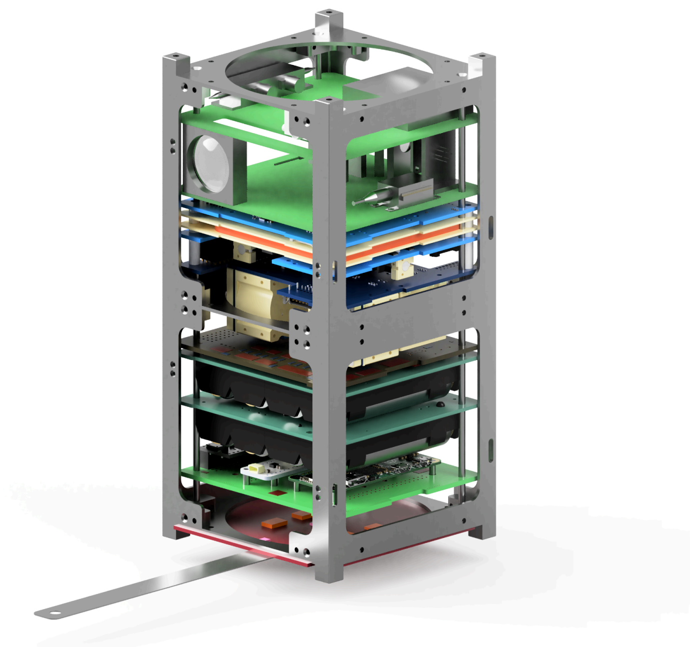
University of Chicago NASA CSLI Proposal

In response to solicitation NNH23ZCF001

PULSE-A: Polarization modUlated Laser Satellite Experiment

November 2023



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PULSE-A: Polarization modUlated Laser Satellite Experiment
A 2U CubeSat Mission

Table 0.1: PULSE-A Mission Parameters

<table>
<tr><th colspan="9">PULSE-A Mission Parameters</th></tr>
<tr><th>Mission Name</th><th>Mass (kg)</th><th>Cube Size</th><th colspan="2">Desired Orbit</th><th>Acceptable Orbit Range</th><th>400 km @51.6° incl. Acceptable - Yes or No</th><th>Readiness Date</th><th>Desired Mission Life</th></tr>
<tr><td rowspan="2">PULSE-A</td><td rowspan="2">2.4 kg</td><td rowspan="2">2U</td><td>Altitude</td><td>500 km</td><td>400 km - 550 km</td><td rowspan="2">Yes</td><td rowspan="2">Dec. 2025</td><td rowspan="2">1 Year</td></tr>
<tr><td>Inclination</td><td>45°</td><td>42.5°-90°</td></tr>
</table>

Table 0.2: PULSE-A Project Details

<table>
<tr><th colspan="7">PULSE-A Project Details</th></tr>
<tr><th rowspan="2">Focus Area</th><th rowspan="2">Student Involvement: Yes or No</th><th colspan="2">NASA Funding</th><th rowspan="2">Sponsoring Organizations</th><th colspan="2" rowspan="2">Collaborating Organizations</th></tr>
<tr><td>Yes or No</td><td>Organization</td></tr>
<tr><td rowspan="2">Education, Technology</td><td rowspan="2">Yes</td><td rowspan="2">No</td><td rowspan="2">N/A</td><td rowspan="2">University of Chicago; Chicago Quantum Exchange (CQE); ANSYS, Inc.</td><td>List</td><td>International? Y or N?</td></tr>
<tr><td>University of Chicago</td><td>No</td></tr>
</table>

Table 0.3: Points of Contact

Points of Contact				
Name	**Title**	**Address**	**Phone**	**Email**
Prof. Tian Zhong	PULSE-A Team Advisor	[EXPUNGED]	[EXPUNGED]	[EXPUNGED]
Lauren Ayala	PULSE-A Project Director	[EXPUNGED]	[EXPUNGED]	[EXPUNGED]
Logan Hanssler	PULSE-A Head of Engineering and Feasibility	[EXPUNGED]	[EXPUNGED]	[EXPUNGED]
Rohan Gupta	PULSE-A Head of Funding and Outreach	[EXPUNGED]	[EXPUNGED]	[EXPUNGED]

Logan Hanssler is the PULSE-A Technical Point of Contact.

Addresses, phones, and emails have been removed for the distributable version of the proposal.

Table of Contents

1. Abstract

The PULSE-A mission is a student-led project intending to demonstrate 10 Mbps polarization-keyed, space-to-ground laser communications in a 2U CubeSat form factor, being developed by The Students for the Exploration and Development of Space at the University of Chicago (SEDS-UChicago).

The current state of space-to-ground communication is characterized almost exclusively by radio frequency (RF) communications. In recent years, however, the rate at which sensor output and data collection rates have grown has vastly outpaced the available transmission speeds of RF, especially at small form factors. Ever-decreasing launch costs and inexpensive commercial off the shelf (COTS) hardware are both driving forces in the development of earth-wide sensor constellations, which are largely limited by the capabilities of RF data transmission. Free-space optical communications offer a significant advantage to these limitations, improving on power, space, and effective data rates over RF. Optical communications are significantly more secure, because of their much narrower beamwidth, which makes them more difficult to intercept and jam. Given these advantages, PULSE-A's primary mission objective is to create, test, and launch a small form-factor, open-source optical payload, which promises significantly higher data transfer rates and enhanced security compared to traditional RF communication at the same form factor. Additionally, PULSE-A aims to pave the way for a future Quantum Key Distribution CubeSat: "PULSE-Q" (Quantum).

In pursuit of later mission success for PULSE-Q, PULSE-A acts as both necessary flight heritage and as a risk reduction mission. By developing key systems, including downlink pointing, accuracy and tracking (PAT), uplink tracking, and a polarization-based optical ground-station, PULSE-A demonstrates the viability of such systems prior to PULSE-Q. The PULSE-A ground station is a critical component of any later QKD mission as it enables the reception and analysis of the polarization-keyed laser-transmission, which QKD also relies on, and the current mission allows for that system to be rigorously tested.

Additionally, PULSE-A's success relies on its ability to accurately demonstrate pointing, acquisition, and tracking of the uplink beacon laser. To achieve this, the satellite will include a robust and flight-tested Attitude Determination and Control System (ADCS) sourced from a reputable ADCS vendor (the team has received quotes from CubeSpace and AAC Clyde Space; the team is actively working with these organizations). PULSE-A's PAT sequence will direct the satellite's body, along with the optical ground station's telescope, enabling them to scan for one another. By demonstrating that PULSE-A can maintain the necessary orientation, pointing accuracy, and slew rate for effective laser

communication, we prove that a CubeSat can point accurately enough to perform well in a later QKD mission.

In conclusion, PULSE-A's mission parameters encompass demonstrating laser communication's potential to revolutionize space-based data transmission, integrating a reliable optical ground station, adhering to risk reduction principles, implementing a robust ADCS, and assessing the suitability of space based QKD. Thus, this mission represents a significant step forward in advancing small form-factor space communication technology.

2. Acronym List

Table 2.1: PULSE-A Acronym List

APD - Avalanche Photodiode	ADCS - Attitude Determination and Control System
CMOS- Complementary Metal-Oxide-Semiconductor	COTS - Commercial off the Shelf
CSLI - CubeSat Launch Initiative	FSM - Fast Steering Mirror
InGaAs - Indium Gallium Arsenic Detector	NFOV - Near Field of View
PAT - Point Acquisition and Tracking	PBS - Polarizing Beamsplitter
PDU - Power Distribution Unit	QKD - Quantum Key Distribution
RF - Radio Frequency	LEO - Low Earth Orbit
TEC - ThermoElectric Cooler	RSO - Registered Student Organization
EDFA - Erbium Doped Fiber Amplifier	FPGA - Field Programmable Gate Array

3. Mission Goals

3.1. Primary Mission: Open-Source Laser Communications Package

The current state of satellite communications relies on RF systems [1]. While RF communications are well-established and widely used, they have limitations in terms of data transfer rates, bandwidth, and security. Free-space laser communications offer several advantages over RF communications.

Firstly, laser communications use visible or infrared light waves for data transmission, allowing for order-of-magnitude improvements to data transfer rates when compared to RF systems [2]. Thus, laser communications yield a far more efficient data exchange between satellites and ground stations. Additionally, as laser communication systems are less susceptible to interference and jamming, they are more secure for sensitive data transmission. Laser communication can also support longer communication distances with less beam divergence, reducing the need for signal relay stations in space.

PULSE-A's primary mission is to establish free-space laser communications with an optical ground station using a newly designed optical payload, which is less than 0.5U in size. This mission aligns well with the advancements in laser communication technology that are necessary for future space sensor networks and develops technology that will make laser communications more widely accessible among small form-factor satellites. We are one of the first universities to undertake such an endeavor, and we aim to accomplish it at a smaller form factor and for cheaper than any university has done before. Additionally, PULSE-A plans to employ a novel laser communication standard using circular polarization-keyed data transmission as compared to On-Off Keying (which almost all existing laser communications satellites use). Polarization-keyed data transmission is less susceptible to atmospheric interference than On-Off Keying.

NASA already has significant investments in the growing development of LEO laser communications. The TeraByte InfraRed Delivery (TBIRD) mission (deployed 2022), the joint MIT/NASA CubeSat Laser Infrared CrosslinK (CLICK-A/B/C) mission (deployed 2022), the Aerospace Corporation's Optical Communications and Sensor Demonstration (OCSD) mission (deployed 2017), and ILLUMA-T (deployed November 2023) all represent recent work toward this goal. Through the development of an open-source and cost-efficient laser optics setup, PULSE-A makes CubeSat laser communications more accessible and furthers current research.

PULSE-A's focus on laser communications also aligns with NASA's efforts to develop and deploy advanced scientific instruments and imaging systems for planetary exploration. Missions to the Moon and Mars are expected to generate a vast amount of data, including high resolution imagery and scientific measurements, so missions will need improved methods of communications to transmit information. Optical communications are far more suited for such missions than RF communications due to their directionality, which reduces power requirements drastically, and their capacity for much higher transfer speeds.

3.2. Secondary Mission: QKD Risk Reduction

Quantum Key Distribution (QKD) utilizes the unique properties of quantum mechanical systems to generate and distribute cryptographic keying material. QKD represents a significant step forward in the security of data transmission as compared to classical optical communication because it is provably secure. Furthermore, QKD requires the exchange of entangled photons, which demands the establishment of very low-loss optical links. In its secondary mission, PULSE-A acts as verification, flight heritage, and risk-reduction for many of the systems necessary to create this level of precision in a classical optical link.

Ground-based, long-distance QKD has already transitioned into reality, with extensive networks of optical fibers spanning hundreds of kilometers establishing links between strategic locations across the globe. The largest QKD network in the United States spans 124 miles, featuring critical nodes in Chicago and at Argonne National Laboratory. As a leading university in quantum information sciences, the University of Chicago plays a pivotal role in this quantum network. Despite having garnered significant attention due to the low-loss for optical links in the vacuum of space, spaced-based QKD remains in its nascent stages. With space-to-ground QKD, atmospheric effects are only a minor consideration (affecting only 9-17 km of the link path, as this is the altitude of the tropopause [3]). The University of Chicago's experience with ground-based networks positions our team uniquely by endowing us with an abundance of expertise in quantum development, making us exceptionally well-suited for a space-to-ground QKD project.

At the time of this proposal, the most well-known demonstration of bi-directional space-ground QKD is the Micius satellite, launched by the Chinese Academy of Sciences in 2016 [4]. There also exists a limited heritage in nanosatellites when it comes to missions demonstrating quantum communications technologies. The SpooQy-1 CubeSat Mission, launched by the National University of Singapore in 2020, is the first nanosatellite (3U) to demonstrate in-orbit quantum entanglement (photon generation) [5]. The United States has yet to launch a satellite of any size that performs QKD to date. The concept of a QKD space-to-ground satellite under NASA's jurisdiction represents an innovative venture in the field of enhanced security communications.

PULSE-A's secondary mission is therefore to advance and establish a track record for the critical systems that will play a pivotal role in PULSE-Q, a future CubeSat form-factor QKD terminal. Mainly, achieving an optical laser downlink and attaining flight heritage with the pointing specifications necessary for QKD. The successful development of polarization-based modulation, ADCS hardware, the optical ground station, and the pointing software required for PULSE-A will result in the establishment of key systems with flight heritage that can be readily applied on a future QKD satellite with little to no modification. PULSE-Q would represent a novel and pioneering achievement, being one of the first CubeSat form-factor Quantum Key Distribution (QKD) satellites.

4. CSLI Applicability

4.1. Applicability to the 2022 NASA Strategic Plan

PULSE-A embodies multiple facets of the 2022 NASA Strategic Plan and is directly applicable to objectives 2.4, 3.1, and 4.2 [6].

NASA's strategic objective 2.4 is to "Enhance space access and services." PULSE-A's small form factor and open-source scientific payload will make the implementation of laser communications on small satellite buses more accessible. In turn, PULSE-A contributes to the development of efficient communications for future satellites made by the United States. This would be especially helpful for communicating over long distances, such as to the Moon and Mars, as outlined in NASA's strategic goal 2.4.

NASA's strategic objective 3.1 outlines the need to "innovate and advance transformational space technologies," and strategic objective 4.2 is to "Transform mission support capabilities for the next era of aerospace." The open-source nature of PULSE-A's scientific payload promotes economic growth and drives innovation by increasing access to high-speed optical data transfer. PULSE-A also lays the groundwork for a theoretically unhackable space-to-ground QKD mission, which would be a first for an American satellite. Furthermore, laser communication is inherently more secure than RF communication because it is more challenging to intercept or jam laser signals. Thus, PULSE-A strongly aligns with the national security objectives detailed in strategic objective 3.1 and 4.2.

Beyond NASA's general strategic goals, our mission also directly supports JPL's strategic goal 3: "Catalyze Economic Growth and Drive Innovation to Address National Challenges," as it contributes to the potential development of laser communication and QKD satellite networks.

4.2. Applicability to Education

The PULSE-A project is the first of its kind at the University of Chicago, an institution without an official aerospace engineering program. PULSE-A provides a unique medium through which current and future students passionate about the development of space technology will expand their knowledge and practical skills. The project's challenges empower team members to learn and develop a full-stack approach to finding solutions through its focus on undergraduate student collaboration. Members of the team have already gained extensive knowledge in satellite design, construction, and integration through their involvement in the PULSE-A project. This experience has proven instrumental in helping interested team members secure aerospace internships, further enhancing their practical skills and industry readiness. Furthermore, as PULSE-A is an entirely student-run project, the team is gaining experience in project management, benchmark setting for development, and community engagement initiatives.

The PULSE-A project embodies multiple facets of the NASA Strategy for STEM Engagement [7] because of our status as an accredited higher education institution. Throughout the course of the project, the team members, all undergraduate, are gaining extensive experience in evidence-based practices and outreach with industry experts and partners. Multiple members of our team were previously engaged in K-12 science competitions and STEM engagement events focused on the aerospace sector and are highly interested in continuing that engagement. We have been documenting our development process through our Funding and Outreach Department, and we are planning to run lecture-format courses for K-12 students on satellite design and space science based on our documentation. Multiple team members have connections to local high schools and elementary schools and have volunteered in similar capacities.

5. Project Organization

The SEDS-UChicago PULSE-A project is led by **Lauren Ayala**: the Project Director and a fourth-year undergraduate Molecular Engineering and Astrophysics double major. The project's Faculty Advisor is **Professor Tian Zhong**, Assistant Professor of Molecular Engineering at the University of Chicago. The team is subdivided into two departments: Engineering and Feasibility, and Funding and Outreach.

- The **Funding and Outreach Department** is led by Department Head **Rohan Gupta**, a fourth-year undergraduate Astrophysics, Physics, and Computer Science triple major. Rohan oversees the PULSE-A team's budget and external communications. The Department of Funding and Outreach performs tasks such as fundraising, seeking sponsorships, and engaging in outreach efforts with the broader community and potential collaborators.
- The **Engineering and Feasibility Department** is led by Department Head **Logan Hanssler**, a second-year undergraduate Molecular Engineering and Astrophysics double major. Logan is responsible for overseeing the subteams which constitute the department.

For the research phase of the project, the engineering subteams are Computer-Aided Design (CAD) and Structure, Payload and Integration, and Analysis.

- The **CAD and Structure Subteam** designs and models the physical structure and components for PULSE-A. The CAD and Structure Lead is **Graydon Schulze-Kalt**, a second-year undergraduate Physics and Computer Science double major.
- The **Payload and Integration Subteam** manages the development of PULSE-A's scientific payload and its integration with bus components from the Artemis kit. The Payload and Integration Lead is **Seth Knights**, a second-year undergraduate Computer Science major.
- The **Analysis Subteam** performs physical calculations and models PULSE-A systems in various analysis software to ensure the feasibility of PULSE-A's missions. The Analysis Lead is **Vincent Redwine**, a fourth-year undergraduate Physics major.

For the development phase of the project, beginning after the CSLI proposal submission deadline, the engineering subteams will be redesigned as Avionics, Optics, and Systems Integration.

- The **Avionics Subteam** will be responsible for developing and maintaining PULSE-A's avionic sensors, control systems, and associated software; it will be led by **Graydon Schulze-Kalt**.
- The **Optics Subteam** will manage the prototyping process for PULSE-A's scientific payload and optical ground station as well as their associated software; it will be led by **Seth Knights**.
- The **Systems Integration Subteam** will oversee the integration of PULSE-A's scientific payload with its bus during the prototyping process, and it will work to integrate software between the other subteams; the Systems and Integration Subteam will be led by **Vincent Redwine**.

Lauren Ayala, Rohan Gupta, and Vincent Redwine are the only 3 members of PULSE-A's leadership that are graduating at the end of the 2023-2024 academic year. By SEDS-UChicago tradition, the team will hold elections for all leadership positions at the end of the academic year. It is expected that Logan Hanssler, Seth Knights, and Graydon Schulze-Kalt will in some arrangement fill the roles of Project Director, Head of Engineering and Feasibility, and one of the Subteam Leads. The Head of Funding and Outreach position as well as the remaining 2 Subteam Leads will be filled by 3 of our other most qualified team members.

The PULSE-A team is made up of 20 undergraduate student members. Every team member is majoring in some combination of Physics, Astrophysics, Computer Science, Molecular Engineering, or Mathematics, although some members are taking additional majors or minors in other disciplines. With the exception of technical and financial advice, all work on PULSE-A was completed by the team's undergraduate student members. Additionally, all members have access to a shared Google Drive, which contains thorough documentation of all work done on PULSE-A. After 4th-year undergraduate students graduate, the team's knowledge loss will be minimized, as all members have been kept up-to-date on project progress and can access notes on work done since the project's inception.

The majority of PULSE-A's research phase has taken place within conference rooms at the University of Chicago's Department of Astronomy and Astrophysics as well as the University of Chicago's Department of Physics. A small portion of PULSE-A's early research phase took place over Zoom video conference meetings. The PULSE-A team has secured laboratory space at the University of Chicago's Pritzker School of Molecular Engineering to carry out PULSE-A's construction. Additionally, we plan to construct the final, launch-ready version of PULSE-A in a clean room at the Pritzker School of Molecular Engineering.

6. Compliance Requirements

The PULSE-A project will not be requesting any waivers for deviance in design and is in full compliance with

- Launch Services Program Requirements Document [8]
- NanoRacks CubeSat Deployer Interface Control Document revised on 09/29/2022 [9]
- Federal Aviation Administration Laser Law and Enforcement [10]
- The Cal Poly CubeSat Design Specification (CDS) [11]
- UChicago University Research Administration (URA) [30]

Part of the PULSE-A development process includes a full complement of thermal, vibration, and vacuum testing that will be implemented in accordance with Table 1 of the Launch Services Program Requirements Document [8]. Most testing is currently set to be conducted in laboratory spaces within the campus area of the University of Chicago, with further long range testing (≥ 5 km) to take place in a yet-to-be determined location in Illinois. Any testing which requires instrumentation that is not available at the University of Chicago will be conducted at nearby universities that we are in active communication with.

As a research project at the University of Chicago, PULSE-A was required to seek approval from the University Research Administration for the submission of CSLI [30]. We have received this approval.

Because one of the central technologies integrated within our communication systems is laser-based, the PULSE-A project will be in full compliance with the Federal Aviation Administration (FAA) Laser

Law and Enforcement [10]. Relevant permits and precaution methods will be taken within the testing phase of the project in accordance with University and FAA safety regulations, as well as for uplink (Rx) and downlink (Tx) protocols. Our team will communicate with the FAA to receive a letter of non-objection for the construction of our ground station. In the event the team does not receive approval at the physical location of the University of Chicago, as it is within Class-B airspace, the team has alternate plans in place to construct our ground station at a more remote location such as the Yerkes Observatory in Williams Bay, Wisconsin.

Additionally, members of the team leadership have acquired Technician-level Radio Frequency Licenses as well as machine-shop training and certification.

7. Development Schedule

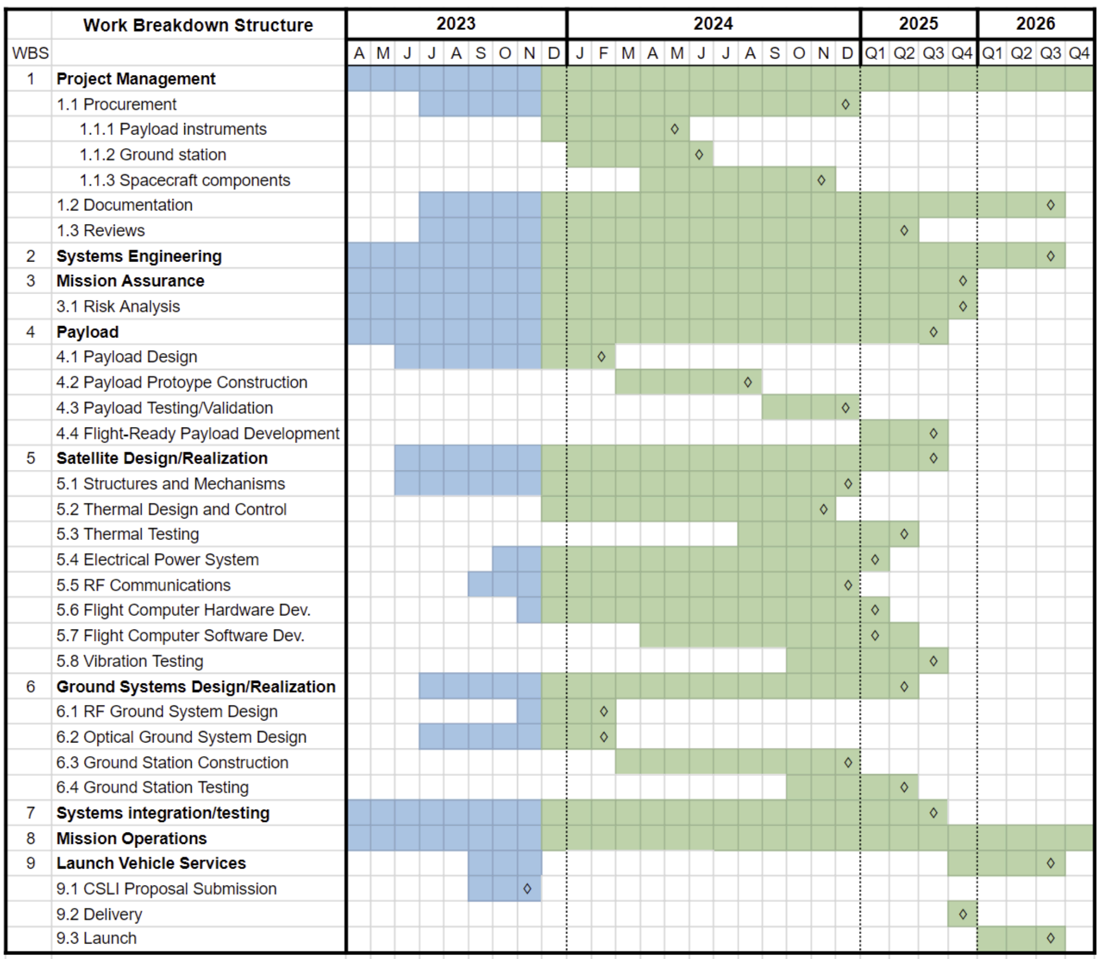

Figure 7.1: Gantt Chart (The diamond symbols refer to an item's completion, blue denotes work done before the CSLI proposal submission, and green denotes work done after the CSLI proposal submission.)

Mission operations will continue up to a maximum of one year after the launch date, depending on the initial orbit of the satellite. For additional justification on the development schedule, please refer to Appendix B.10.

8. Financial Information

8.1. Budget

This section contains an overview of PULSE-A's budget. The budget is broken down by cost category (pre-construction costs, testing costs, and contingency) and system (bus, power, ADCS, scientific payload, and ground station). SEDS-UChicago has budgeted for two copies of the scientific payload (aside from the modulator and laser, both of which will be repurposed in the launch-ready version of the payload from the prototype version of the payload). This decision stems from the complexity of the system, and having two copies will facilitate extremely rigorous testing of the payload and overall optical system. Any testing done at the University of Chicago will have negligible associated costs. We are in contact with other universities, and we anticipate securing access to their testing facilities in the event that instrumentation is not available at the University of Chicago. The $250 testing cost estimate is for transportation to said external testing facilities. Additionally, the contingency cost is estimated to be 10% of PULSE-A's net cost.

Table 8.1: Budget by System

Cost Category/System	Quantity	Cost Per ($)	Total Cost ($)
Pre-Construction Costs	1	100.00	100.00
Bus	1	4,000.00	4,000.00
Power	1	5,000.00	5,000.00
ADCS	1	24,155.95	24,155.95
Scientific Payload	2	7455.18	14,910.35
Ground Station	1	17,265.67	17,265.67
Testing Costs	1	250.00	250.00
Contingency	1	6,568.20	6,568.20
Overall Total			**72,250.17**

Please see Appendix B.11. for a more detailed version of PULSE-A's budget, which lists costs of individual components constituting cost categories and systems in Table 8.1.

8.2. Funding

The PULSE-A team has multiple funding sources that are itemized below:

- The Chicago Quantum Exchange, University of Chicago Department of Astronomy and Astrophysics, University of Chicago Department of Physics, University of Chicago Pritzker School of Molecular Engineering, and University of Chicago Physical Sciences Division have together agreed to provide a commitment for $25,000 to PULSE-A.
- Our advisor, Professor Tian Zhong, has agreed to provide the components of the ground station which has a monetary cost of $17,265.67.
- As a University of Chicago Registered Student Organization (RSO), SEDS-UChicago has allocated $5,000 toward PULSE-A from the RSO's funds. We possess these funds in our account.
- [NAME EXPUNGED] has agreed to provide PULSE-A team with $25,000 as a private donor.
    - This person's name has been removed for the distributable version of the proposal.

In total, monetary donations are $72,265.67 and exceed PULSE-A's full budget, including the 10% contingency, thus making the project fully funded. We have also received several full-featured licenses of STK and Zemax from Ansys; each license is valued at upwards of $50,000 on the commercial market.

PULSE-A's Department of Funding and Outreach is focused on leveraging the University of Chicago's alumni network and other contacts to develop and maintain relationships with external and internal contacts. Throughout the optical prototyping phase, the department will continue fundraising efforts in collaboration with the University of Chicago's academic departments and industry partners. Any further funds will be used to purchase additional duplicate components for PULSE-A beyond what has already been included in the budget so that more rigorous testing may be done.

9. Merit Review

9.1. Merit Review Process Overview

The PULSE-A team selected 4 scientists and engineers in relevant fields to conduct our merit review. The merit review was non-competitive, and it occurred during October-November 2023. Each reviewer received a Merit Review Packet, which was a document detailing PULSE-A's project abstract, mission goals, CSLI applicability, compliance with regulations, and development schedule. These sections were all preliminary versions of their counterparts in the PULSE-A CSLI proposal. Along with the Merit Review Packet, each reviewer was sent the Merit Review Survey (a Google Form) to submit their review responses. The survey contained 10 questions pertaining to PULSE-A's educational and technological merit, including the overall mission merit and its ability to satisfy NASA's strategic goals. Each question asked reviewers to rate PULSE-A on a scale from 1 to 5 in a specific area, then (optionally) share the rationale for their response. The 10th question offered reviewers a space to provide general comments on PULSE-A's merit.

9.2. Merit Reviewers

The PULSE-A Merit Review Panel was comprised of the following 4 reviewers, whose names have been removed for the distributable version of the proposal:

1. **[REVIEWER 1]**, Computational Engineering PhD Candidate in the Center for Predictive Engineering and Computational Sciences at the University of Texas at Austin, was chosen for his specialization in optics and laser measurements.
2. **[REVIEWER 2]** Materials Science Division Staff Scientist at Argonne National Laboratory, was chosen for her experience researching quantum optics.
3. **[REVIEWER 3]**, Postdoctoral Researcher at NASA Jet Propulsion Laboratory (JPL), was chosen for her experience working with CubeSats at Planet and with Transiting Exoplanet Survey Satellite (TESS) in graduate school at the University of Chicago.
4. **[REVIEWER 4]**, Electrical Engineering PhD Candidate in Professor Paul Kwiat's Laboratory at the University of Illinois at Urbana-Champaign, was chosen for his specialization in developing QKD communication for drones.

All 4 reviewers are intimately connected with furthering engineering education and technological innovation. None of the merit reviewers have contributed to the development of PULSE-A beyond providing advice for technical and project merit concerns.

9.3. Merit Review Results

The Merit Review Survey was made up of 3 sections:

Section 1 contained 5 prompts for reviewers to rate PULSE-A's merit with respect to the 2022 NASA Strategic Plan on a scale from 1 to 5. The project received an average score of 4.65 out of 5 on this section. [REVIEWER 1] commented: "I think this is exactly the type of project NASA should be engaged in. It fosters the education and development of students to be the next generation of space leaders while also developing an important new technology with applications to small-scale operations such as cubesats and large-scale operations such as crewed deep-space missions." Our other merit reviewers echoed his sentiment.

Section 2 contained 4 prompts for reviewers to rate the overall merit of PULSE-A's missions on a scale from 1 to 5. The project received an average score of 4.44 out of 5 on this section. Reviewers highly praised PULSE-A's primary mission: establishing an open-source laser communications package. Regarding PULSE-A's secondary mission: QKD risk reduction, reviewers stated that the project had merit, yet they requested that we expand on our description of the secondary mission and specify which systems of PULSE-A will contribute to the risk reduction effort. In response, we expanded on PULSE-A's secondary mission statement in Section 3.2. and detailed how the optical system establishes the groundwork for a QKD modification in Sections B.1., B.2., and B.3.

Section 3 provided a space for reviewers to share any other comments they may have regarding PULSE-A's merit. In this section, [REVIEWER 4] wrote: "The PULSE-A project is in the strategic interests of the U.S. and NASA and deserves to move forward." His statement represents the overall views shared by PULSE-A's merit reviewers.

Overall, PULSE-A received an average numeric merit review score of 4.56 out of 5. For a detailed list of the questions merit reviewers were asked, average numeric responses to each question, all written comments left by our reviewers, and how we addressed their responses, please see Appendix B.12.

10. Feasibility Review

10.1. Feasibility Review Process Overview

The PULSE-A team selected 5 scientists and engineers in relevant fields to conduct our feasibility review. The feasibility review was non-competitive, and it occurred during October-November 2023. The feasibility review process was structured very similarly to the merit review process, with each reviewer receiving a Feasibility Review Packet and Feasibility Review Survey (in the form of a Google ganForm). The Feasibility Review Packet detailed PULSE-A's project abstract, mission goals, project organization, compliance with regulations, scientific payload, ground station, PAT sequence, bus integration, development schedule, risk assessment, budget, funding, and leadership team's resumes. These sections were all preliminary versions of their counterparts in the PULSE-A CSLI proposal. We aimed to be as comprehensive as possible in the materials sent to reviewers so that they could accurately assess the project's feasibility, hence the large volume of material in the Feasibility Review Packet. The Feasibility Review Survey contained 10 questions pertaining to the technical and financial feasibility of PULSE-A's successful deployment. Each question asked reviewers to rate PULSE-A on a scale from 1 to 5 in a specific area, then (optionally) share the rationale for their response. The 10th question offered reviewers a space to provide general comments on PULSE-A's feasibility.

10.2. Feasibility Reviewers

The PULSE-A Feasibility Review Panel was comprised of the following 5 reviewers, whose names have been removed for the distributable version of the proposal:

1. **[REVIEWER 1]**, Computational Engineering PhD Candidate in the Center for Predictive Engineering and Computational Sciences at the University of Texas at Austin.
2. **[REVIEWER 2]**, Materials Science Division Staff Scientist at Argonne National Laboratory.
3. **[REVIEWER 5]**, Safety and Mission Assurance Engineer at NASA Johnson Space Center.
4. **[REVIEWER 6]**, Systems Engineer on CST-100 Starliner at Boeing.
5. **[REVIEWER 7]**, President of Liftoff Strategic Advisors, former Senior Manager of Strategic Development at Ball Aerospace.

[REVIEWER 1] was selected as a reviewer for both the merit and feasibility panels, as his specialty in optics makes him an ideal candidate for assessing the PULSE-A mission's merit and the feasibility of the optical system's success. Similarly, [REVIEWER 2] was selected for both panels because her expertise in quantum optics is invaluable for assessing PULSE-A as a precursor to PULSE-Q, both in the mission's merit and feasibility. [REVIEWER 5], [REVIEWER 6], and [REVIEWER 7] were selected as reviewers for their experience working in the aerospace industry, making them excellent candidates for assessing PULSE-A's feasibility. None of the feasibility reviewers have contributed to the development of PULSE-A outside of providing advice for technical and feasibility concerns (aside from [REVIEWER 2] and [REVIEWER 1] who also provided merit-related advice).

10.3. Feasibility Review Results

The Feasibility Review Survey was made up of 3 sections:

Section 1 contained 6 prompts for reviewers to rate PULSE-A's technical feasibility (concerning the payload, integration, optical ground system, PAT sequence, risk mitigation, and overall design) on a scale from 1 to 5. The project received an average score of 4.53 out of 5 on this section. The feasibility reviewers praised our team's broad technical backgrounds, optical system design, and ability to integrate the scientific payload. The reviewers requested more detail on PAT and atmospheric-scattering related challenges, which we expanded on in Appendices B.1. and B.3.

Section 2 contained 3 prompts for reviewers to rate PULSE-A's organizational and financial feasibility (concerning fundraising, team organization, and development timeline) on a scale from 1 to 5. The project received an average score of 4.33 out of 5 on this section. The most significant concern raised was regarding the team's capability of funding the project. However, in the time since we have submitted the feasibility review, our funding has been resolved. Please see Section 8.2. for funding sources. Regardless of this concern, the responses to this review section were very positive.

Section 3 contained a place for reviewers to leave comments about the overall feasibility of the project and any other comments they may have about PULSE-A. In this section, [REVIEWER 5] commented "The team has prepared a thorough and professional feasibility report. I believe they will have success if they continue to work with the same standards and processes they have used so far." Her sentiment represents the overall views shared by the review panel.

Overall, PULSE-A received an average numeric feasibility review score of 4.47 out of 5. For a detailed list of the questions feasibility reviewers were asked, average numeric responses to each question, all written comments left by our reviewers, and how we addressed their responses, please see Appendix B.13.

Appendix A. Compliance Documentation, Resumes, and Commitment Letters

A.1. Commitment Letters

Below are the commitment letters that fully cover PULSE-A's project. See Section 8.2 for more information. The commitment letters and proof of funding sources are in the order presented in Section 8.2.

The commitment letters have been removed for the distributable version of the proposal.

A.2. Compliance Documentation Checklist

Table A.2.1: Compliance Checklist

Requirement	Compliant?
Respondent is a U.S. public, private, or charter school that serves students grades K-12, an accredited higher education institution, an informal education institution such as a museum or science center, an out-of-school-time youth-serving organization that provides youth development activities on a permanent basis	YES, The University of Chicago is an accredited higher education institution.
If Education Institution: Is the project student led, built, and/or managed, with faculty member(s), educator(s) clearly identified to assist, guide, and educate the students throughout the process?	YES, the project is student led, built, and managed. We have a faculty advisor who guides the project.
Proposal has education as the primary focus area (required) and secondary focus area(s) (encouraged) and the proposal clearly identifies the relevance to NASA for all focus area(s) based upon the 2022 NASA Strategic Plan, NASA Strategy for STEM Engagement, and other NASA strategic documents.	YES, see Section 4.1, 4.2
CubeSat Project meets eligibility requirements?	YES, further information can be found in Section 6
Proposal includes funding commitment information and funding commitment letter(s) that reflect the budget is fully covered including any potential launch and integration costs above $300,000.	YES, further information can be found in Appendix A.3. Because of standard size, integration costs are not expected to exceed $300,000.
Proposal states that the CubeSat payload fully complies with the Launch Services Program Requirements (LSP-REQ-317.01B) or identifies any potential waivers utilizing the Waiver Request Table?	YES, mentioned in Section 6
The proposal is specific to a single CubeSat mission and clearly identifies the alignment to NASA strategic goals and objectives?	YES, see CSLI Applicability in Section 4
Proposal meets requirements regarding page limitations, font size and file size?	YES
Proposal cover page is complete and includes proposal contact information including the faculty member(s), educator(s)?	YES
Proposal title page includes a completed CubeSat Mission Parameters Table, CubeSat	YES

Project Details Table in the format provided, and if applicable the Waiver Request Table?	
Proposal includes the contact information for all points of contact (POC), including a technical POC, has a table of contents, and abstract?	YES
Proposal includes a budget and schedule for the CubeSat development that supports a launch in 2025-2028?	YES
Merit review process is described and includes what factors were used, titles and qualifications of review committee are provided, findings documented and were responded to and/or addressed; were changes implemented?	YES
Feasibility review process is described and includes what factors were used, titles and qualifications of review committee are provided, findings documented and were responded to and/or addressed; were changes implemented?	YES
Appendices include the Resumes/Qualifications and Compliance Documentation as required?	YES

A.3. Leadership Resumes

The resumes of the project's leaders have been removed for the distributable version of the proposal.

Appendix B. Additional Project Details and Documentation

B.1. Scientific Payload

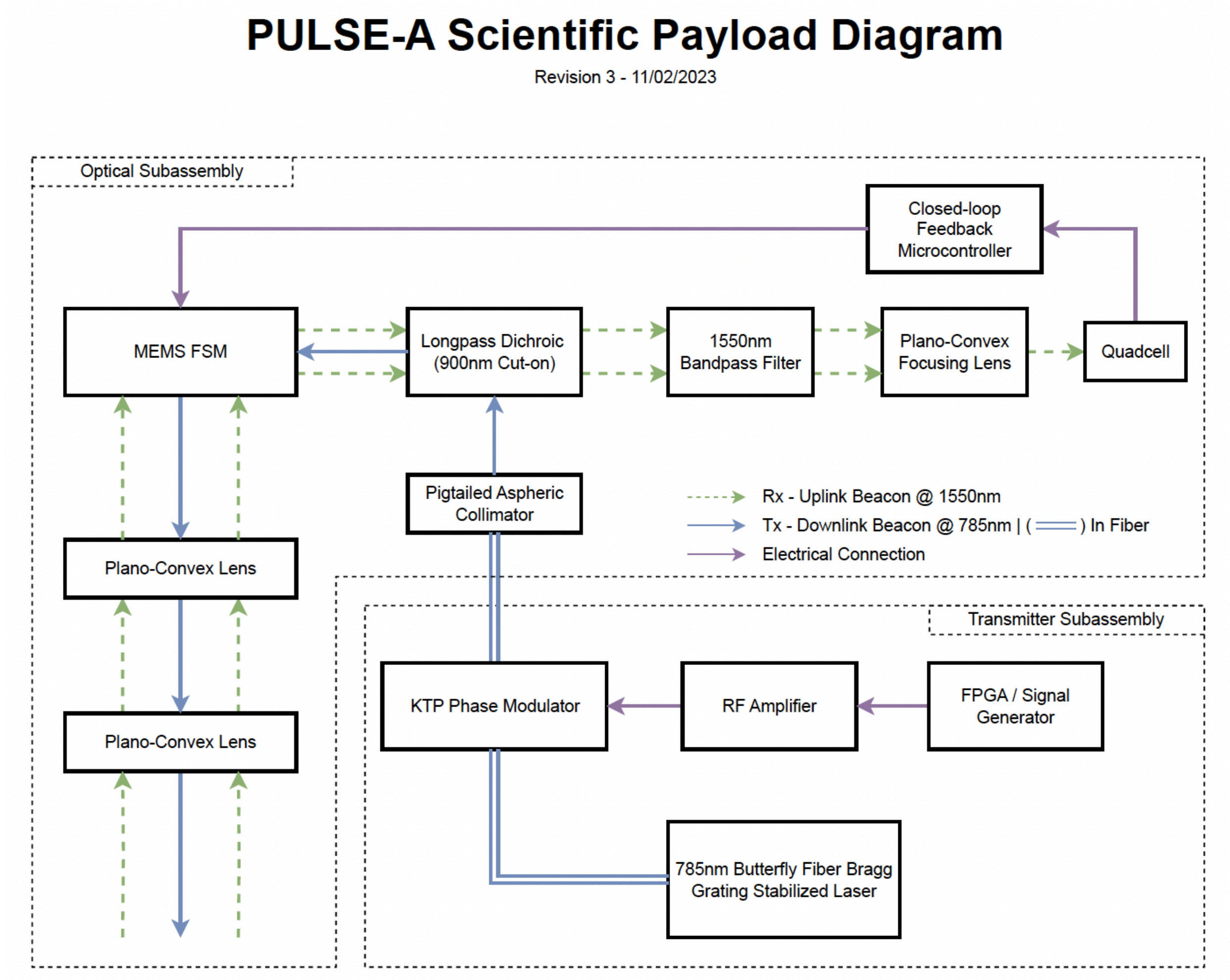

Figure B.1.1: Scientific Payload Overview

B.1.1. Optical Subassembly: Design Requirements

For space-based optical communication systems, consideration must be given to a few major constraints:

(a) Maximizing ground station light capture
(b) Spacecraft pointing accuracy
(c) Downlink beam divergence
(d) Spacecraft attitude determination accuracy

(e) The spacecraft aperture's effective field of view
(f) Size, weight, and power margins

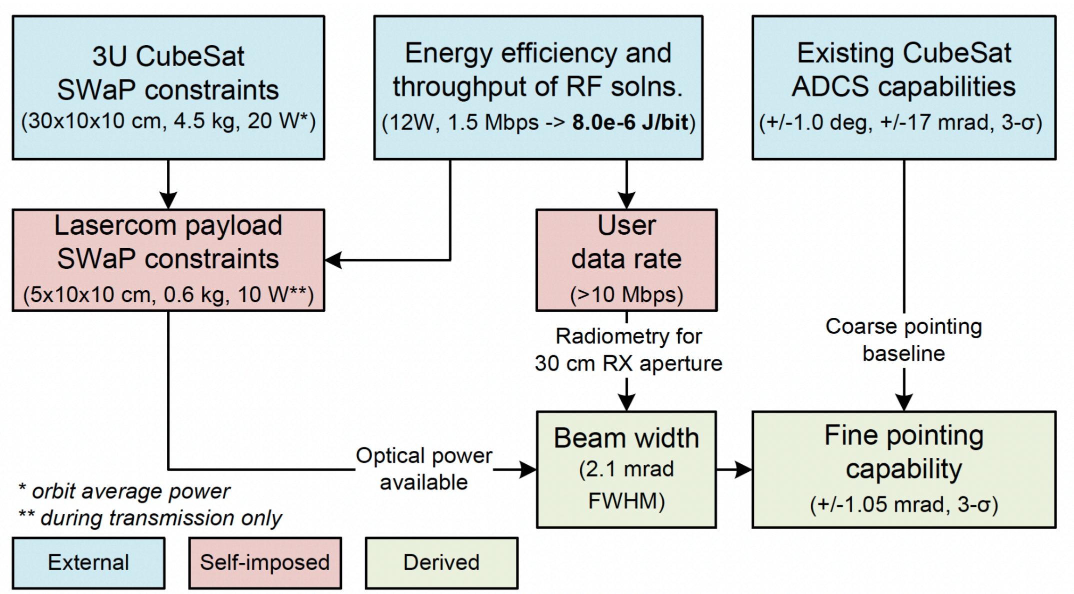

Figure B.1.2: Requirements "flow-down" for the CLICK-A laser communications system showing external (blue), self-imposed (red) and derived (green) requirements. Current best estimates for the various constraints are included. Note: Only an example image; does not represent PULSE-A. [12]

PULSE-A derives its necessary parameters through the assumption of a 10 Mbps transmission rate. While other recent small form-factor laser communications payloads have achieved higher data transmission rates, they are much larger, heavier, and more power intensive given their 3U or 6U size [13]. PULSE-A's transmission rate is still at least one order of magnitude greater than its RF-based transmission (<256 Kbps from Artemis) [14]. Given a requirement of 10 Mbps transmission, we assume a full-width half-max (FWHM) beam divergence of 2.1 mrad. This is mainly derived from existing work by the MIT CLICK-A team, as referenced in Figure B.1.2 [12]. This requirement aligns well with available COTS fiber-coupled laser collimators, which offer options in this range [15].

Additionally, PULSE-A employs a downlink wavelength of 785 nm. While other similar satellites, including both CLICK-A and PIXL-1 use 1550 nm, mostly due to the fact that it is a common wavelength in modern telecommunications, PULSE-A does not. This is primarily due to size and cost considerations: 1550 nm lasers are most often generated and modulated at significantly lower power levels and then amplified using rare-metal doped fiber amplifiers. While these amplifiers have decreased in size significantly over the past decade, even the most compact take up anywhere from 0.15-0.3U of space, and remain relatively costly [16].

A second major consideration for downlink wavelength choice is the price of large-format sensors in the optical ground station. Higher wavelengths (above 1100 nm) require the use of significantly more costly Indium-Gallium-Arsenide (InGaAs) sensors. While smaller sensors, such as the InGaAs quadcell aboard PULSE-A, remain cost-effective, CMOS-size sensors for initial tracking in the optical ground station are not. PULSE-A employs a 785 nm downlink to allow the optical ground station to use silicon based sensors, which are more widely accessible and almost two orders of magnitude less expensive. While the atmospheric losses are worse for 785 nm as opposed to 1550 nm, the PULSE-A team has calculated that the system performs as desired with a laser of this wavelength, despite increased losses. Further justification is provided in Section B.1.6. Transmitter Subassembly: Link Budget.

Lastly, PULSE-A plans on using a COTS ACDS system, with a flight-proven, blind pointing accuracy of ± 1°. This results in the same derived values as Kingsbury, where the fine pointing capability must be at least ± 1.05 mrad. To meet this requirement, PULSE-A elects to use a fast/fine-steering mirror, the details of which are described in the following section.

B.1.2. Optical Subassembly: Implementation

PULSE-A's scientific payload consists of a central Optical Path within which the Uplink and Downlink beams propagate. The uplink beam begins at the optical ground station, while the downlink originates from PULSE-A. The optical path (Figure B.1.1) consists of the following components, listed in order starting in free-space and ending within the body of the spacecraft.

1. Beam Condenser: The beam condenser consists of a 25.4 mm diameter Plano-Convex Lens with a focal length of 50 mm and a 9 mm diameter Plano-Convex Lens with a focal length of 12 mm.
2. Fast Steering Mirror (FSM): The FSM is a micro-electromechanical systems device which contains a small (6.4mm diameter) mirror that can be tilted by applying a voltage. This allows for greater than ±1° pointing of the downlink laser.
3. Bandpass Filter: The bandpass filter is a 12 mm diameter Hard-Coated NIR Bandpass Filter that filters out light in the 200-1530 nm and 1570-1700 nm range.
4. Dichroic Mirror: The Dichroic Mirror is a 12.7 mm diameter Longpass Dichroic Mirror with a cut-on wavelength of 900 nm. The DM will reflect wavelengths below 900 nm and transmit wavelengths above 900 nm.
5. Focusing Mirror: The Focusing Mirror is a 12.7 mm diameter Plano-Convex Lens with a focal length of 14 mm.

6. Quadcell: The quadcell is a 1 mm diameter segmented InGaAs photodiode sensitive from 900 nm to 1700 nm.

The downlink beam is generated and modulated by the transmitter subassembly, described in further detail below. Following the transmitter subassembly, the downlink beam enters the Optical Path via a Pigtailed Aspheric Collimator and subsequently reflects off of the Dichroic Mirror, onto the FSM and is directed outward through the Beam Condenser. The uplink beam enters the Optical Path through the Beam Condenser, is collimated onto the FSM, and then reflected and transmitted through the Dichroic Mirror and onto the quadcell. By tilting the FSM, we move the position of the uplink beam on the quadcell, providing feedback as to the pointing of the downlink beam.

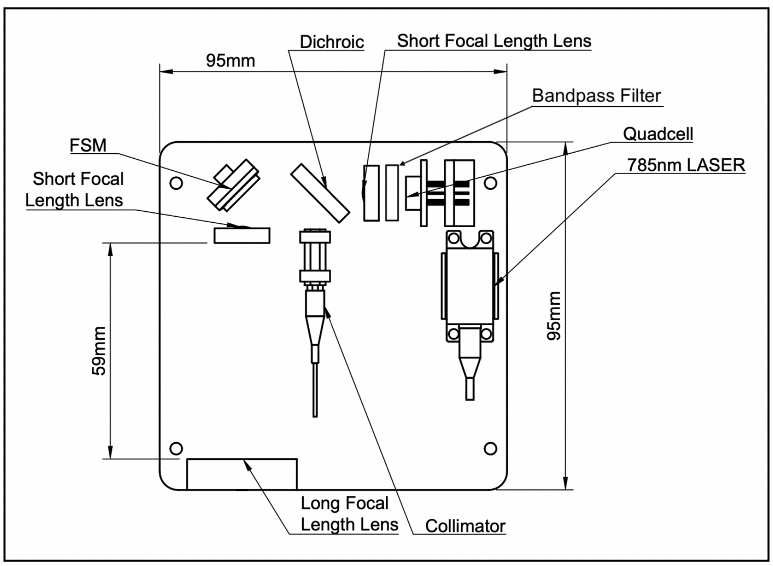

Figure B.1.3: Optical Subassembly Layout

In order to confirm that the chosen optical layout provides for the necessary pointing and aperture requirements, the system was constructed and simulated in Zemax OpticStudio. Lens information was taken directly from the manufacturers. Figure B.1.6 shows an overview of the Zemax recreation. Assuming an initial state where the FSM maintains a near-exact 45° angle with respect to the incoming light, Zemax confirms that the beam condenser, FSM, dichroic, and focusing lens properly direct the beam onto the quadcell.

B.1.3. Optical Subassembly: References and Simulations

The current optical subassembly is designed based on two major technical references: MIT's research for the CLICK-A (previously NODE) mission [17], and separate work by the German Aerospace

Center (DLR) on the PIXL-1/OSIRIS4CubeSat mission [13]. Both systems retain similar characteristics to ours, including similar laser power, beam divergence, and FSM-based pointing. PULSE-A elects to follow DLR in the use of a monostatic design, where the satellite relies on a single, near field-of-view (NFOV) quadcell to detect and then provide pointing feedback on the downlink and uplink beams. By comparison, CLICK-A originally elected to use a bistatic design, where both a NFOV quadcell and a wide field-of-view beacon camera are used to view the uplink beam [18]. This was later changed to have no near-field component, and CLICK-A was launched with a singular 10° FOV CMOS-based camera [19] .

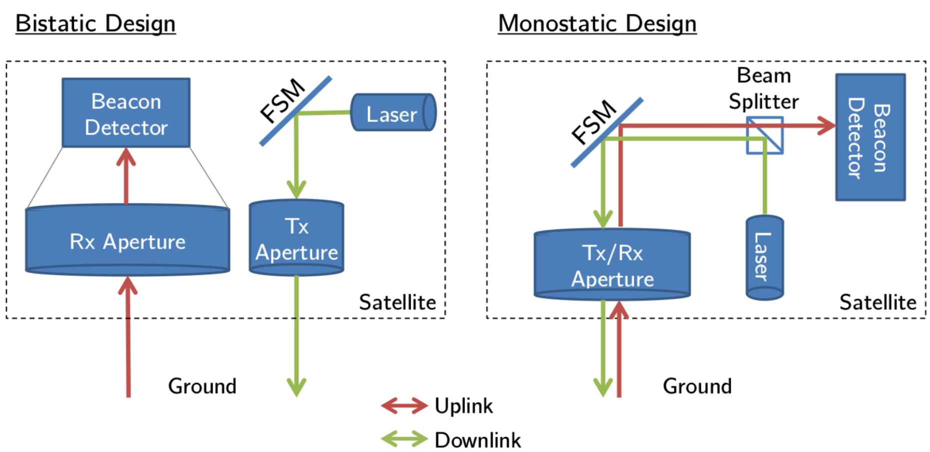

Figure B.1.4: Monostatic vs. Bistatic Architectures [18]

To confirm the expected physical properties, the Optical Setup was simulated in Zemax OpticsStudio. The system was reconstructed using basic calculations as to the focal length and size constraints of the layout. Testing in Zemax confirmed the ability of the FSM to correct for >1° of body pointing error. Additionally, due to spacing between the quadrants of the quadcell, the system must focus the uplink beam to an approximate 0.5 mm diameter, allowing for all four quadrants to excite when the FSM has correctly recentered the incoming beam. Testing in Zemax also confirmed that the focal length and placement of the focusing lens allowed for this constraint to be met, as can be seen in Figure B.1.5 and Figure B.1.6, the latter of which demonstrates a general overview of the simulated setup. A comparison of a straight-on (0.0°) versus 1.1° body pointing error (implying that the uplink is received at an angle), and its effect on the quadcell is depicted in Figure B.1.7. This figure demonstrates that the quadcell provides the necessary resolution to distinguish between <1° differences in body pointing. The 1550 nm bandpass filter was not included in the Zemax simulation, but is expected to create minimal to no effective difference in focus and spot size. Further experimentation will inform where the filter will be placed in the system. Additionally, the quadcell has yet to be simulated with the necessary spacing between individual quadrants. The team plans to conduct more intense simulations in Zemax as the design progresses.

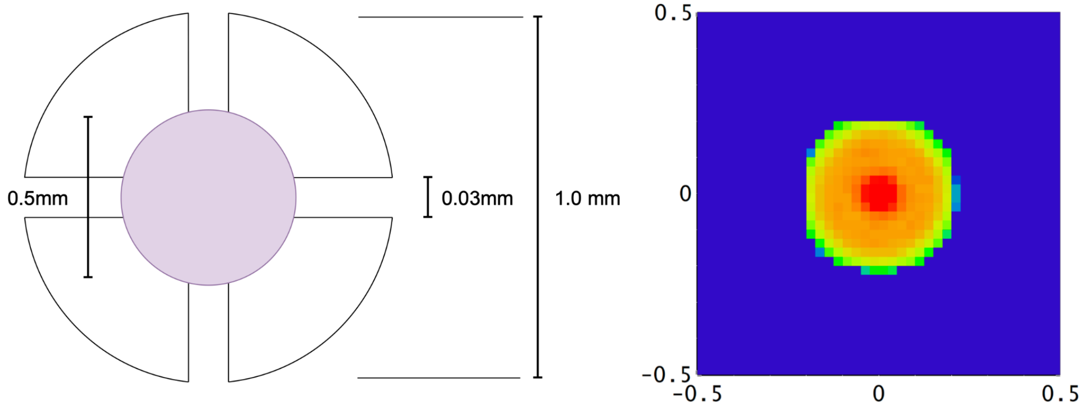

Figure B.1.5: Necessary Quadcell Beam Diameter vs. Zemax Simulation

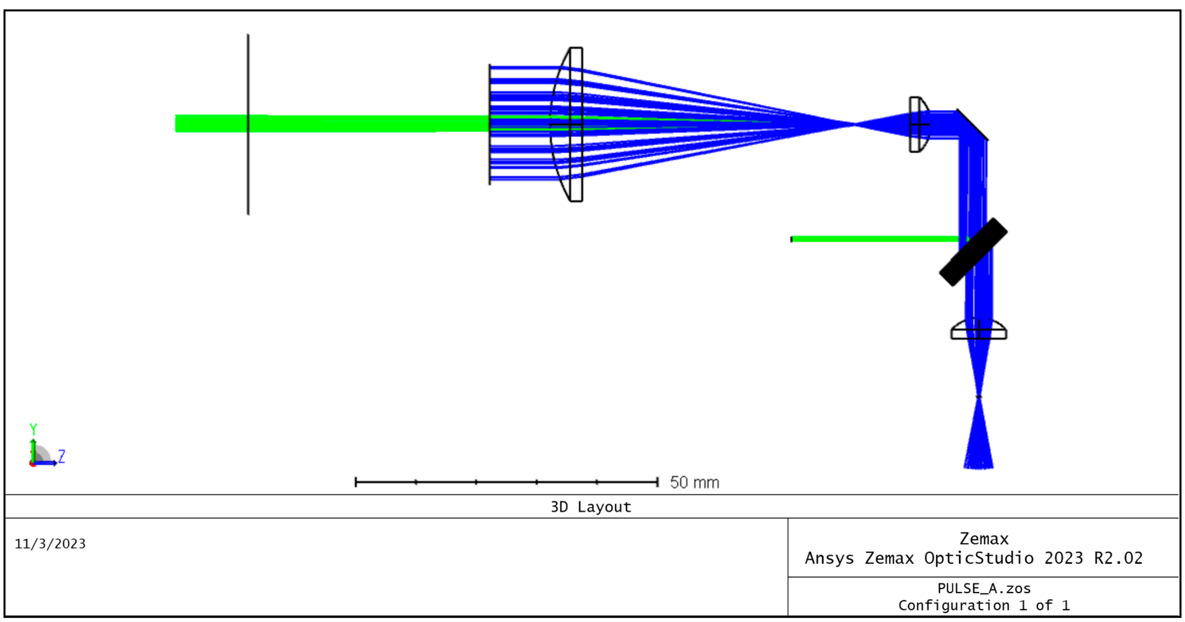

Figure B.1.6: Zemax Optical Simulation

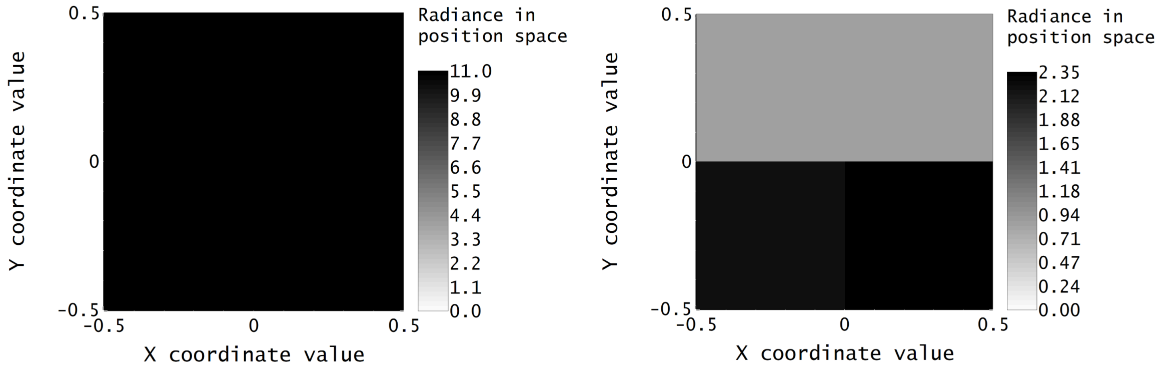

Figure B.1.7: 0.0° versus 1.10° Body Pointing Error - Quadcell

B.1.4. Transmitter Subassembly: Design Requirements

The transmitter subassembly is designed mainly to the constraints of the KTP Phase Modulator used to circularly polarize the transmitted beam. Requirements for the subassembly were therefore based on fiber-coupled KTP Phase Modulators from AdvR Inc., configured as a Pockels rotator. The choice of a polarization modulator of this type, as compared to the more common Lithium-Niobate ($LiNbO_3$) phase modulators, or alternative Pockels cell polarization modulators is twofold. Firstly, $LiNbO_3$ modulators have significantly lower input power limits, thus the output laser power of the transmitter subassembly, and in turn the payload's required power, is greatly reduced. Second, Pockels cells have substantially higher half-wave voltage requirements, on the order of 100-1000+ V, as compared to the 5-10V inputs on KTP Phase Modulators. Lastly, KTP modulators rely on very narrow spectral width inputs (<0.1 nm), which informs our choice of a Fiber Bragg Grating (FBG) stabilized source laser. While we remain in discussion about KTP Phase Modulators with AdvR Inc., we are also in the process of considering other electro-optic modulation techniques, including resonant modulators that may allow higher input power limits and significantly lower voltage requirements using $LiNbO_3$ crystals, but would require in-house construction of the fiber to free-space connections.

Polarization keying itself was chosen to transmit data for its applicability to QKD, better resistance to atmospheric turbulence, and increased data transmission efficiency due to the 100% duty cycle.

B.1.5. Transmitter Subassembly: Implementation

Transmission begins with the production of the beam using a 250 mW 785 nm Fiber Bragg Grating stabilized laser diode, connected to polarization-maintaining (PM) fiber. In the current design, this fiber is routed into a fiber-coupled KTP Phase Modulator which will induce a right circular or left circular polarization based on a modulated input signal. The modulator is driven by an RF signal generator which is amplified to the 8 V half-wave voltage. The polarization of this light therefore defines the bases for our 0 and 1 bits. The polarized light is then collimated out of the fiber and into the optical subassembly.

By modulating the polarization of the transmitting beam, the optical ground station detects bits in a similar manner to on-off keying (OOK), detecting 0 and 1 bits based on their polarization, rather than requiring the absence of a photon, or pulses, to represent individual bits.

We are currently planning on using a COTS solution for RF signal generation and amplification, though we intend to research, build, and test a single-board solution for vertical compactness. As previously mentioned, we are currently in contact with AdvR Inc. who would be capable of manufacturing our phase modulator.

B.1.6. Transmitter Subassembly: Link Budget

To confirm the viability of our downlink data transmission, a link budget was calculated based on our input laser power, known losses, estimated losses, and constrained ultimately by the sensitivity of the optical ground station's detector sensitivity.

Table B.1.1: Optical Communication Link Budget

Transmitted Power (dBm)	23.98
Polarizer Loss (dB)	-5.00
Transmitting Gain (dB)	70.46
Free-space Loss (dB)	-262.15
Receiving Gain (dB)	120.41
Misc. Loss (dB)	-15.00
Received Power (dBm)	-67.30
Detector Sensitivity (dBm)	-80.00

Misc. Loss is an estimate combining telescope transmission losses, atmospheric losses, and other losses from similar laser communication setups. With a margin of 12.7 dB we are confident that this preliminary link budget indicates that we will be able to successfully transmit and detect data [1]. While not as accurate as is possible to simulate, we intend to more rigorously define the link budget using the AMSAT/ISRU Standard Link Budget System [20].

We have roughly confirmed these estimates using Ansys STK, which has confirmed that PULSE-A will have continuous intervals up to two minutes long where the intensity of the incoming light is greater than the sensitivity of the detector, given our laser parameters for both the optical ground station and PULSE-A (cf. Appendix B.9.)

Additionally, the effects of atmospheric attenuation were considered while selecting the wavelength of the laser. Ultimately, it was decided that while we would suffer increased loss due to atmospheric effects due to the lower wavelength of 785 nm, the increased loss in clear air was marginal (5.5 dB in clear air for 785 nm vs 2.2 dB in clear air for 1550 nm). Furthermore, calculations performed by Kim et al. 2015 [21] show that as weather conditions deteriorate (as we expect them to during the Midwestern winter), the gap in losses between the two wavelengths narrow even further. We note that usage of a 785 nm downlink allows for the use of Silicon-based CMOS tracking cameras, which are far cheaper than cameras designed for 1550 nm which must use expensive InGaAs detectors. Since one of the primary objectives of PULSE-A is to reduce the costs associated with space-to-ground optical communication, this cost saving was one that could not be ignored. Our feasibility reviewer, [REVIEWER 2] also suggests 785 nm for its resilience against having its polarization state be distorted due to air turbulence.

B.2. Ground Station

B.2.1. Optical Ground Station Overview

The optical ground station receives the encoded laser transmission signal from PULSE-A. It separates the incoming photons based on polarization, which separates bits reading 0 from bits reading 1, then detects the separated bits to record transmitted data. The optical ground station is essential to PULSE-A's primary and secondary mission; by operating a polarization-based optical ground station, we are establishing a simplified version of the ground station that would be needed for an eventual CubeSat to perform QKD in a downlink. Transitioning the optical ground station to a QKD setup would require minimal changes.

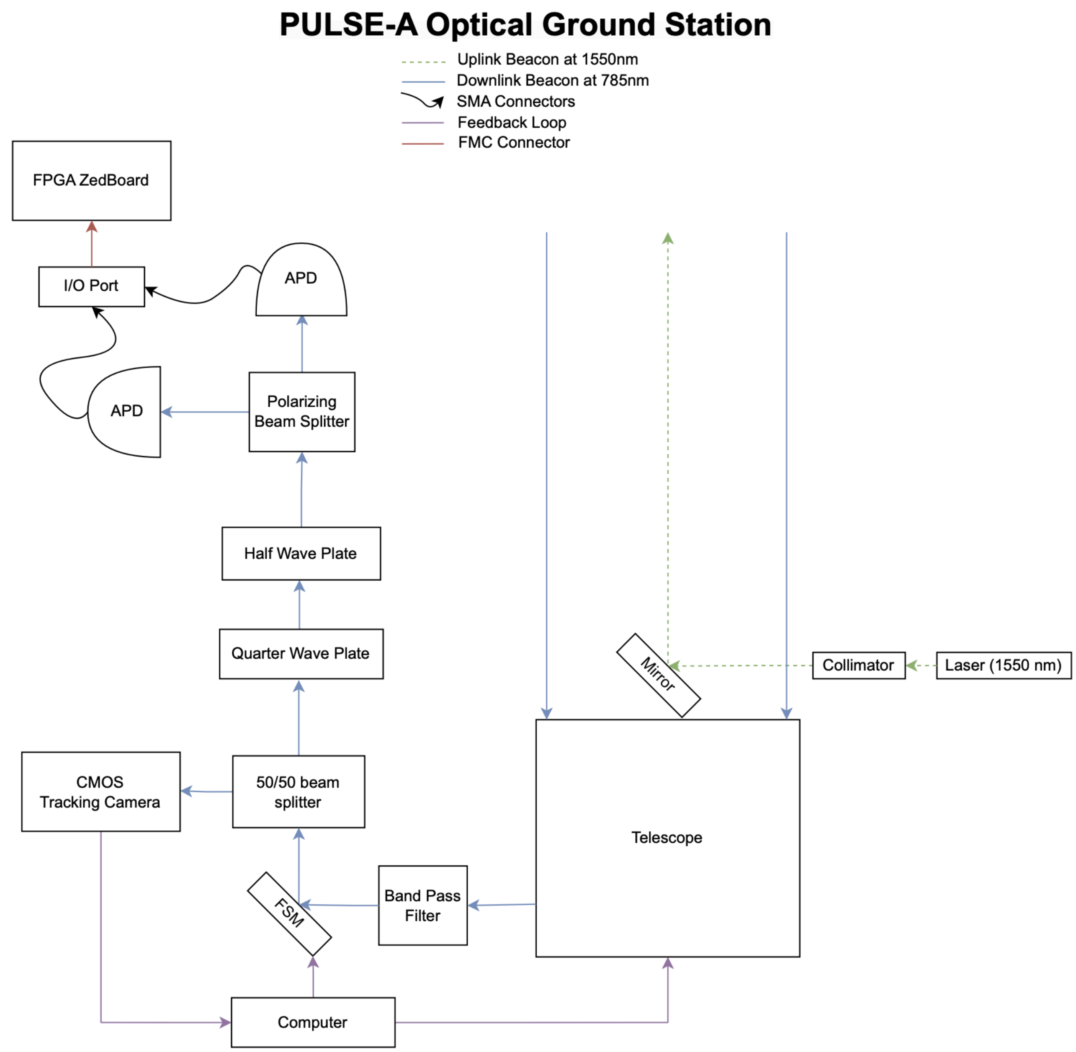

Figure B.2.1: PULSE-A Optical Ground Station

PULSE-A will utilize a combined RF-Optical ground station. The RF portion of the ground station will receive telemetry data from an antenna onboard PULSE-A, and provide a robust communication uplink to the satellite. The ground station will then establish an optical link with the satellite through a laser uplink beacon attached to the ground station. The team will be working with the FAA to obtain a no-objection letter for the ground station, which utilizes a 5 W laser at 1550 nm. The team is actively working on alternative sites for the ground station (such as Yerkes Observatory in Williams Bay, Wisconsin) if there are safety concerns that cannot be avoided by having the ground station on-site at the University of Chicago.

Inside the telescope, a 5 W, 1550 nm laser is first collimated, then directed at a mirror and reflected into free space in alignment with the telescope's direction. This laser beam serves as the beacon directed into

PULSE-A's aperture. The telescope's tracking capabilities provide the beacon with coarse and fine pointing. PULSE-A has a pointing feedback loop where the beacon's incoming beam is directed into the quadcell, and the optical ground station has a pointing feedback loop where the transmission's incoming beam is directed into the CMOS Tracking Camera. These feedback loops are shown in Figures B.2.1 and B.1.1, respectively.

The optical ground station receives the circularly encoded laser transmission signal from PULSE-A through an 8 inch telescope. After being focused, the downlink beacon is passed through a bandpass filter to get rid of photons with undesired wavelengths, reducing noise, then directed into a fast steering mirror. The beam is then split by a 50/50 beamsplitter into the CMOS tracking camera which is in a feedback loop with the FSM, and into a quarter wave plate to linearly polarize the circularly polarized light. This linearly polarized light is sent through a half wave plate which will rotate the polarization of our beam to allow it to be sent into a polarizing beam splitter. It is important to emphasize that the connection between the half and quarter wave plates requires precision, a factor achievable through meticulous calibration on an optical bench in a controlled laboratory setting along with extensive modeling in Zemax. Furthermore, any misalignment can be rectified during ground operations. Then, the optical ground station will then utilize the polarizing beam splitter to separate left and right circularly polarized light into two APDs.

Depending on the polarization of the light, the APDs will receive a signal, allowing for 0 and 1 binary inputs. These binary inputs will be transmitted through an I/O Port to an FPGA that will be programmed to time tag incident photons.

The current FPGA plan is designed based on technical reference to The University of Padua's paper on High Performances Systems for Applications of Quantum Information [22]. In this paper, an FPGA designed for time-tagging purposes was able to achieve an overall time precision of ~17.9 ps which is more than suitable for the detection rate of 10 Mbps [22]. We plan to modify and simplify the design slightly to use a singular FPGA programmed to time tag the two inputs from the APDs, connected to the FPGA through an I/O port board. The FPGA used in our technical reference had a sampling rate of 100 MHz for a single input, implying that an FPGA setup with two inputs should generate a sampling rate of at least 50 MHz. Our single layer time tagging system would result in a high information generation rate which well exceeds the 10 Mbps transmission goal.

Through the use of the APDs and FPGA programmed to time-tag each photon, the optical ground station will record transmitted data. The individual components of the optical ground station are described in greater detail in the following section.

B.2.2. Optical Ground Station Components

The optical path in the optical ground station consists of the following components in order, entering the first component from free space:

1. Telescope: The Celestron CPC 1100 GPS Computerized Telescope will track PULSE-A across the sky with a maximum slew speed of 5º per second using a GPS signal transmitted from PULSE-A to the RF ground station. The telescope contains a primary convex mirror with a 27.94 cm diameter, and it focuses the transmission signal into a fast steering mirror.
2. Bandpass Filter: The incident beam is directed into a bandpass filter to reduce noise from outside sources, allowing only the downlink frequency to go through.
3. Fast Steering Mirror (FSM): The fast steering mirror directs the downlink beam into a 50/50 beamsplitter. It is in a closed loop with the tracking camera in order to more accurately direct the downlink beam.
4. 50/50 Beamsplitter: Splits the incident beam so half of the beam is transmitted to the Quarter Waveplate, and the other half is reflected to the CMOS tracking camera. The 50/50 beamsplitter preserves polarization, so transmitted bits are unaffected in polarization
5. Tracking Camera: The CMOS tracking camera receives information from the downlink laser. It is in a closed feedback loop with both the FSM and the telescope in order to accurately aim the uplink beacon towards the satellite.
6. Quarter Waveplate: The quarter waveplate takes circularly polarized light as its input and outputs linearly polarized light. The 0 bits and 1 bits will be shifted to ±45°, respectively.
7. Half Waveplate: The Half Waveplate is used to shift the direction of the linearly polarized light. This will shift our ±45° to 0° and 90°, respectively.
8. Polarizing Beamsplitter (PBS): The PBS separates the transmission signal by polarization. Since our transmission signal has data encoded through polarization, the PBS effectively separates bits that read 0 from bits that read 1.
9. Avalanche Photodiodes (APDs): After the PBS separates the transmission signal into 2 output paths, each path reaches a silicon APD. The APDs turn the incoming photons into electrical signals. The electrical signal from one APD represents a 0 bit, and the electrical signal from the other APD represents a 1 bit.
10. FPGA Set-up: Each APD is connected through SMA wires to an I/O port board. This board is connected through an FMC (LPC) connector to a ZedBoard Zynq-7000 FPGA. This FPGA can be programmed for time tagging of the incident beam with a time precision of approximately 17.9 ps [22]. By connecting the FPGA to the optical ground station's APDs, the APDs' electrical signals can be accurately strung together to record the data transmitted through the optical link.

B.2.3. RF Ground Station

The RF section of the ground station will communicate with PULSE-A's RF antennas taken from the Artemis bus kit. Artemis uses a fairly standard HopeRF RFM23BP modular radio, which the RF section will receive the RF downlink and transmit to the satellite using ISM band 915 MHz. The transceiver on the ground will use a COTS cross Yagi antenna for communication.

As PULSE-A uses an RF communication system from the Artemis CubeSat project, which has had relatively extensive testing, we have yet to complete a comprehensive radio-frequency link budget analysis.

B.3. PAT Sequence

B.3.1. Optical PAT Sequence

The PULSE-A PAT sequence involves a two-step process. PULSE-A utilizes an open-loop control scheme until the uplink beacon is acquired, at which point it switches to closed-loop control, where blind body pointing error is corrected for by the onboard FSM.

B.3.1.1. Open-Loop Sequence

The open-loop sequence is initiated in both the optical ground station and on PULSE-A during the approach to any upcoming pass. PULSE-A will begin its open-loop pointing sequence at or just before initial RF communication. Given the required ground station elevation constraints, this sequence points the downlink laser at the expected location of the optical ground station well before the ground station is able to make line-of-sight contact with the satellite itself. This is confirmed with pass simulation in Ansys STK, where average pass length, including time for first alignment, results in well above two minutes of transmission time (cf. Section B.9.).

The open-loop sequence continues until the uplink beacon is acquired, at which point the closed-loop sequence is initiated. In the case that the uplink beacon is not acquired with blind pointing, a constant velocity Archimedes spiral scan is initiated, during which the FSM is actuated to an increasing degree in order to redirect more intense uplink beam angles onto the quadcell. This sequence is designed with reference to the MIT NODE/CLICK-A PAT Sequence defined in Nguyen, et al 2015 [23] and the Space Development Agency's Optical Communication Terminal Standard [24]. If the uplink beacon is not acquired after the scan pattern is completed, the open-loop sequence is re-initiated and the scan pattern will be re-run. A similar open-loop sequence will be used in PULSE-Q.

B.3.1.2. Closed-Loop Sequence

The closed-loop sequence is initiated when the uplink beacon is detected on at least one quadrant of the quadcell. At this point the FSM halts the scanning pattern, if started, and initiates actuation routines in feedback with the quadcell to center the uplink beam on the sensor. Based on data from STK, the maximum slewing rate for both the optical ground station and PULSE-A during predicted passes are well below their conservative maximum rates (2.5 deg/s for the optical ground station, 2 deg/s for PULSE-A).

The closed-loop control will be initiated based on feedback from the quadcell. Refer to Appendix B.1.2. for details on this loop. This system will provide the pointing accuracy necessary for PULSE-A's link budget. Once the beacon is focused at the center of the quadcell, the data transmission sequence will be initiated.

Total loss of the uplink beacon will lead to re-initiation of the open-loop sequence as described.

B.3.2. RSS Determination

The total pointing accuracy will be calculated using the residual sum of squares (RSS) of each source's constituent errors [19].
(*Sections* and *subsections* are italicized while final constituents are not)

- *Body Pointing Error* - ±1° 3-σ from manufacturer
    - *Pointing Accuracy*
        - Sun Sensor - manufacturer spec (0.3° 1-σ) [25]
        - Earth Sensor - manufacturer spec (0.2° 3-σ) [26]
        - Magnetometer - Bosch BNO055 [27]
    - Reaction Wheels - manufacturer spec (Momentum at 6000 rpm: 1.77 mNms) [28]
    - Magnetorquers - manufacturer spec (Minimal Magnetic Moment: 0.2 Am^2)[29]
    - *Alignment Error*
        - Calibration - lab measurement
        - *Environment*
            - Thermal - thermal analysis

                - Launch - vibration testing
- *FSM Pointing Error*
    - Quadcell Error - lab measurement
    - *Alignment Error*
        - Calibration - lab measurement
        - *Environment*
            - Thermal - ANSYS Thermal Desktop / ANSYS IcePak
            - Launch - vibration table testing

Much of our pointing accuracy has not yet been accurately determined as it will either come from lab measurements or more in-depth software analysis. From preliminary optics analysis in Zemax, we are confident that our manufacturer-specified body pointing accuracy will be sufficient to transition to closed-loop FSM pointing. FSM pointing will ultimately bring our beam pointing to the order of milliradians, which satisfies our link budget requirements.

B.3.3. RF PAT Sequence

On each pass, the ground station will orient itself towards the calculated position of the satellite based on the current ephemeris. This will be updated with the most recently received GPS position from a previous pass when necessary.

The RF PAT sequence is established based on documentation from the Artemis system. Due to the proven nature of this system, this section is not discussed in greater detail. Further specifics will be determined in ongoing conversations with Hawaii Space Flight Laboratory.

B.4. ADCS

Design Specification Requirements

(a) Determination requirement of $\pm 1°$body pointing accuracy needed for quadcell detection
(b) Slew rate in x, y, z axes is 2 deg/s, shows to be suitable to acquire a laser connection as show in STK modeling in B.8
(c) Size, weight, and power margains

From the design specification dictated by the mission requirements, our team did extensive modeling in Ansys STK to stimulate fly-overs and relevant slewing maneuvers which are described below in Appendix B.9. SEDS-UChicago then selected components to construct a suitable ADCS based on the aforementioned requirements and demonstrated stimulations.

For pointing determination, PULSE-A will utilize an Earth Sensor and a Sun Sensor which have accuracies of 0.2° 3-σ and 0.3° 1-σ, respectively. These sensors will be bought from CubeSpace and AAC Clyde Space, respectively, and both components have significant flight heritage. PULSE-A will also have a GPS sensor from the Artemis kit and an on-board magnetometer with a built-in accelerometer.

To accomplish detumbling and the fast slewing requirements necessary for a pointing acquisition, PULSE-A will have 3 magnetorquers and 3 reaction wheels. The magnetorquers and the reaction wheels will be sourced from CubeSpace. Both components have extensive flight heritage. The selected magnetorquers have a minimal magnetic moment of 0.2 Am^2[29]. The reaction wheels, at 6000 rpm, have a momentum of 1.77 mNms [28]. The pointing and fast slewing and also described in the RSS determination in Appendix B.3.2.

B.5. Artemis Integration

As part of our goal to make PULSE-A an open-source project, the satellite's bus will be heavily based on the University of Hawai'i at Manoa HSFL's Artemis 1U Kit, which we will modify for our specific scientific payload, power requirements, and overall goals. The list of components implemented from the kit includes:

- Structural components (aluminum frame, metal rods, fasteners, and bolts)
- Power generation and storage components (lateral solar panels, battery boards, PDU)
- Radio communication components (antenna board)

Frame integration from 1U to 2U will be facilitated by buying a 2U frame and importing the relevant components from Artemis as described below.

In order to meet the power requirements of all on-board systems, PULSE-A doubles the number of batteries (from one to two boards), increases the number of solar panels (from four lateral to seven, with an additional custom-made top solar panel, as well as modified lateral solar panel implementing a window element for the Optical Assembly). Implementation of the power system will be facilitated through the design of a custom power distribution board.

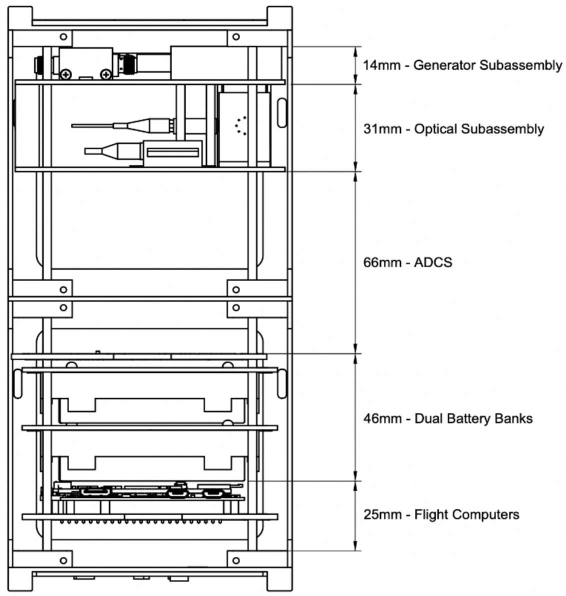

Figure B.5.1 Vertical Drawing showing Sub-Assemblies

The final main custom component we will be redesigning is the on-board computer. The on-board computer will handle radio communication, ADCS, and control of the scientific payload (including laser generation, pulse modulation, fast-steering mirror control and quadcell readout). These tasks will be split between multiple programmable microcontrollers.

B.6. Mass Budget

Table B.6.1: Mass Budget

Subsystem/Component	**Quantity**	**Mass per (g)**	**Total Mass (g)**
Scientific Payload	1	430	430
Battery Assembly	2	250	500
Solar Panel	9	45	405
Flight Computer Assembly	1	150	150
Frame	1	260	260
ADCS	1	290	290
Fasteners, Wires, etc.	-	-	100
Contingency	-	-	265
Total Mass			**2,400**

PULSE-A's second battery bus is a redundancy measure intended to produce the longest possible transmission link during a given pass. PULSE-A's operations could be carried out successfully without the second battery bus; in the event that the total mass must be reduced, the second battery bus could be removed for a new total mass of 2,150 g.

B.7. Power Budget

PULSE-A will utilize two distinct Artemis power banks facilitated by a custom Power Distribution Unit. One battery bus will power the Artemis spacecraft and subsystems (Flight computers, etc.) as well as the ADCS system. The second battery bus will power the optical payload and respective subsystems.

Each Artemis battery bus consists of four Samsung 18650-35E Lithium Ion Batteries in a 2-series, 2-parallel configuration. Each battery has a capacity of 3500 mAh, giving each battery bus a capacity of 14,000 mAh, or approximately 50 Wh with a nominal voltage of 7.2 V out of the battery bus. The maximum draw is 8 A at 4.2 V, or 33.6 W.

The approximate power consumption of the Artemis system is a maximum 5 W during nominal flight (16 W during antenna deployment). Combined with a worst-case estimate of 5 W power draw for the ADCS system, which will only be activated during passes (a worst-case maximum of 15 minutes), the battery bus meets the needed instantaneous power draw requirements and capacity by a significant margin.

While it is likely that the entire system could be run off of a single battery bus, we are choosing to run the optical system off of its own battery bus for redundancy and margins sake. The following list describes every component with a significant power draw (> 0.01 W) as well as the duration they are estimated to be active. All values are worst-case estimates.

Table B.7.1: Power Budget

Component	Power (W)	Active Time (hrs)
Laser & TEC	10 W	0.1
Polarization Modulator & TEC	10 W	0.1
Signal Generator	0.5 W	0.1

Voltage Amplifier	0.5 W	0.1
High Voltage Amplifier Array	0.025 W	0.1

Assuming the unlikely case where all components are active for the same duration, the power draw would be 22 W, and with the active time of 0.1 hrs which we would expect with an average pass, it would be well within both the max draw and capacity limits.

An important consideration is that PULSE-A does not need the second battery bus. At this stage in development, it is being included for the sake of redundancy. Should it be found through testing, because of mass considerations or some other reason, that a battery bus needs to be removed, the power system will function as intended.

B.8. Risk Assessment and Mitigation

B.8.1. Risk Assessment

As part of the Risk Assessment, we have comprehensively done a Failure Mode and Effects Analysis (FMEA) for key systems in order to ascertain that there is redundancy where needed. The three tables below define the process that went into grading each potential failure mode for both likelihood and severity and the risk grading scale.

Table B.8.1: Likelihood vs. Severity Risk Level

		SEVERITY				
		1	2	3	4	5
LIKELIHOOD	1	1	2	3	4	5
	2	2	4	6	8	10
	3	3	6	9	12	15
	4	4	8	12	16	20
	5	5	10	15	20	25

Table B.8.2: Risk Level Rating Scale

Overall Risk Level Rating Scale			
1 – 5 Low Risk	6 – 10 Moderate Risk	11 – 15 High Risk	16 – 25 Very High Risk

Table B.8.3: Likelihood and Severity Descriptor

	LIKELIHOOD DESCRIPTOR	SEVERITY DESCRIPTOR
1	The likelihood of the failure mode is estimated as extremely low or has never been experienced in similar missions. Only occurs in 0.1% of similar cases.	No vital subsystem is affected by any failure.
2	The likelihood of the failure mode is estimated as low, or it has been experienced once in similar missions. Could occur in 1% of similar missions.	One (or more) component(s) are affected by failure, but the system can overcome that failure through redundancies or other subsystems.
3	The likelihood of failure mode is estimated as moderate, or it has been experienced twice in similar missions. Could occur in 5% of similar missions.	One subsystem is completely inefficient, but the mission is still active by means of another subsystem, eventually cutting off operations not vital for mission purposes.
4	The likelihood of the failure mode is estimated as high, or it has been experienced several times in similar missions. Could occur in 10% percent of similar missions.	One (or more) component(s) are affected and the mission is partially compromised in terms of efficiency, limited operations, or lifetime.
5	The likelihood of failure mode is estimated as extremely high, or it has been experienced in almost every single mission. Expected to occur.	Mission is totally compromised.

Table B.8.4: Failure Modes

Risk #	Potential Failure Mode	Potential Cause(s)	Potential Effect(s)	Likeli-hood Rating (1-5)	Severity Rating (1-5)	Risk Level Rating (1-25)	Accep-table?	Mitigation Plan
1	Flight Computer	Software failure	Inability to perform maneuvers	1	5	5	YES	Watchdog timer inconsistencies will cause computer reboot
2	No Acquisition for a Given Pass	Poor ground seeing conditions, scheduled/ unscheduled ground station or payload downtime	Inability to form optical connection	5	1	5	YES	Can retry acquisition at next pass over ground station

3	Acquisition Impossible on Any Pass	Optical alignment failure, optical ground station or payload failure	Inability to form optical connection	2	5	10	YES	Test optical systems extensively in payload prototype, will conduct a long-range (multiple km) test in rural IL to test quadcell
4	Attitude Determination Failure	Sensor failure	Inability to detect orientation	1	4	4	YES	Use components with flight heritage; design and test extensively
5	Attitude Control Failure	Magnetorquer /Reaction wheel failure	Inability to point	2	4	8	YES	Use components with flight heritage; design and test extensively
6	Quadcell Pixel Failure	Solar Radiation	Pointing accuracy decreased	2	4	8	YES	¼ redundancy with ¾ pixels being able to detect with reasonable accuracy; bandpass filter reduces excess light on quadcell
7	Mounting Point/Optical Alignment Failure or Lens Crack	Launch vibration causes damage to optical subassembly	Unable to point transmission or pointing accuracy decreased	2	5	10	YES	Extensive vibration tests to be carried out
8	Software Corruption	Memory Deterioration	Inability to perform maneuvers	3	2	6	YES	Boot with backup memory space; update flight software in-flight
9	Thermal Instability	Components not properly shielded	Operations outside of absolute maximum operating temperature range	2	4	8	YES	Test in thermal vacuum chamber
10	RF Communicati-on Failure	Antenna Failure	Inability to establish RF communica-	2	5	10	YES	Use components with flight heritage; design and test

			tion with PULSE-A					extensively
11	Radiation Hardware Failure	High degree of radiation dosage	Electronic deteriorat-ion; oversaturat-ion	2	5	10	YES	Proper shielding and orientation of payload reduce the likelihood of radiation-induced failure; reboot detector if occurs

Table B.8.5: Risk Numbers Plotted on Likelihood vs. Risk Level Chart

		SEVERITY				
		1	2	3	4	5
LIKELIHOOD	1				4	1
	2				5, 6, 9	3, 7, 10, 11
	3		8			
	4					
	5	2				

B.8.2. Flight Heritage

Although the PULSE-A system has never been flown before in its entirety, many subsystems have elaborate flight heritage and/or extensive documentation.

The Artemis CubeSat Kit, which we are iterating on, was developed by the University of Hawaii Mānoa after a $500,000 grant from NASA. Although the Artemis kit has not been flown before, all of its subsystems have been intensively tested, documented, and distributed to many universities across the country. As a result, we have high confidence in the subsystems that we are utilizing from this platform, which include the structure, flight control boards, battery boards, antenna systems, and solar power generation systems.

The ADCS will be utilizing entirely COTS, and has undergone extensive testing as well as flight heritage. All ADCS components are from CubeSpace or AAC Clyde Space which have extensive heritage. Because the ADCS system is incredibly important to the mission, utilizing a well-tested, flight-proven COTS solution was an important choice for risk reduction.

B.8.3. Minimum Mission

PULSE-A's minimum mission is to establish a laser transmission from the scientific payload to the optical ground station, so the ADCS and PAT sequence are of utmost importance. Our payload must accurately connect with the laser beacon uplink from the optical ground station, thus enabling the ADCS to steer the satellite within 1° of accuracy for coarse pointing and tilt the FSM up to 4.25° for fine pointing. Considering the effects of PULSE-A's beam condenser, simulations in Zemax have demonstrated that the FSM provides roughly 2° of pointing redundancy.

PULSE-A will use attitude determination sensors and control actuators that have been flown on several missions before (the team is currently in active communication with CubeSpace and AAC Clyde Space, both reputable ADCS manufacturers). This provides us with a proven system that has been rigorously tested both on the ground and in previous missions. PULSE-A's GPS system will allow the optical ground station to locate the satellite's position. The uplink beacon will then point to the location given from the GPS data. As the ground station detects the downlink laser, a tracking camera will be fed that data to lock-on to the satellite. The PAT sequence is described in more detail in Section B.3. During PULSE-A's development phase, we will thoroughly test our optical system to ensure that the pointing system works as intended.

It is anticipated that acquisition will not occur on every pass. In the Ansys STK simulations detailed in Appendix B.9., we demonstrate that we have a surplus of viable passes compared to what can be accommodated within the power constraints imposed by charging the solar panels. Consequently, we will adopt a selective approach in determining which passes to target for acquisition. In the event that we do not achieve acquisition in a chosen pass, we will make subsequent attempts during the next pass over the ground station.

Our critical components include the solar layout, power system, microcontrollers, Earth tracker, arrangement of the scientific payload, and PAT sequence. If any of these systems completely fail, our mission will result in failure. Furthermore, if acquisition is impossible on every pass, our mission will result in failure.

B.9. Ansys STK Simulation

Ansys Systems Tool Kit (STK) is a multi-physics software that allows users to perform complex time-dynamic analyses of mission payloads. The PULSE-A team used STK to establish simulated flyovers of the CubeSat and to perform analyses of laser communication feasibility.

Using STK, the team simulated three months of flyovers, with the optical ground station located at Yerkes Observatory. Four separate inclinations were simulated for circular orbits at an initial altitude of 500 km, the results of which inform an ideal orbit choice of 45° at 500 km, using which maximizes the mean duration and number of viable passes.

Table B.9.1: STK Orbit Simulation Results

Inclination	Viable Passes	Mean Duration	Max. Duration	Min. Duration
45°	207	202.0 s	221.1 s	121.3 s
60°	102	178.4 s	218.1 s	120.1 s
80°	78	185.3 s	213.5 s	124.2 s
90°	82	184.4 s	211.0 s	125.1 s

Viable passes were decided based on the consideration of certain major constraints, including but not limited to:

1) Optical Ground Station Elevation Range between 30-90° above horizon.
2) Optical Ground Station Angular Slew Rate between 0-2.5 deg/s.
3) Optical Ground Station Received Optical Power > -80 dBm.
4) Passes must happen during umbra.
5) PULSE-A Angular Slew Rate between 0-1 deg/s magnitude on any individual axis.
6) PULSE-A Slew Maneuvers must begin after RF connectivity is established.

Conservative maximum angular slew rates were chosen based on torque values given in the datasheets for our expected COTS ADCS. The simulation confirmed that the given RF constraints allowed for ample time between RF signal acquisition and optical link acquisition, around 1-2 minutes. Ideal 45° inclination orbit provides consistent daily passes throughout the entire simulated three month period providing RF communication with the satellite. Night-time passes for optical link acquisition are consistent over approximate 20-day intervals, ranging from 1-4 viable passes on any individual night.

For around ten days in every month, the simulated orbit aligns itself with the day-night cycle to provide little to no night-time coverage.

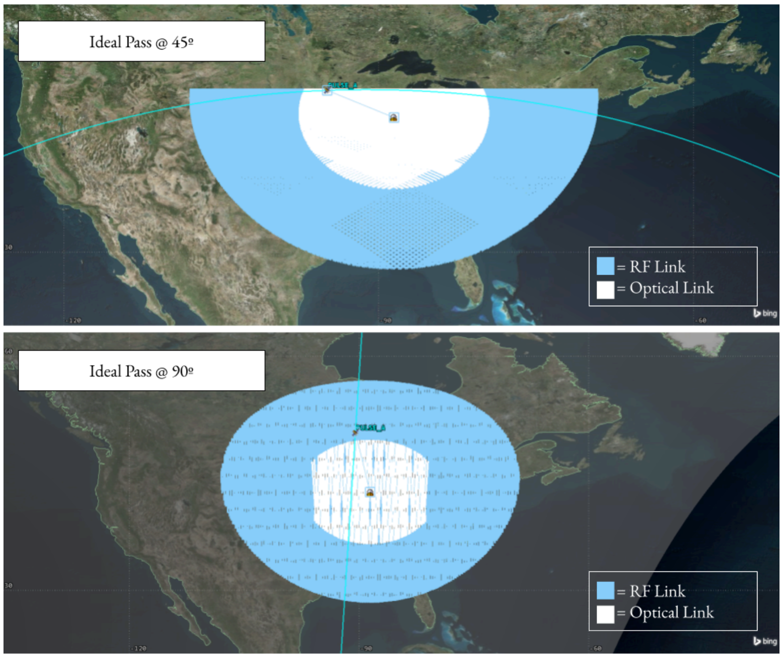

Figure B.9.1: Comparison of Simulated Inclinations

B.10. Justification of Development Schedule

Below is the same Gantt chart shown in Section 7.

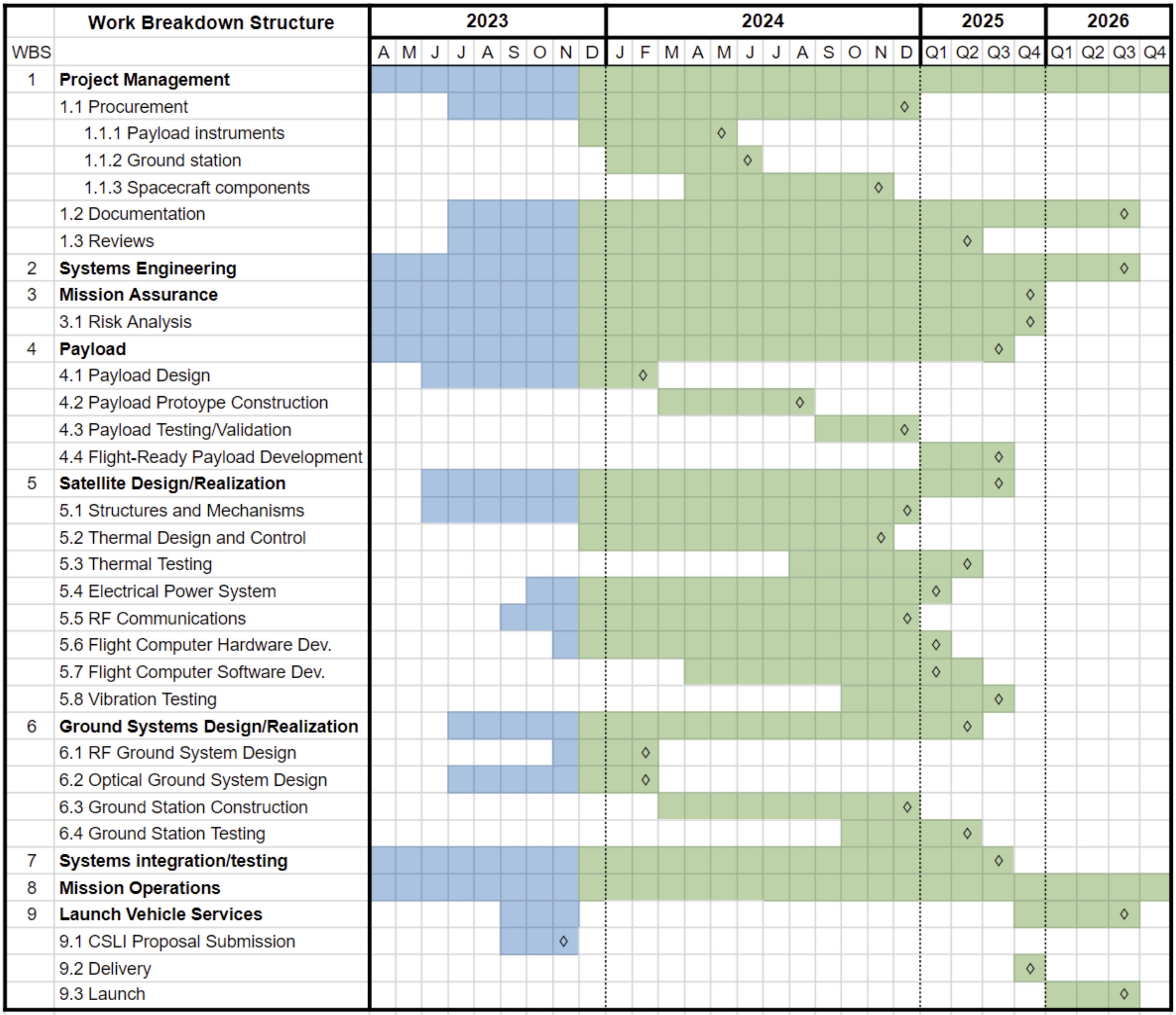

Figure B.10.1: Gantt Chart (The diamond symbols refer to an item's completion, blue denotes work done before the CSLI proposal submission, and green denotes work done after the CSLI proposal submission.)

Current work during Summer and Fall 2023 has been dedicated to writing the PULSE-A CSLI proposal and designing the Spacecraft Bus and Ground Systems.

From the proposal's submission through Q1 2024, the team will continue to finalize design choices for the optical ground station and the scientific payload. Procurement of necessary optical components for the payload (prototype and flight-ready model) will begin effective immediately as development of the payload is dependent on successful acquisition of such components, with certain components having longer lead times and needing prioritization. Initial development of the payload's prototype will be finished by August of 2024. Procurement of key ground station components will begin in January 2024 as the high powered ground-based laser has a long lead time. This will also give the team enough time to discuss ground station location options with potential hosts (such as Yerkes Observatory) before the acquisition process begins.

Following procurement, the focus will shift towards integration and construction of the optical ground station and onboard CubeSat systems. During this time, we will design the flight software for PAT, with this being something that would require a significant portion of time due to anticipated complexity of the software. We anticipate full-completion of the flight-ready satellite by Q3 2025, with vibration testing being slated for Q2 of 2025, with completion by Q3 of 2025. Extra time has been given for this to account for any potential failures during testing along with finalization of where testing will occur. Due to complexity of the software and the fact that this can only begin after the hardware has somewhat matured, we have provided an extra quarter for software development, with software being finalized by Q1 2025.

Ground station construction will begin by the end of Q1 2024, allowing for initial RF testing to begin towards the end of 2024, with optical testing to follow soon after.

The team plans to test the prototype payload in-lab during Q4 2024. The team plans to conduct its first longer-range tests of the optical system in the beginning of 2025, which would require the team to travel to a yet-to-be determined rural location in Illinois and set up the satellite and the ground station to test the PAT system. The ground system is designed to be portable and can be set up in a few hours.

We anticipate all other forms of testing to occur in Q2 of 2025. This would allow for a successful handoff in Q4 2025.

B.11. Detailed Budget

Table B.11.1.: Detailed budget with costs per component

Section	Item	Quantity	Part Price	Price	Totals
Pre-Construction	Software Costs			$0.00	
	Internal Marketing Costs			$0.00	
	Misc. Costs			$100.00	
				Total	**$100.00**
Bus	2U Frame	1	$1,500.00	$1,500.00	
	HSFL Artemis Kit	1	$2,500.00	$2,500.00	
				Total	**$4,000.00**
Power	Battery Assembly	1	$1,250.00	$1,250.00	
	2U Solar Panel Assembly	1	$3,750.00	$3,750.00	
				Total	**$5,000.00**
ADCS	Earth Sensor Gen 2	1	$6,800.00	$6,800.00	
	Sun Sensor SS200	1	$2,200.00	$2,200.00	
	Bosch BNO055 (IMU + Magnetometer)	1	$29.95	$29.95	
	Reaction Wheels CW0017	3	$4,346.00	$13,038.00	
	Magnetorquer CR002	3	$696.00	$2,088.00	
				Total	**$24,155.95**
Scientific Payload	785 nm Laser	1	$2,132.43	$2,132.43	
	Polarization Modulator	1	$4,000.00	$4,000.00	
	Voltage Amplifier	2	$120.61	$241.22	
	Signal Generator	2	$1,249.00	$2,498.00	
	Collimator	2	$376.69	$753.38	
	1550 nm Bandpass Filter	2	$208.00	$416.00	

	900 nm Cut-On Dichroic	2	$303.98	$607.96	
	Fast Steering Mirror	2	$1,159.00	$2,318.00	
	High Voltage Amplifier Array	2	$20.80	$41.60	
	Lens Assembly	2	$106.88	$213.76	
	Quadcell	2	$454.00	$908.00	
	PCBs	2	$140.00	$280.00	
	Machined Optical Mounting Hardware	1	$500.00	$500.00	
				Total	**$14,910.35**
Ground Station	1550 nm Laser	1	$1,526.00	$1,526.00	
	Avalanche Photodiode	2	$1,369.61	$2,739.22	
	CMOS Tracking Camera	1	$3,000.00	$3,000.00	
	Star Tracking Camera	1	$300.00	$300.00	
	Time Tagging FPGA SetUp	1	$763.64	$763.64	
	Polarizing Beamsplitter	1	$203.82	$203.82	
	Quarter Waveplate	1	$497.30	$497.30	
	Half Waveplate	1	$497.30	$497.30	
	Telescope	1	$3,999.00	$3,999.00	
	PCBs	1	$150.00	$300.00	
	Fast Steering Mirror	1	$1,159.00	$1,159.00	
	Bandpass Filter	1	$729.00	$729.00	
	Collimator	1	$376.69	$376.69	
	50/50 Beam Splitter	1	$174.70	$174.70	
	Machined Optical Mounting Hardware	1	$1,000.00	$1,000.00	
				Total	**$17,265.67**

Testing	Travel to/from External Test Facility			$250.00	
				Total	**$250.00**
Contingency	10% of Net Cost			$6,568.20	
				Total	**$6,568.20**
Overall Total					**$72,250.17**

B.12. Detailed Merit Review Results

B.12.1. Numeric Merit Review Results

Table B.12.1: Numeric Merit Review Results

Section	Question	Average Numeric Response (Out of 5)
1 (NASA Strategic Goals)	1. Does PULSE-A follow NASA's strategic goal 2: "Extend Human Presence to the Moon and on towards Mars for Sustainable Long-term Exploration, Development, and Utilization?	4.25
	2. Does PULSE-A follow NASA's strategic objective 2.4: "Enhance space access and services?"	4.50
	3. Does PULSE-A follow NASA's strategic objective 3.1: "Innovate and advance transformational space technologies?"	5.00
	4. Does PULSE-A follow NASA's strategic objective 4.2: "Transform mission support capabilities for the next era of aerospace?"	4.75
	5. More generally, does PULSE-A satisfy NASA's strategic goals?	4.75
	Section Average:	**4.65**
2 (Mission Merit)	6. If PULSE-A's mission is successful, then would the mission's results be technologically innovative?	4.50
	7. If PULSE-A's mission is successful, would the ease of access to affordable space-to-ground laser communications be improved through the distribution of open source designs?	5.00
	8. Is space-based Quantum Key Distribution technology worth pursuing?	4.50
	9. Is PULSE-A a valid technology demonstrator for a future satellite, namely PULSE-Q?	3.75
	Section Average:	**4.44**

3	10. Finally, do you have any general comments on PULSE-A's merit?	N/A
	Overall Average Merit Review Score:	**4.56**

B.12.2. Written Merit Review Results

Please note that all written comments are quoted as reviewers submitted them, barring typos and minor grammatical errors, which were corrected by the PULSE-A team. No other changes were made to the comments, aside from expunging reviewers' names for the distributable version of the proposal.

Question 1 (NASA Strategic Goal 2: Moon and Mars):

- [REVIEWER 1]: "Laser-based communications are going to be a key technology in future deep-space exploration, I'd say you are making great steps in that effort."
- [REVIEWER 2]: "I don't see how it is related to extending human presence to the Moon and Mars. Maybe I missed it. It might be good to strengthen your reasoning on this."
- [REVIEWER 3]: No written comment.
- [REVIEWER 4]: "Space-based free-space optical links are expected to provide high-bandwidth and long-distance communication channels for future missions to Mars."

Question 2 (NASA Strategic Objective 2.4: Enhance Space Access):

- [REVIEWER 1]: "I think this project develops a key technology for enhancing cubesat operations and the fact that you are a student team points to greater access to space we are seeing through programs such as this"
- [REVIEWER 2]: No written comment.
- [REVIEWER 3]: No written comment.
- [REVIEWER 4]: "The open-source design of PULSE-A would certainly improve and support space access to other groups which could leverage their results."

Question 3 (NASA Strategic Objective 3.1: Advance Space Technologies):

- [REVIEWER 1]: "There's no doubt that space-space and space-ground optical communication is a transformational technology as you describe in your review document"
- [REVIEWER 2]: "I see the potential in transformational space technologies from the built-in potential for quantum communication based on quantum key distribution. You might want to strengthen it in saying "it lays the fundamental step needed towards space based quantum communication and entanglement distribution"

- [REVIEWER 3]: No written comment.
- [REVIEWER 4]: No written comment.

Question 4 (NASA Strategic Objective 4.2: Transform Mission Support Capabilities):
- [REVIEWER 1]: “I think this project addresses that strategic objective in two ways: fostering relationships between NASA and external actors (in this case universities, labs and potentially industry), and address current and future cybersecurity threats”
- [REVIEWER 2]: “It is a good idea to start with laser based communication which could be extended further to quantum communication based on quantum key distribution. An important step to take.”
- [REVIEWER 3]: No written comment.
- [REVIEWER 4]: “Free-space optical communication links are expected to be a critical enabling technology for long-distance space-based communication.”

Question 5 (Generally Satisfying NASA’s Strategic Goals):
- [REVIEWER 1]: “I think this is exactly the type of project NASA should be engaged in. It fosters the education and development of students to be the next generation of space leaders while also developing an important new technology with applications to small-scale operations such as cubesats and large-scale operations such as crewed deep-space missions.”
- [REVIEWER 2]: No written comment.
- [REVIEWER 3]: No written comment.
- [REVIEWER 4]: No written comment.

Question 6 (Would PULSE-A’s Success be Technologically Innovative?):
- [REVIEWER 1]: “The demonstration of this technology would be very innovative. Developing a compact laser-based communications framework has many possible applications for a wide-array of missions.”
- [REVIEWER 2]: No written comment.
- [REVIEWER 3]: No written comment.
- [REVIEWER 4]: “A successful mission for PULSE-A's would be the one of the few satellites to ground optical communications from a cubesat.”

Question 7 (Ease of Access to Space-to-Ground Laser Communication):
- [REVIEWER 1]: “Absolutely, I am always in favor of open-source distribution of designs. Consider the development work you will put into the project and how much effort will be saved by others when they can reference your designs.”

- [REVIEWER 2]: No written comment.
- [REVIEWER 3]: No written comment.
- [REVIEWER 4]: "PULSE-A's open source design would enable democratizing satellite based free-space optical communication to other groups including in the developing world."

Question 8 (Space-Based QKD Merit):

- [REVIEWER 1]: "I think it is, there doesn't seem to be much US development of the technology as you point out."
- [REVIEWER 2]: "This is definitely worth exploring. It enables new quantum technology and is of national interest (both on the economic side and the national defense side). There are challenges associated with it. But it's worth exploring."
- [REVIEWER 3]: "I had trouble understanding this section (4.2)" (In the CSLI Proposal, this references Section 3.2. Secondary Mission: QKD Risk Reduction.)
- [REVIEWER 4]: "Quantum Key Distribution (QKD) is the only provably secure encryption method which exists. Space-based QKD links would enable long-distance, intercontinental secure communication."

Question 9 (PULSE-A as Technology Demonstrator for PULSE-Q):

- [REVIEWER 1]: "The main contribution from PULSE-A as a technology demonstrator may be in the pointing accuracy achieved in the optical setup? I'm sure this will be helpful for QKD but the report does not demonstrate this in any detail."
- [REVIEWER 2]: "It is a good start. There are some challenges I want to mention: (1) the air turbulence can distort the polarization of light. One needs to anticipate it as part of loss. (2) All optics can distort polarization also. One needs to carefully align half waveplate and quarter waveplate to cancel out as much as possible this distortion (angle control of the plates are crucial here) (3) Telecom wavelength is not necessarily the best wavelength of light for earth-space. It is excellent for fiber networks. But not for space from an air turbulence point-of-view. So One might need to account for this also. Generally speaking 785 nm+-10 works well from resisting polarization distortion due to air-turbulence. But telecom can be a starting point to learn. Just want to share this technical aspect that is not addressed in the proposal."
- [REVIEWER 3]: "I'm not sure I understand the goal of PULSE-Q vs. PULSE-A. In general, I think it is better to emphasize the importance of PULSE-A on its own merit rather than saying "the purpose of PULSE-A is to help PULSE-Q""

- [REVIEWER 4]: “Space-based Quantum Key Distribution (QKD) is technically risky. PULSE-A burns down a significant amount of technical risk associated with a space-based QKD demonstration effort.”

Question 10 (General Comments):

- [REVIEWER 1]: “I think this is an outstanding mission concept and has great merit as a demonstrator for an important new space technology.”
- [REVIEWER 2]: “Overall, I think it is a good idea to explore pulse-A and even go to pulse-Q for quantum communication. It fits NASA's and defense's mission. I think you could strengthen your statement towards quantum communication and also how your project helps exploration of the moon and beyond. You could organize the table under "development schedule" better to make it clear what test, what engineering is to be carried out so that any review can just look at it and tell what you plan to do/test and what you plan to do for the challenges. One could explain the color and symbols better with some legend to label it.”
- [REVIEWER 3]: “How come you aren’t interested in a polar orbit?”
- [REVIEWER 4]: “The PULSE-A project is in the strategic interests of the U.S. and NASA and deserves to move forward. The technical team is leveraging best-practices techniques to reduce technical risk of the follow-on effort PULSE-Q, which would be the first U.S. sponsored quantum communications satellite. I have personally interacted with the technical team, and they are very intelligent and driven to succeed in this effort. I would highly recommend moving forward with the PULSE-A and PULSE-Q efforts.”

B.12.3. PULSE-A Team Responses to Merit Review Results

Overall, PULSE-A’s merit review results were extremely positive, with an average numeric score of 4.56 out of 5. Reviewers praised PULSE-A for its primary mission and open-source design, which would greatly benefit future missions. They also stated that the project would benefit greatly from partnership with NASA.

Several reviewers wrote that they had trouble understanding how PULSE-A assisted with QKD risk reduction. In response, we expanded Section 3.2 (Secondary Mission: QKD Risk Reduction) and detailed the specific systems present in PULSE-A which lay the groundwork for a future QKD mission. [REVIEWER 2] commented that it was unclear how PULSE-A supported future missions to the Moon and Mars. In regards to this, we included the project’s applicability to such missions in the mission statement. Considering [REVIEWER 2]’s response to Q10, greater specification was included in our development timeline. Also under Q10, [REVIEWER 3] asked whether we would be interested in a polar orbit. In response, we confirmed using the simulation detailed in Section B.9. (Ansys STK Simulation) that while a polar orbit (between 60-90° inclination) would work for PULSE-A, it was *not* more desirable than lower inclination orbits.

[REVIEWER 2] listed 3 suggestions for PULSE-A in response to Q9, each of which has been taken into account. Firstly, we anticipate transmission loss due to atmospheric effects on polarization in the contingency "Misc. Loss" and "Free-Space Loss" of the link budget, included in Section B.1.6. Transmitter Subassembly: Link Budget. Secondly, (as stated in Section B.2. Ground Station) we plan to carefully align the waveplates in the optical ground station based on both simulation and characterization prior to the first transmission attempt. However, given the ground station is always available to be worked on, we have the ability to realign waveplates if necessary during PULSE-A's operation. Thirdly, the telecom wavelength, 1550 nm, is only used for PULSE-A's uplink beacon and does not carry polarization-modulated data, so concern over atmospheric effects is minimized. Additionally, and according to MIT CLICK-A results, 1550 nm light does not experience any significant atmospheric loss not previously accounted for [15].

B.13. Detailed Feasibility Review Results

B.13.1. Numeric Feasibility Review Results

B.13.1.1: Feasibility Review Aggregated Results

Section	Question	Average Numeric Response (Out of 5)
1 (Technical Feasibility)	1. Is the PULSE-A team capable of creating an optical system that accomplishes its goals?	4.40
	2. Is the PULSE-A team capable of integrating the scientific payload with the commercial Artemis kit?	4.80
	3. Is the PULSE-A team capable of developing its proposed PAT (pointing, acquisition, and tracking) systems?	4.00
	4. Is the PULSE-A team capable of completing the technological requirements for its ground station?	4.60
	5. Does the PULSE-A team realistically and sufficiently address potential risks to PULSE-A's missions?	4.60
	6. Is the PULSE-A team capable of fully designing and testing PULSE-A?	4.80
	Section Average:	**4.53**
2 (Financial and Organizat-ional Feasibility)	7. Has the PULSE-A team set achievable and realistic timelines for its goals?	4.80
	8. Is the PULSE-A team financially capable of funding PULSE-A?	4.00
	9. Is the PULSE-A team organized and developed in an appropriate manner?	4.20
	Section Average:	**4.33**
3	10. Please leave any other comments you may have.	N/A
	Overall Average Feasibility Review Score:	**4.47**

B.13.2. Written Feasibility Review Results

Please note that all written comments are quoted as reviewers submitted them, barring typos and minor grammatical errors, which were corrected by the PULSE-A team. No other changes were made to the comments.

Question 1 (Optical System):

- [REVIEWER 1]: “I think the nominal design of the optical system is really sound and I have no doubt the team can implement it in a laboratory setting. My concern is that with such tight pointing angle requirements, you will have to be extremely resistant to any misalignments that may occur in the assembly, shipping, launch and deployment of the spacecraft. Extremely rigorous testing will need to be done to make sure your system can survive the trip from the lab to space while maintaining precise enough alignment. I'm not sure on this but many space missions have optics which can be aligned on orbit using electronic mounts, translation stages, etc. This may be too much for your mass/space budget but is probably worth considering to add resiliency in your mission critical objective.”
- [REVIEWER 2]: “I think you have the right mix of people to get this done. Good team”
- [REVIEWER 5]: “The team has thought through all aspects of the design and operations of their cubesat and have data and technical basis for their decisions.”
- [REVIEWER 6]: “While I'm not an optics expert, demonstrating flight heritage components, modeling of proposed solution, and detailed design discussion show compelling evidence of successful design practices.”
- [REVIEWER 7]: “I'd like to see more description of atmospheric effects; overall the optical design looks well thought out and the analysis looks strong.”

Question 2 (Artemis Integration):

- [REVIEWER 1]: “Compact optomechanics can be difficult to find and configure but I'm sure the team can meet the space constraints of the cubesat and stay within the mass/power budgets you've outlined.”
- [REVIEWER 2]: No written comment.
- [REVIEWER 5]: No written comment.
- [REVIEWER 6]: “Three reasons I believe in your success in this area: reliance on COTS + flight heritage components, having a ground-based test rig/twin, and preparing for an extensive suite of testing. I do have mild concerns about component lead times, as COTS does not always equal in stock, but that's how I feel about all space-rated hardware in 2023 and is not specific to this project's proposed solution.”

- [REVIEWER 7]: No written comment.

Question 3 (PAT):

- [REVIEWER 1]: “This to me seems like the trickiest part of the project. How long will a pass over the ground station be and how quickly do you believe the cubesat can find and orient itself to the tracking signal? I think it can be done but trying to lock mirrors on both the cubesat and ground station simultaneously with a moving target will definitely be a challenge and hard to test on the ground.”
- [REVIEWER 2]: “pointing to the ground telescope is not an easy task. you might need a narrower beam divergence. Not sure if you have accounted for possible scattering of light going through air and the effect of air turbulence on distortion of polarization of light.”
- [REVIEWER 5]: No written comment.
- [REVIEWER 6]: “I'd like to see additional discussion on the uncertainty calculations with the Zemax Optics Studio calculations (though I understand you may be page-count limited)”
- [REVIEWER 7]: “Again, I'd like to see more discussion of atmospheric effects.”

Question 4 (Ground Station):

- [REVIEWER 1]: “The ground station seems to be the most straightforward piece of the project with lots of heritage technology. It's also easy to debug and test things on the ground.”
- [REVIEWER 2]: “I just want to point out that all optics have some effect in distorting polarization of light. One needs to carefully test it and eliminate it by adjusting the angle of the half-wave plate and quarter-wave plate. The angle of it is key. Also air turbulence changes the polarization of light too. It is worth keeping that in mind as this can be a source of error for your testing. You may want to add it as part of testing.”
- [REVIEWER 5]: No written comment.
- [REVIEWER 6]: “In future work, I'd like to see additional discussion on the potential impacts of Midwestern weather (and Lake Effect Snow) on your ground station operations and the associated mission impact. Otherwise, I think working the multiple paths to FAA certification is really important and should remain a project priority due to extended turnaround times from the FAA.”
- [REVIEWER 7]: No written comment.

Question 5 (Risk Assessment):

- [REVIEWER 1]: “I would emphasize the likelihood of Risk 3. I think the risk is much higher (maybe a 3?) that you struggle to get a signal on any of your passes given that this is a new system design with very little (no?) heritage. Otherwise you seem to be mostly using COTS hardware with plenty of heritage so it all looks reasonable."

- [REVIEWER 2]: "Polarization detection is simple but a lot of things can distort polarization of light even your instrument's imperfection."
- [REVIEWER 5]: "The team has thought through a variety of risks, and have a mitigation plan in place for each. I found no major gaps."
- [REVIEWER 6]: "I think your risk matrix is adequately mature for your current state of the project. In the future, I would like to see more elaboration on mission risks from the Mission Operations team, as well as a risk related to deltas in environments and configurations for your heritage hardware. Additionally, it's important to evaluate the risk of an Artemis mission delay after satellite delivery. How are you determining what's been experienced in previous missions? Are there published in-flight anomaly records?"
- [REVIEWER 7]: "I'm impressed with the assessment and mitigation strategies."

Question 6 (Design and Testing):

- [REVIEWER 1]: "I think the design already looks great! I'm sure there are iterations still to come as the design matures and the testing will almost certainly discover some issues but I think you'll have no problems converging on a working design."
- [REVIEWER 2]: No written comment.
- [REVIEWER 5]: No written comment.
- [REVIEWER 6]: "The team demonstrated diverse backgrounds, and sufficient depth of knowledge in the various areas covered. In future reports, I think it would be value-added to discuss proposed testing limits for your thermal, vibe, and vacuum testing and how those requirements were derived."
- [REVIEWER 7]: "Generally, I'd like to see more discussion of test, validation, and verification. Stating some fundamental requirements will help here."

Question 7 (Timeline for Goals):

- [REVIEWER 1]: "I think the timelines are very reasonable. Don't underestimate how long it will take to configure and test everything, especially when things inevitably go wrong at some point, but I think the timeline is solid"
- [REVIEWER 2]: No written comment.
- [REVIEWER 5]: No written comment.
- [REVIEWER 6]: "At this point in the project, I believe your timelines are realistic. I think your largest risks are component lead times and completing your suite of testing for flight. I've seen

far more broken vibe tables and machinery falling out of calibration in industry than I ever expected."

- [REVIEWER 7]: "It's difficult to assess given the GANNT chart. See comments in document." (This comment reads: "It is hard to assess the realism of your schedule with this GANTT, because each task basically takes up the entire project duration. Do you have a schedule showing dependencies?")

Question 8 (Finances):

- [REVIEWER 1]: "$70,000 is a large hole to be in but you have plenty of time. Some good fundraisers and especially corporate or academic donations will go a long way."
- [REVIEWER 2]: No written comment.
- [REVIEWER 5]: "The team still has a way to go to fully fund their cubesat, but they have a plan and initial funding sources which indicate a high probability of success."
- [REVIEWER 6]: "Having approx a third of the project funded this early on is a huge achievement. I would be happy to provide additional recommendations for funding sources as well."
- [REVIEWER 7]: "Not yet! But I think you've got a strong case to make as you fundraise."

Question 9 (Team Organization):

- [REVIEWER 1]: "I think the organization looks solid. I assume you have some good plans in place to deal with turnover in students as they graduate? Knowledge loss and brain drain can be devastating to student projects if not handled well. I'll also say that you probably will need to keep the "research team" efforts going even when you move into prototyping as those efforts never really stop and I'm sure the prototyping will lead to more design requirements and thus more "research""
- [REVIEWER 2]: No written comment.
- [REVIEWER 5]: "The team has a variety of members with appropriate skill sets and experience."
- [REVIEWER 6]: "Your team looks incredible. What is the succession plan after the fourth-year graduate?"
- [REVIEWER 7]: "I think so, but you might want to think about having resumes of your team members to show your potential funders, especially space companies."

Question 10 (Other Comments):

- [REVIEWER 1]: "I think the project looks great! You have a really cool mission concept and a very plausible design to address the stated goals. As with any early-stage space project there are many things that still need to be worked on and fleshed out but I'm sure you can get to a space-ready design from the start you have! I'm looking forward to seeing you fly!”

- [REVIEWER 2]: “Generally, it is a good idea captured here and well documented. One could consider the following: (1) the development schedule table could be polished to list the kind or class of testing you do, the engineering you do (in short words). One could label the colors and symbols so reviewers can easily tell what is to be done and how. (2) Fig. 8.5 to Fig. 8.7 are results you have regarding your design. but I feel the discussion is not clear enough. The figure is not well labeled for others to tell easily what is calculated and why yours is better or more promising” (These figures refer to images that are now in Section B.1. Scientific Payload.)
- [REVIEWER 5]: “The team has prepared a thorough and professional feasibility report. I believe they will have success if they continue to work with the same standards and processes they have used so far.”
- [REVIEWER 6]: “I had a few other questions that came up in the review process: Do you have funds set aside for transit to the integration/launch site? What are ongoing labor and materials costs for the ground stations? What is the maintainability of the ground station hardware/software? What is the expected mission life of the hardware?”
- [REVIEWER 7]: “Great work! I'm really impressed by the material, the depth of design and analysis work, and the writing.”

B.13.3. PULSE-A Team Responses to Feasibility Review Results

Overall, PULSE-A’s feasibility review results were extremely positive, with an average numeric score of 4.47 out of 5. Reviewers praised the quality of the information in the Feasibility Review Document, writing that our mission has many associated challenges, yet there is confidence that we will effectively address them during the prototyping and testing phase of the project.

[REVIEWER 1] was most concerned about the PAT sequence’s success in his feasibility review; we thoroughly expanded the PAT sequence’s description through the inclusion of Section B.3. PAT Sequence and simulated its successful functionality in STK, as described in Section B.9. Ansys STK Simulation. We expect to spend a large portion of PULSE-A’s prototyping phase on developing the PAT sequence and testing related components.

[REVIEWER 2]’s largest apprehension with PULSE-A’s feasibility was the potential for optical components and atmospheric effects to interfere with light polarization and transmission; other reviewers, particularly [REVIEWER 7], echoed [REVIEWER 2]’s concern for atmospheric effects. We will rigorously test for adverse effects on polarization in the optical setup when we construct a prototype of PULSE-A's scientific payload, and we intend to conduct a long-range test of the optical setup as well. Additionally, we have accounted for atmospheric effects on the transmission in Section B.1.6. Transmitter Subassembly: Link Budget. We will thoroughly test the waveplates in the ground station in simulations and during testing, and we will be able to adjust them as needed when operations begin.

For Q5 (rating our risk assessment), [REVIEWER 1] wrote that he believes there is a likelihood of 3 out of 5 that our PAT sequence fails on every pass. In response to this, we reaffirmed our likelihood rating of 2 out of 5 by conducting additional orbit simulations (cf. Section B.9: Ansys STK Simulation) and adding long-range testing to our verification plan. Our current desired orbit allows for more than double the number of viable passes as compared to others, meaning that the total number of non-failing passes would significantly increase, assuming a constant failure rate. Additionally, [REVIEWER 5] expressed that our risk assessment is "adequately mature" for the "current state of the project." She noted that in the future, we should account for additional risks related to environmental changes and hardware; we intend to further develop our risk assessment during the development stage of the project.

For Q7 (rating our development schedule) and Q10 (providing general comments), multiple reviewers noted that our development schedule should be more detailed and include a legend. In response, we overhauled Section 7. Development Schedule and added Section B.10. Justification of Development Schedule to provide far more detail.

Q8 (rating our ability to fund PULSE-A) received mixed responses from reviewers. We were praised for having raised $30,000 by the time feasibility reviews were conducted, but some responses were skeptical of our ability to raise enough funds to cover PULSE-A's total cost. The $30,000 funds described in the feasibility review consisted of $5,000 from SEDS-UChicago's RSO fund and $25,000 from [PRIVATE DONOR NAME EXPUNGED] as a private donor. Since the feasibility reviews were completed, we have received commitment for $25,000 from the University of Chicago's academic departments and commitment for $17,265.67 (the ground station's full cost) from our project advisor, Professor Tian Zhong. We have also reduced PULSE-A's total required budget to $72,250.17 (the total was estimated at $100,000 for feasibility reviews). PULSE-A is now fully funded, as described in Section 8.2. Funding. Throughout the optical prototyping phase of PULSE-A's development, our Department of Funding and Outreach will continue fundraising to purchase duplicate components beyond what has already been budgeted for, so that more rigorous testing may be completed.

Finally, reviewers commended the PULSE-A team organization under Q9 (rating team organization), writing that our members bear a wide range of experience. However, several reviewers asked about our plans for the leadership team and knowledge loss mitigation after the current 4th-year undergraduate students graduate. We added on to Section 5. Project Organization to address reviewers' concerns.

Appendix C. References

[1] H. Hemmati, Ed., *Near-Earth laser communications*, Second edition. Boca Raton: CRC Press, 2021.

[2] A. Carrasco-Casado *et al.*, “Optical communication on CubeSats — Enabling the next era in space science,” in *2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS)*, Naha: IEEE, Nov. 2017, pp. 46–52. doi: 10.1109/ICSOS.2017.8357210.

[3] “The height of the tropopause.” Accessed: Nov. 13, 2023. [Online]. Available: http://www-das.uwyo.edu/~geerts/cwx/notes/chap01/tropo.html

[4] C.-Y. Lu, Y. Cao, C.-Z. Peng, and J.-W. Pan, “Micius quantum experiments in space,” *Rev. Mod. Phys.*, vol. 94, no. 3, p. 035001, Jul. 2022, doi: 10.1103/RevModPhys.94.035001.

[5] T. Vergoossen, Villar, Aitor, Lohrmann, Alexander, Ying Lim, Huai, Shankar, Divya, and Bedington, Robert, “SpooQy-1: the first nano-satellite to demonstrate quantum entanglement in space”.

[6] “fy-22-strategic-plan-1.pdf.” Accessed: Nov. 13, 2023. [Online]. Available: https://www.nasa.gov/wp-content/uploads/2023/09/fy-22-strategic-plan-1.pdf%20

[7] “NASA Strategy for STEM Engagement”.

[8] “627972main_lsp-req-317_01a.pdf.” Accessed: Nov. 14, 2023. [Online]. Available: https://www.nasa.gov/wp-content/uploads/2018/01/627972main_lsp-req-317_01a.pdf

[9] “Nanoracks-CubeSat-Deployer-NRCSD-IDD.pdf.” Accessed: Nov. 14, 2023. [Online]. Available: https://nanoracks.com/wp-content/uploads/Nanoracks-CubeSat-Deployer-NRCSD-IDD.pdf

[10] “PLAW-112publ95.pdf.” Accessed: Nov. 14, 2023. [Online]. Available: https://www.govinfo.gov/content/pkg/PLAW-112publ95/pdf/PLAW-112publ95.pdf

[11] “CDS+REV14_1+2022-02-09.pdf.” Accessed: Nov. 14, 2023. [Online]. Available: https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/62193b7fc9e72e0053f00910/1645820809779/CDS+REV14_1+2022-02-09.pdf

[12] Kingsbury, Ryan W., “Optical Communications for Small Satellites,” *DSpace@MIT*.

[13] B. Rödiger *et al.*, “High data-rate optical communication payload for CubeSats,” in *Laser Communication and Propagation through the Atmosphere and Oceans IX*, D. T. Wayne, J. A. Anguita, and J. P. Bos, Eds., Online Only, United States: SPIE, Aug. 2020, p. 3. doi: 10.1117/12.2567035.

[14] “FSK two-way transceiver module RFM23BP.” Accessed: Nov. 13, 2023. [Online]. Available: https://www.iot-rf.com/FSK-Two-way-Transceiver-Module-RFM23BP-pd47488196.html

[15] “Aspheric Fiber Collimators, Pigtailed PM Fiber.” Accessed: Nov. 14, 2023. [Online]. Available: https://www.thorlabs.com

[16] bktel-photonics, “Miniature Telecom EDFA,” Bktel photonics. Accessed: Nov. 13, 2023. [Online]. Available: http://www.bktel-photonics.com/product/miniature-edfa/

[17] E. Clements *et al.*, “Nanosatellite optical downlink experiment: design, simulation, and prototyping,” *Opt. Eng.*, vol. 55, no. 11, p. 111610, Sep. 2016, doi: 10.1117/1.OE.55.11.111610.

[18] Riesing, Kathleen Michelle, “Development of a pointing, acquisition, and tracking system for a nanosatellite laser communications module,” *DSpace@MIT*, [Online]. Available: http://dspace.mit.edu/handle/1721.1/7582

[19] Long, Michael J., “Pointing Acquisition and Tracking Design and Analysis for CubeSat Laser Communication,” *DSpace@MIT*, 2018, [Online]. Available: http://dspace.mit.edu/handle/1721.1/7582

[20] “Tools for Spacecraft and Communication Design – AMSAT.” Accessed: Nov. 13, 2023. [Online]. Available: https://www.amsat.org/tools-for-calculating-spacecraft-communications-link-budgets-and-other-design-issues/

[21] I. I. Kim, B. McArthur, and E. J. Korevaar, “Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications,” presented at the Information Technologies 2000, E. J. Korevaar, Ed., Boston, MA, Feb. 2001, pp. 26–37. doi: 10.1117/12.417512.

[22] Stanco, Andrea, “High Performances Systems for Applications of Quantum Information,” *Univ. Padova*.

[23] T. Nguyen, K. Riesing, R. Kingsbury, and K. Cahoy, “Development of a pointing, acquisition, and tracking system for a CubeSat optical communication module,” presented at the SPIE LASE, H. Hemmati and D. M. Boroson, Eds., San Francisco, California, United States, Mar. 2015, p. 93540O. doi: 10.1117/12.2080591.

[24] “SDA-OCT-Standard-v3.0.pdf.” Accessed: Nov. 14, 2023. [Online]. Available: https://www.sda.mil/wp-content/uploads/2022/04/SDA-OCT-Standard-v3.0.pdf

[25] “SS200 - Digital Sun Sensor for CubeSats | AAC Clyde Space.” Accessed: Nov. 14, 2023. [Online]. Available: https://www.aac-clyde.space/what-we-do/space-products-components/adcs/ss200

[26] “CubeSense Earth Gen 2,” CubeSpace Satellite Systems. Accessed: Nov. 14, 2023. [Online]. Available: https://www.cubespace.co.za/products/gen-2/sensors/cubesense-earth/

[27] “BNO055,” Digi-Key Electronics. Accessed: Nov. 14, 2023. [Online]. Available: https://www.digikey.com/en/products/detail/bosch-sensortec/BNO055/6136301

[28] “CubeWheel Gen 2,” CubeSpace Satellite Systems. Accessed: Nov. 14, 2023. [Online]. Available: https://www.cubespace.co.za/products/gen-2/actuators/cubewheel/

[29] “CubeTorquer Gen 2,” CubeSpace Satellite Systems. Accessed: Nov. 14, 2023. [Online]. Available: https://www.cubespace.co.za/products/gen-2/actuators/cubetorquer/

[30] “Research Administration at the University of Chicago,” University Research Administration Accessed: Nov. 17, 2023. [Online]. Available: https://ura.uchicago.edu/