km, longitude of ascending node $\Omega = -30$ degrees, argument of periapsis $\omega = 80$ degrees, true anomaly $\nu = 121$ degrees. This is an example orbit that meets CLOVER-Sat's orbital requirements detailed in the CubeSat Mission Parameters.

# B Payload Concept and Implementation

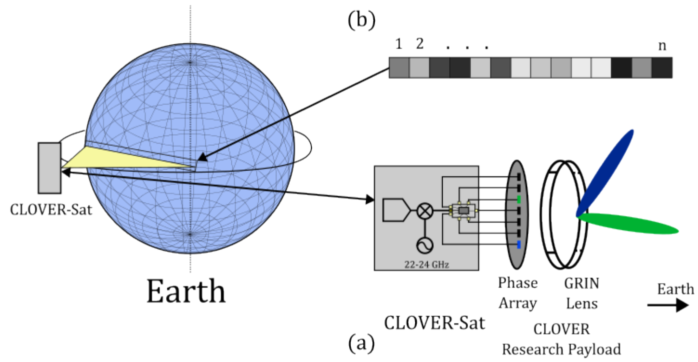



**Figure 2.** CLOVER-Sat mission concept, depicting CLOVER-Sat in LEO performing measurements by electronically scanning across one dimension. (a) The payload consists of a phased array fed gradient index lens antenna (b) The data received via 1D electronic beam-scanning will be an array of noise power amplitudes, i.e. an array of pixels.

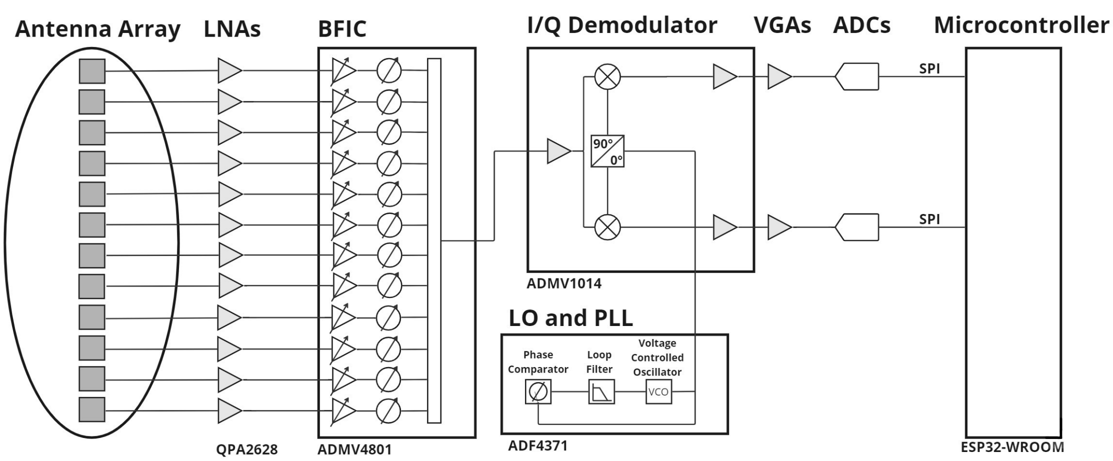



**Figure 3.** Block diagram showing the main electronic components that makeup the phased array fed lens payload. Each antenna element is in series with a low noise amplifier (LNA) that connects to the beamformer integrated circuit (BFIC). The resultant RF signals pass through a demodulator that interfaces with a analog digital converter (ADC) before being processed by a microcontroller.

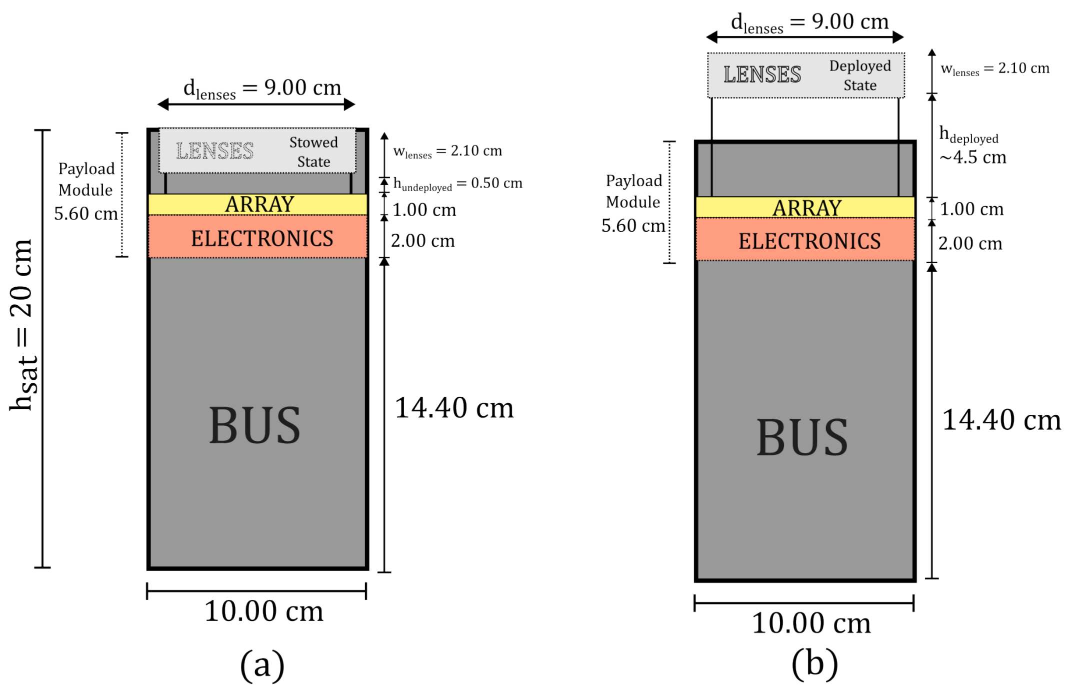



**Figure 4.** Mechanical deployment scheme for the PAFL antenna payload. This scheme shows the volumetric savings made by deploying payload lens to desired focal length. (a) Diagram of the stowed state, showing the lens payload stowed within the 2U envelope. This will be CLOVER-Sat's state during launch. (b) Diagram of the deployed state. The antennas are linearly actuated out of the 2U envelope, ensuring a 0.5 focal distance over aperture diameter ratio. This will be CLOVER-Sat's state during operations in orbit.

# C Organizational Structure and Makeup

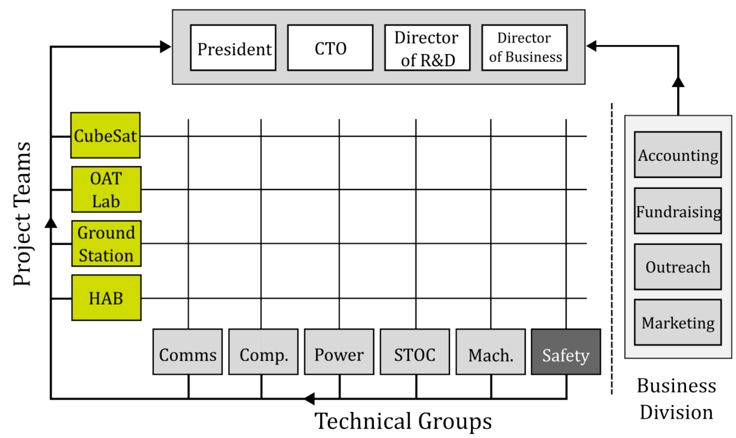



**Figure 5.** Organizational structure of IrishSat. As shown above, the project leads and technical leads exist within a matrix-style structure and report to the executive board.

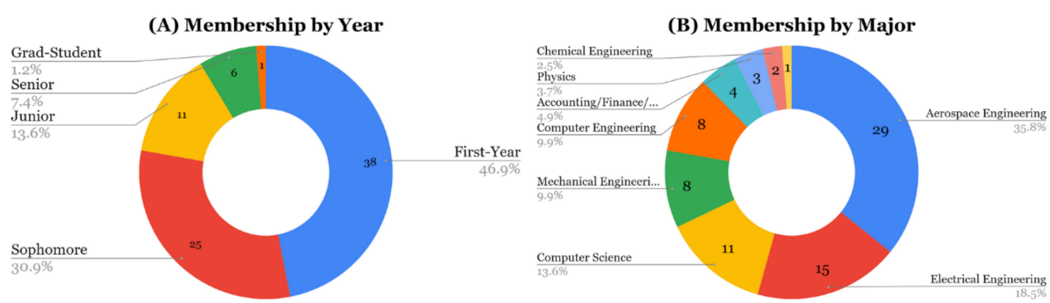



**Figure 6.** Active member make-up of the IrishSat organization an active member is defined to be a member that is present at weekly full-team meetings and project work sessions. Chart A shows make-up by year, in order of highest to lowest count: First Year (38), Sophomore (25), Junior (11), Senior (6), Graduate Student (1). Chart B shows make-up by majors, in order of highest to lowest count: Aerospace Engineering (29), Electrical Engineering (15), Computer Science (11), Mechanical Engineering (8), Computer Engineering (8), Accounting/Finance/Business Analytics (4), Physics (3), Chemical Engineering (2), and the Notre Dame ESTEEM Masters Program (1).

# D Project Timeline

| Project Timeline | |
|---|---|
| Project Start Date: | Aug-2023 |

| TASK | START | END |
|---|---|---|
| **Concept Development** | Aug-23 | Nov-23 |
| **Securing Funding** | Aug-23 | May-24 |
| Necessary Funding: | Aug-23 | Dec-23 |
| Contingency Funding: | Jan-24 | May-24 |
| **Merit & Feasibility Reviews** | Sep-23 | Nov-23 |
| Internal Merit & Feasibility Review: | Sep-23 | Oct-23 |
| Merit & Feasibility Review Panel: | Oct-23 | Nov-23 |
| **CubeSat Design** | Sep-23 | Nov-24 |
| Prototyping: | Sep-23 | Dec-23 |
| CLOVER-Sat PDR: | Nov-23 | May-24 |
| CLOVER-Sat CDR: | Jun-24 | Nov-24 |
| **CSLI Proposal Submittal** | Sep-23 | Nov-23 |
| **Selection and Manifesting** | Mar-24 | Apr-26 |
| **Mission Coordination** | Mar-24 | Jun-26 |
| **Regulatory Licensing** | Oct-23 | Apr-24 |
| **Flight Documentation Submittal** | May-24 | May-25 |
| **Ground Station (GS) Testing** | Dec-23 | Dec-24 |
| GS-to-HAB Communications Test: | Dec-23 | Jan-24 |
| **CubeSat Hardware Fabrication and** | Aug-24 | Dec-25 |
| Hardware Fabrication: | Aug-24 | Dec-24 |
| Unit Testing: | Nov-24 | Feb-25 |
| Integrated System Testing: | Feb-25 | Oct-25 |
| Full System Testing and Verification: | Oct-25 | Dec-25 |
| **Mission Readiness Review** | May-26 | Jun-26 |
| **Integration and Testing** | Jun-26 | Jun-26 |
| CubeSat-to-Dispenser: | Jun-26 | Jun-26 |
| Dispenser to Launch Vehicle: | Jun-26 | Jun-26 |
| **Launch** | Jun-26 | Jun-26 |

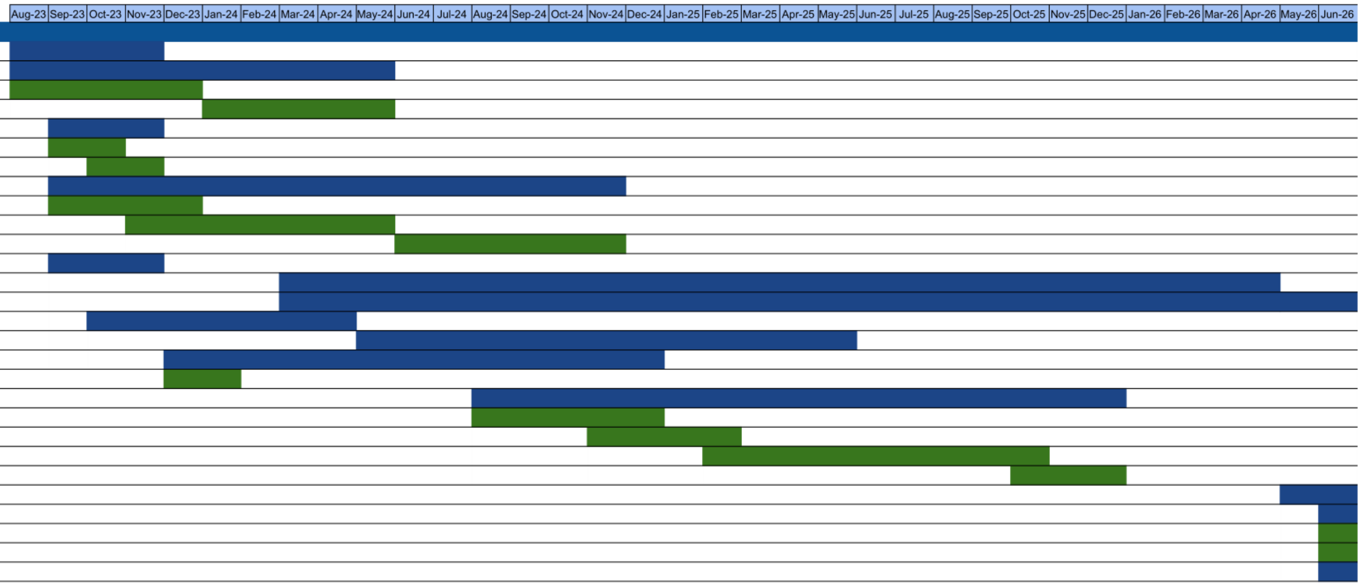



**Figure 7.** Project timeline until launch. CLOVER-Sat plans for a launch opportunity during the Spring/Summer of 2026. The above project timeline does not include the six months of mission operations following launch.

# E Project Budget and Funding Sources

| Subsystem Cost Breakdown of CLOVER-Sat | |
|---|---|
| Subsystems | Cost |
| 1. Power | |
| • Solar Panels & Shipping/Insurance | $20,300 |
| • Battery/Electronic Power System (EPS) | $9,890 |
| • Wiring Harnesses | $1,000 |
| 2. Attitude Determination and Control System | |
| • Reaction Wheels | $23,100 |
| • Magnetorquers | $500 |
| • State Estimation Sensors | $8,000 |
| • GNSS Module | $10,000 |
| • ADCS Computer | $450 |
| 3. Communications | |
| • Monopole Antenna | $50 |
| • Patch Antenna | $3,800 |
| • Software Defined Radio | Donated |
| 4. Structures and Thermal | |
| • Structural Material Cost | $1,400 |
| • Machining Cost | $6,500 |
| • Thermal Heating System | $1,200 |
| • Solar Panel Deployment | $350 |
| 5. Payload | |
| • Antenna Array | Funds Donated |
| • GRIN Lens | Donated |
| • Deployment Mechanism | $1,800 |
| Total Cost | $88,340 |

**Table 1.** Material cost of CLOVER-Sat breakdown based on supplier quotes and estimated manufacturing costs. Most components will be purchased from a verified supplier with the exception of magnetorquerss and PCBs that will be designed and ordered from a manufacturer.

| Breakdown of IrishSat Funding Sources | |
|---|---|
| **Funding Source** | **Amount per Year** |
| 1. Notre Dame Electrical Engineering Department | $5,000 |
| 2. Corporate Donations | $7,000 |
| 3. Individual Fundraising | $10,000 |
| 4. Notre Dame Club Coordination Council Funds | $14,000 |
| **Additional Funding** | **Amount** |
| 5. Notre Dame Research | $55,000 or As Needed |
| **Total Revenue** | **$91,000** |

**Table 2.** Summary of each source of funding for IrishSat that will cover the expected cost of the CLOVER-Sat project. Sources 1-4 are annual donations while Notre Dame Research has agreed to finance any funding gaps based on the expected budget (Letter of Intent from Dr. Jeffrey Rhoads, Vice President of Notre Dame Research attached in Appendix G).

# F Panel Member Qualifications

| Panel Member | Workplace | Title |
|---|---|---|
| Lisa Maradik | Boeing | Director of Mechanical and Structural Engineering |
| Reena Byrne | Boeing | Director of Program Management |
| Chris Vitro | Boeing | Guidance, Navigation, Control Engineer |
| George Porter | Boeing | Guidance, Navigation, Control Engineer |
| Jack McBride | Boeing | Structures and Materials Engineer |
| Zach Kowalcyzk | Boeing | Electrical Design Engineer |
| Patrick Danielson | Boeing | Engineer in Autonomous Systems |
| Luke Renaud | Boeing | Communications Engineer |
| Tom Harkins | Northrop Grumman | Staff Engineer Systems |
| Jonathan Volk | Sierra Space | Senior Manager, In-Space Manufacturing |
| Jim Lampariello | Blue Origin | Senior Guidance, Navigation, Control Engineer |
| Tim Kennedy | NASA Johnson Space Center | Deputy Chief, Wireless and Communications Systems Branch |

**Table 3.** Merit review panel member qualifications.

| Panel Member | Workplace | Title |
|---|---|---|
| Lisa Maradik | Boeing | Director of Mechanical and Structural Engineering |
| Reena Byrne | Boeing | Director of Program Management |
| Chris Vitro | Boeing | Guidance, Navigation, Control Engineer |
| George Porter | Boeing | Guidance, Navigation, Control Engineer |
| Jack McBride | Boeing | Structures and Materials Engineer |
| Zach Kowalcyzk | Boeing | Electrical Design Engineer |
| Patrick Danielson | Boeing | Engineer in Autonomous Systems |
| Luke Renaud | Boeing | Communications Engineer |
| Tom Harkins | Northrop Grumman | Staff Engineer Systems |
| Jim Lampariello | Blue Origin | Senior Guidance, Navigation, Control Engineer |
| Tim Kennedy | NASA Johnson Space Center | Deputy Chief, Wireless and Communications Systems Branch |

**Table 4.** Feasibility review panel member qualifications. As seen above, most of the feasibility review panelists were also merit review panelists.

# G Supporting Financial Documentation

UNIVERSITY OF NOTRE DAME | RESEARCH

Jeffrey F. Rhoads
Vice President for Research
Professor of Aerospace and Mechanical Engineering

Notre Dame Research, 317 Main Building, Notre Dame, IN46556 USA
+1 574-631-8384 | jrhoads2@nd.edu | research.nd.edu

November, 17, 2023

University of Notre Dame Research
317 Main Building
Notre Dame, IN 46556 USA

NASA/Goddard Space Flight Center Procurement Office,

I am writing on behalf of Notre Dame Research to formally express our intent to collaborate with IrishSat in supporting their undergraduate CubeSat project at the University of Notre Dame. As a distinguished research institution committed to fostering innovation and excellence in education, we are genuinely excited about the potential of IrishSat's CLOVER-Sat mission and we recognize the intrinsic value and contributions this will make toward space exploration and scientific discovery.

The CLOVER-Sat mission, orchestrated by a team of devoted undergraduate students under the guidance of experienced faculty members, aims to demonstrate the viability of a novel antenna - first developed by an electrical engineering research professor Dr. Jonathan Chisum. This mission embodies the spirit of pioneering advancements in aerospace and electrical engineering. Notably, this initiative resonates with our university's overarching mission to provide immersive, hands-on research opportunities for students, thereby catalyzing progress in these pivotal fields.

In alignment with our commitment to facilitate and propel meaningful research endeavors, Notre Dame Research is prepared to extend partial financial support (amount to be determined) for the remaining material costs associated with the CubeSat bus. This commitment underscores our unwavering dedication to ensuring the success and sustainability of the CLOVER-Sat mission.

We look forward to the prospect of a collaborative partnership that not only furthers the goals of IrishSat but also exemplifies the synergy achievable through the convergence of academic prowess and innovative exploration. Please consider this letter as a formal declaration of our commitment to supporting this noteworthy undertaking.

Sincerely,

Jeffrey F. Rhoads

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