Optical Night Sky Brightness Measurement

NOVA: Night-time Optical Visibility Assessment

ENG 4000

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Team 24

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Executive Summary

This document outlines the final design of the NOVA stratospheric balloon payload capstone project. Designed to launch as a subpayload on the RSOnar III stratospheric balloon satellite, it aims to provide a significant advancement in high signal-to-noise ratio (SNR) imaging for stratospheric brightness measurements and resident space object (RSO) detection. With over 200,000 RSOs in Low-Earth Orbit over 2 cm in size and rising, accurate RSO tracking is a critical research area that NOVA aims to improve.

Building directly upon the lessons and challenges identified during the previous RSOnar II mission, where excessive background noise limited the ability to detect RSOs effectively [1], NOVA remedies this by providing a second camera in the same FOV. This will allow the distinction between unwanted noise sources like cosmic rays and RSOs. Likewise, the process will provide high SNR measurements of optical stratospheric brightness. By maintaining the same field of view (FOV) and viewing angle as the main payload, NOVA enables precise background subtraction. The payload is composed of six key subsystems, each addressing specific technical challenges;

1. Scientific Subsystem - The core scientific instrument is the ZWO ASI120MM Mini CMOS camera [2], paired with the Raspberry Pi 6mm wide-field lens [3]. This configuration is optimized for high SNR imaging at a low cost rather than high resolution, allowing reduced noise while keeping the expenses limited.
2. Computational Subsystem - Data processing is handled by the BeagleBone Black Industrial OBC [8] and a 256 GB microSD, providing a robust and reliable onboard computing platform. Designed for continued operation after any power loss without any loss of image data.
3. Environmental Subsystem - NOVA must survive extreme high-altitude conditions, including low temperatures (-30°C to +50°C), near vacuum pressures, and radiation exposure [7]. Thermal management strategies include passive techniques such as mylar insulation, heat sinks, and resin coatings. Since the mission duration is relatively short, radiation mitigation will rely on software-based error correction techniques [6].
4. Mechanical Subsystem - The payload structure is engineered to withstand mechanical stresses from launch, ascent, and descent, ensuring long-term structural integrity within the 40 km mission altitude range[6]. Thoroughly tested with extreme FEM and vibration analysis.
5. Electrical Subsystem - The power system is designed to operate within a 5V DC supply, drawing power from the main payload while maintaining a maximum power consumption of 4W.
6. Software Subsystem - NOVA employs custom software solutions to handle data acquisition, processing, and error correction, ensuring scientific validity and data integrity.

The key objectives of the NOVA payload are to: 1. Enhance the calibration of the RSOnar III payload through precise background characterization. 2. Increase RSO detection reliability by reducing false positives attributed to noise sources like cosmic rays. Coupled with a detailed risk management plan to tackle the extreme temperatures, pressures, and vibrations, this document outlined NOVAs rigorous testing and validation process with extensive FEM load and vibration analysis, subsystem and integrated system level testing. This document outlines the mission goals and objectives, finalized design, requirements, and rigorous testing process that aims to ensure a successful mission.

Table of Contents

List of Figures

List of Tables

Acronyms, Abbreviations, and Definitions

Table 1: Abbreviations

Term	**Definition**
SSA	Space Situational Awareness
LEO	Low Earth Orbit
BOM	Bill of Materials
CMOS	Complementary Metal-Oxide-Semiconductor- a type of image sensor
CSA	Canadian Space Agency
DC	Direct Current
DFM	Design For Manufacturing
FOV	Field of View
NOVA	Night-time Optical Visibility Assessment, Name given to the payload
NOVA team	Group of Individuals working on the Capstone Project
OBC	On-Board Computer
PSD	Power Spectral Density
RSO	Resident Space Object (i.e., space debris)
RSOnar II	The previous mission
RSOnar III	The main payload
SDK	Software Development Kit
SNR	Signal-to-Noise Ratio
SSD	Solid State Drive
TVAC	Thermal Vacuum
WBS	Work Breakdown Structure

Introduction

Space situational awareness (SSA) is the act of collecting detailed knowledge of Resident Space Objects (RSOs), typically in the near-Earth orbit ranges. With this number rapidly increasing, the need for more SSA likewise grows. Typical tracking and detection methods rely heavily on large ground-based telescopes that require a narrow field of view (FOV) to capture dim RSOs, limiting their sky coverage and therefore their ability to detect a substantial number. Likewise, increased light pollution can significantly lower the limiting magnitude, making it significantly harder to track smaller objects that reflect less light. The RSOnar II team tackled this issue by launching a stratospheric balloon to the near-space environment, utilizing a wide FOV star tracker-like camera along with commercial off-the-shelf components (COTS). Although partially successful, this highlighted significant limitations with the ability to effectively detect RSOs throughout the mission due to increased background noise near dusk and dawn. NOVA is a dual-purpose payload for RSOnar III that aims to accurately measure the stratospheric brightness while also providing a second camera imaging the same FOV as the main camera to provide redundancy when imaging RSOs, and accurately measure night sky brightness.

The ability to both detect RSOs and measure night sky brightness with very high precision is vital for understanding our immediate surrounding space environment. RSOs are expected to pose a significant threat to LEO spacecraft operations in the near future. Accurately detecting and determining the position and velocity of these objects is crucial for enabling safe LEO operations. Inaccurate calibration and knowledge of the expected sky brightness was a key limiting factor for the RSOnar II team. The NOVA sub-payload has been designed as a solution to this challenge by providing precise sky brightness measurements to calibrate the RSOnar III system with unprecedented accuracy.

This document outlines the NOVA team's rigorous process that the payload has undergone to emerge with the final, robust design. The remainder of the document is structured as follows in order to facilitate a clear understanding of the NOVA payload: Section 2- Mission Objectives, Section 3- Requirements, Section 4- As-Built Design, Section 5- Verification and Validation.

Background

The RSOnar mission, led by the Lassonde School of Engineering, aimed to develop and test a nanosatellite-scale star tracker to improve space-based surveillance of Resident Space Objects (RSOs), which include active satellites, defunct spacecraft, and orbital debris [1]. The mission sought to evaluate the use of a commercial-grade, wide field of view camera for space situational awareness (SSA) by capturing RSO images from the stratosphere [1].

For the first mission, a stratospheric balloon launched from Timmins, Ontario, on August 21, 2022, as part of the Strato-Science 2022 Campaign, reaching altitudes of 37 to 40 kilometers. Over a 12-hour overnight flight, the system captured approximately 95,000 night sky images [1]. Preliminary analysis identified over 500 RSOs, including satellites and rocket bodies, confirming the potential of wide field cameras for RSO detection [1]. Ground-based observations supported the validation of the star tracker's performance, and post-flight analysis helped refine algorithms for attitude determination and object tracking [1].

The second mission, RSOnar II, launched in August 2023 with upgraded hardware to enhance image resolution, real-time detection, and attitude determination capabilities [2]. Using a 4U CubeSat-inspired platform with a dual-purpose camera system, it captured over 95,000 images under both daytime and nighttime conditions at altitudes around 37 kilometers. RSOnar II demonstrated successful daytime tracking and real-time onboard processing using both AI and traditional methods [2]. The mission also included community outreach in the Timmins area to promote interest in space research [2].

The R3 mission builds on the progress of NOVA and RSOnar, focusing on improved data collection, real-time processing, and noise reduction [1]. Its objective is to achieve continuous day and night observations while addressing previous limitations such as thermal instability and variable imaging performance [1]. Equipped with a high-resolution camera and advanced onboard computing system, R3 aims to generate accurate optical calibration data, enhance real-time tracking, and support future nanosatellite missions focused on global SSA [1].

Collectively, these missions represent a significant step toward more accessible, scalable, and cost-effective solutions for space monitoring. By demonstrating that commercial-grade components and stratospheric balloon platforms can yield valuable data for SSA, the team has opened the door to more frequent and flexible observation missions. The lessons learned from RSOnar and R3 are helping to inform the next generation of satellite payloads, ultimately contributing to safer and more sustainable use of orbital space.

Mission Objectives

Redundant Calibration Enhancement: Provide redundant calibration images for high SNR optical measurements to improve the accuracy of the RSOnar III payload RSO tracking.

Robust RSO Discrimination: Enable more reliable detection of RSOs vs external noise sources (e.x. cosmic rays) by imaging in the same FOV as the RSOnar III payload.

System Endurance and Performance: Demonstrate a minimum of 780 minutes of full system functionality under extreme stratospheric conditions(e.x, temperatures and pressures).

Requirements

The NOVA payload's requirements are categorized and numbered to guide design choices, ensuring alignment with mission objectives [6]. These include Electrical, Environmental, Mechanical, Computational, Scientific, Safety & Compliance, Operational Flexibility, Data Integrity, Power, and Software, each with a rationale and verification process.

Table 2: Requirements

Section	Req ID	Reference	Requirement Statement	Rationale	Verification

Electrical (1)	1.1 Status: Complete	[1] Section 5.2.1	The payload shall receive a 5V ± 0.5V DC unregulated power supply from the main payload's Power Distribution Unit (PDU).	Integration with the main payload's PDU ensures stable power delivery and reduces the need for additional resources.	Verify that the power input is within the 5V ± 0.5V range by measuring the voltage at connection points between the main PDU and payload.
Electrical (1)	1.2 Status: Complete	[1] Section 5.2.1	All payload wiring shall use wire gauges that conform to CSA standards for current-carrying capacity and signal quality	CSA wire gauge standards lower the risk of overheating and ensure consistent current flow.	Confirm that wiring conforms to CSA standards by cross-referencing wire gauge with expected current ratings and capacities.
Electrical (1)	1.4 Status: Complete	[6] , Section 4.1.2	The payload wiring shall include shielding that meets CSA standards to protect against electromagnetic interference (EMI)	Shielded wiring reduces EMI risks that could affect data transmission and the stable operation of other payloads.	EMI Testing: Test shielding effectiveness by measuring EMI susceptibility in operational environments and verifying compliance with CSA standards.
Electrical (1)	1.5 Status: Complete	[6] , Section 4.1.2	The payload shall implement grounding practices in accordance with CSA-STRATOS-MAN-0012, Section 4.1.2	Grounding prevents EMI, protects against ESD, and ensures stable electrical performance, which is essential for data integrity and safety of the payload and mission.	Verify grounding continuity and measure resistance to ensure CSA-compliant grounding across all payload components.
Environmental (2)	2.1 Status: Complete	[6], Section 6.3	The payload shall operate nominally at altitudes between sea level and 40 km, ensuring continuous image data collection under variable atmospheric pressure.	Allows continuous operation through changing atmospheric pressures during ascent.	Altitude Testing: Simulate conditions in a vacuum chamber to test for operational capability across pressure ranges. - or Analysis: Computational model simulating pressure changes from sea level to 40 km to assess component resilience.
Environmental (2)	2.2 Status: Complete	[6] , Section 6.3	The payload shall maintain continuous imaging capability in a temperature range between -30°C and +50°C.	Ensures functionality across the temperature range expected during high-altitude	Thermal chamber testing and thermal profile simulation to confirm operational capability within a temperature range

				flights.	
Environmental (2)	2.3 Status: Complete	[6] , Section 6.5	The payload shall incorporate thermal coupling to the chassis to maintain operational temperatures across all components.	Maintains temperature consistency, which is crucial for reliable imaging and data collection.	Inspect thermal coupling and confirm all components achieve optimal temperature.
Environmental (2)	2.4 Status: Complete	[1] Section 5.3.5	Thermal insulation and heat sinks shall be integrated to ensure all components remain within operational temperature limits.	Protects sensitive components from extreme temperature variations, particularly during prolonged exposure.	Analysis: Thermal simulation to verify insulation and cooling systems maintain components within temperature limits.
Environmental (2)	2.5 Status: Complete	[6] , Section 6.1	The payload shall include error-correcting algorithms and hardware-based protections to mitigate the effects of high-altitude radiation exposure.	Protects data integrity and system reliability under radiation exposure.	Analysis: Radiation simulation to model payload susceptibility and error-correction effectiveness
Environmental (2)	2.6 Status: Complete	[6] , Section 6.5	The payload shall function under prolonged exposure to UV radiation and low-pressure conditions typical of the stratosphere without degradation of performance.	Ensures payload durability and functionality under stratospheric conditions.	Analysis: UV and low-pressure simulation to assess performance resilience under environmental stresses.
Environmental (2)	2.7 Status: Complete	[6] , Section 6.5	The payload shall have anti-condensation measures to prevent moisture buildup during rapid changes in altitude and temperature.	Protects sensitive electronics from moisture-related damage during ascent or descent.	Analysis: Testing in controlled environments with varying humidity and temperature to simulate mission conditions. This may involve observing the effectiveness of materials like resin coatings
Mechanical (3)	3.1 Status: Complete	[1] Section 5.4	The payload shall be designed to fit within a right triangular prism with a side length of 14.14 cm, hypotenuse of 20 cm, and depth of 10 cm, corresponding to Bay 2 of the primary payload platform.	Ensures compatibility with spatial constraints of the payload platform.	Analysis: CAD fit simulation within specified dimensions for Bay 2.
Mechanical (3)	3.2 Status: Complete	[1] Section 5.4	The payload mounting system shall maintain the camera's alignment at 45 degrees relative to the main payload platform throughout the mission, ensuring precise imaging.	Provides optimal camera alignment for accurate data capture.	Analysis: Finite Element Analysis (FEA) simulation for alignment stability under mission dynamics.

Mechanical (3)	3.3 Status: Complete	[1] Section 5.3.6	The payload shall meet its performance requirements while under the vibrational loads experienced during launch and ascent typical of stratospheric balloon missions, including random vibration and mechanical shock.	Protects payload integrity and functionality under mechanical stress.	FEA simulation and vibration test to confirm durability during launch and ascent.
Mechanical (3)	3.4 Status: Complete	[1] Section 5.4	The payload shall be constructed using materials and structural reinforcements that ensure mechanical stability, as per CSA/NASA payload weight restrictions.	Balances structural stability with weight restrictions for optimal performance	Analysis: FEA simulation to verify compliance with structural and weight standards.
Mechanical (3)	3.5 Status: Complete	[6] , Section 5.1	The payload shall stay under 500g in total mass.	Complies with weight limits, reducing stress on the main platform for stability during launch.	Measure payload mass prior to integration, confirming it meets the 500g requirement.
Computational/Storage (4)	4.1 Status: Complete	[1] Section 5.2.1	The storage system shall be sufficient to accommodate at least 780 minutes of continuous image data, taking into account the selected camera’s resolution, image format, and bit depth.	Ensures storage capacity for the full mission duration without data loss.	Analysis: Calculate required storage based on camera settings; test for 780-minute data capacity.
Computational/Storage (4)	4.2 Status: Complete	[6] , Section 4.4.4	The storage system shall support non-volatile storage mediums to prevent data loss in case of power interruptions or failures.	Protects against data loss from unexpected power disruptions	Simulate power failure to confirm data retention in non-volatile storage.
Scientific (5)	5.1 Status: Complete	[1] Section 5.2.1	The selected camera shall provide imaging capabilities for a minimum of 780 minutes of continuous data collection, matching the operational time of the primary scientific payload.	Ensures imaging capability covers the full mission duration for complete data collection.	Continuous operation test of the camera in a lab environment to confirm a 780-minute duration.
Scientific (5)	5.2 Status: Complete	[6] , Section 6.5	The camera’s quantum efficiency across the visual wavelength spectrum shall be characterized and calibrated before the mission to ensure accurate sky brightness measurements.	Accurate sky brightness measurements require known quantum efficiency across wavelengths.	Conduct spectral calibration to characterize quantum efficiency across the visual spectrum.
Scientific (5)	5.3 Status: Complete	[6] , Section 6.5	The camera shall have a high enough sensitivity to detect and measure sky brightness efficiently, even under low-light conditions.	Allows accurate sky brightness measurements under varying light conditions.	Test the camera's sensitivity in a controlled low-light setting to confirm adequate brightness

					detection.
Scientific (5)	5.4 Status : Complete	[1] Section 5.2.1	The camera resolution shall be chosen to optimize the signal-to-noise ratio (SNR) while allowing for the detection of stars within the images, balancing image resolution and sensor size.	Ensures image quality and SNR are sufficient for detecting stars and measuring sky brightness.	Analysis: Optical resolution and SNR simulation to determine optimal resolution for star detection and brightness.
Scientific (5)	5.5 Status : Complete	[6] , Section 6.5	The camera system shall include dark current and flat-field calibration procedures to account for sensor noise and variations in detector response.	Corrects for sensor noise and variations, improving data accuracy.	Perform dark current and flat-field calibration in the lab to ensure calibration procedures are effective.
Scientific (5)	5.6 Status : Complete	[1] Section 5.2.1	The payload shall be able to distinguish between sky brightness and resolvable stars to ensure the scientific validity of sky brightness measurements.	Distinguishing between sky brightness and stars is necessary for accurate data interpretation.	Analysis: Image processing simulation to confirm the camera's ability to separate sky brightness from star signals.
Safety and Compliance (6)	6.1 Status : Complete	[6] , Sections 5.1.1 and 5.2.5	The payload shall comply with all safety standards specified by CSA and mission partners to ensure safe integration, deployment, and recovery.	Compliance with mission safety standards prevents damage to the payload and reduces risks to other components or systems.	Review documentation to confirm adherence to CSA and other relevant safety standards.
Safety and Compliance (6)	6.2 Status : Complete	[1] Section 5.2.1	The payload shall include overcurrent protection circuitry to prevent component damage due to unexpected power surges.	Protects sensitive electronics and ensures the stability of power consumption across mission phases.	Test payload circuitry under power sure conditions to confirm the effectiveness of overcurrent protection.
Operational Flexibility (7)	7.1 Status : Complete	[6] , Section 5.3	The payload shall include a failsafe mode that maintains minimal operational functions if primary components encounter faults.	Increases mission success likelihood by enabling basic data collection or system preservation in case of a primary system fault.	Simulate system faults to verify the transition into and operation of failsafe mode.
Data Integrity (8)	8.1 Status : Complete	[6] , Section 4.4.4	The payload shall include redundant data storage.	Redundancy in data storage provides a backup in case of primary storage errors.	Verify data is consistently logged to multiple storage locations, confirming redundancy.
Power (9)	9.1 Status :	[1] Section 5.2.1	The payload shall have a maximum power consumption of 4.0 W during full operational	Ensures that the payload remains within the power	Measure power draw under full operational modes, ensuring peak

	Comp lete		modes.	budget allocated by the mission.	consumption does not exceed 4.0 W.
Software (10)	10.1 Status : Comp lete	[6] , Section 4.1.2	The software shall control and synchronize data acquisition across the camera and OBC to align with mission objectives.	Ensures data is captured in a coordinated manner, aligning with mission goals for consistent observations.	Validate synchronization by comparing image timestamps with an external clock, ensuring timing deviations stay below 50ms.
Software (10)	10.2 Status : Comp lete	[6] , Section 4.1.1	The software shall regulate power consumption, prioritizing critical functions to maintain total usage under 4W.	Ensures compliance with strict power limits, avoiding battery drain and extending mission operation time.	Conduct power profiling to ensure that the software remains within the 4W power limit under various operating conditions.
Software (10)	10.3 Status : Comp lete	[1] Internal Telemetry Requiremen ts	The software shall log essential telemetry and diagnostic data, including camera status, storage availability, power consumption, and error events, to facilitate post-mission performance analysis.	Comprehensive telemetry logs are necessary to assess system health, debug anomalies, and validate scientific data integrity after flight.	Simulate system states, and verify logs for camera status, storage, and errors, ensuring accurate timestamps and data consistency for post-mission analysis.

As-Built Design

The NOVA payload, developed for the RSOnar III balloon satellite mission, is designed to capture high signal-to-noise ratio (SNR) sky brightness measurements to improve RSO detection and optical calibration at 40 km altitude [4]. This section presents the as-built system configuration, ensuring clarity for future replication and refinement.

The payload is structured into six key subsystems: mechanical, environmental, computational, electrical, scientific, and software, each addressing specific operational challenges. The system integrates a ZWO ASI120MM Mini camera with a BeagleBone Black Industrial OBC and a 256 GB micro SSD, ensuring real-time imaging and data storage [5].

This section outlines the finalized design, detailing system interfaces, performance metrics, and key integration processes to document the build process.

Electrical Assembly and Integration

The NOVA sub-payload will be provided with power directly from the PDU of RSOnar 3 [1]. This includes the BeagleBone black industrial OBC with the 256 GB micro SSD, as well as the ZWO ASI120mm mini camera. Power is provided directly to the OBC through the PDU, and the micro SSD and camera will be powered through the OBC to minimize power draw to maintain within our 4W power limit during peak activity.

The payload requires standard electrical connections provided by the RSOnar mission's main power management system. These connections will maintain minimized wire length, and use wire gauge and shielding that adheres to CSA standards as per electrical requirements 1.2, 1.3, and 1.4 [6]. The diagram below shows the NOVA sub-payload location within RSOnar 3's electrical design.

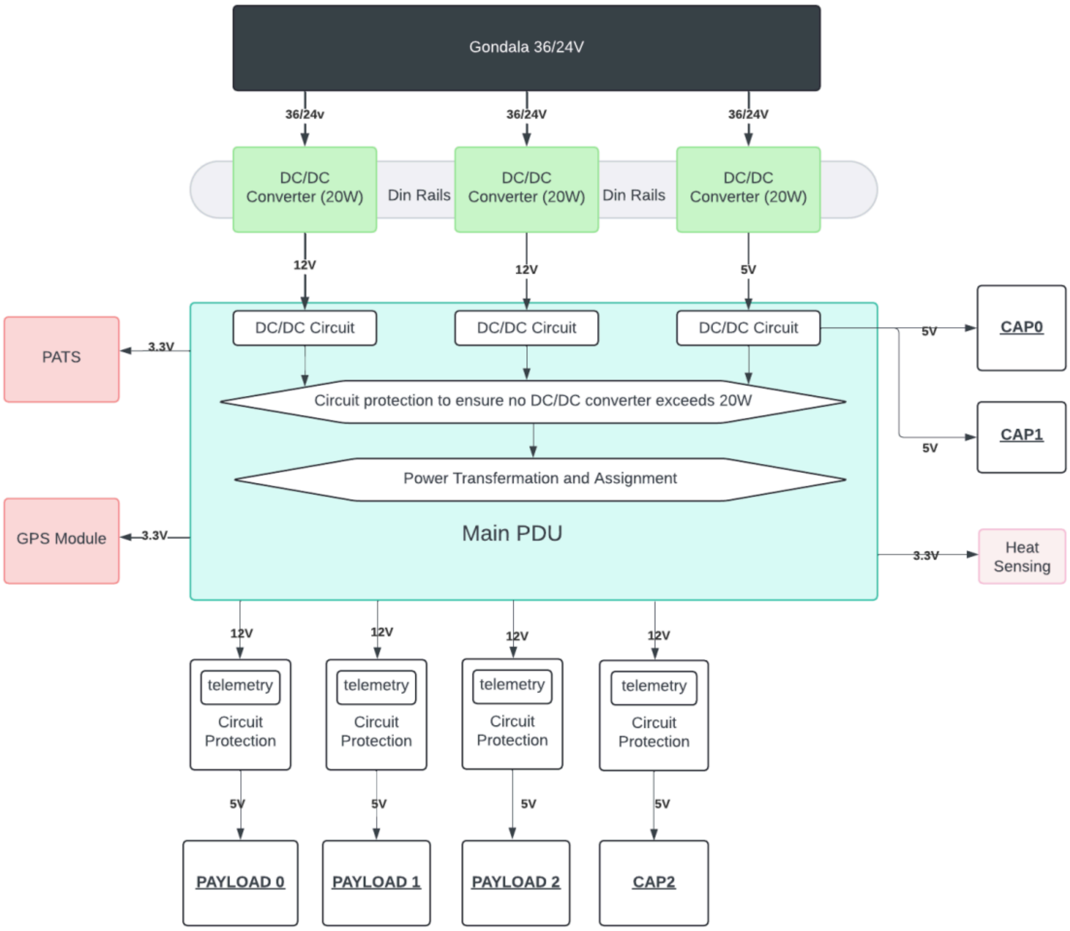

Figure 1 - Shows where the payload's power is provided from RSOnar III (Cap 2) [1]

NOVA's electrical design ensures efficient and reliable continuous imaging for a minimum of 780 minutes. By using the main payload's robust PDU and ensuring all connecting wires adhere to strict electrical standards, NOVA is able to operate efficiently and effectively at 5V within the budget of 4W as per requirements 1.1 and 9.1 [1].

The RSOnar III Power Distribution Unit (PDU) supplies power to the On-Board Computer (OBC), which then distributes it to the Camera. The Camera captures image data and transmits it back to the OBC, where it is processed and stored on the onboard SD Card for post-mission analysis. The diagram below provides a visual representation of this power and data flow within the payload.

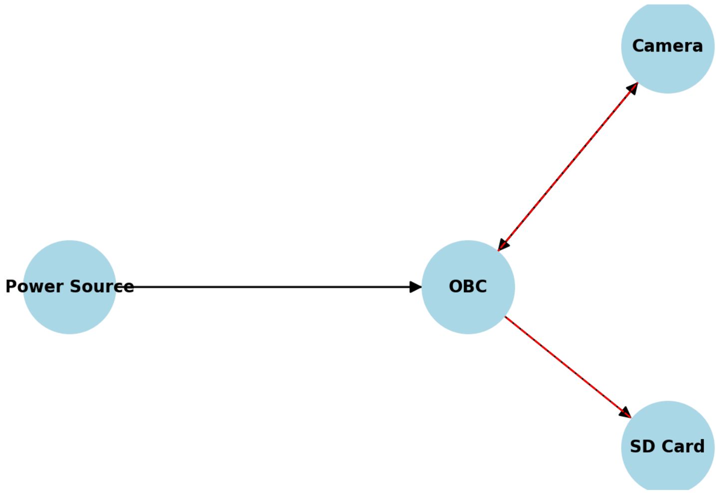

Figure 2 - NOVA Payload Power and Data Flow Structure

Environmental Impact

The NOVA payload is capable of withstanding extreme thermal conditions encountered during ascent and descent, with temperatures ranging from -30°C to +50°C, as specified in Requirement 2.2 [6]. While the OBC was selected to operate within this temperature range, other components, such as the camera, fall outside these limits due to budget constraints. To mitigate this risk, a trade study was conducted to identify the most effective thermal management strategy.

The study evaluated foam insulation, resin coatings, and multilayer Mylar based on thermal performance, mass, durability, outgassing risk, and cost. Initially, Mylar insulation was selected as the primary thermal regulation layer due to its lightweight nature, high reflectivity, and low outgassing properties, providing effective shielding against radiant heat and UV exposure. However, after further analysis and discussion with the R3 Team, the NOVA team has decided to replace Mylar with conformal resin coatings, which offer greater durability, enhanced thermal stability, and improved protection against condensation and outgassing [6].

Although foam insulation demonstrated good thermal resistance, it was ruled out due to high outgassing potential and UV degradation susceptibility. This ensures optimal thermal regulation, enhancing the functionality and reliability of the payload throughout the mission [6].

Figure 3 - Mylar covering for NOVA Prototype #1

Mechanical Design and Assembly Proposal

The NOVA sub-payload will be housed in the far-right bay of the triangular prism, alongside two other NOVA sub-payloads. Initially, the payload was designed to be mounted according to the bolt pattern specified in requirement 3.1 [1]. However, after discussions with the Project Manager, this pattern was modified to optimize NOVA's assembly. The original bolt pattern consisted of a 50 mm by 50 mm square, with evenly spaced holes at 36.75 mm along the centerline of the bottom panel, as illustrated in Figure 4: RSOnar III drawing for mounting points.

This modification facilitated easier part manufacturing and streamlined the assembly process. The revised mounting ensures that the camera maintains a 45-degree viewing angle, in compliance with requirement 3.2 [1].

Early designs positioned the Onboard Computer (OBC) on the side panels to minimize vibrations. However, through further design iterations and collaboration with the Mechanical team of the R3 Team, we decided against mounting any peripherals on the side panels. This adjustment helps keep the center of gravity as close to the geometric center as possible, simplifying calculations and preventing unwanted attitude responses.

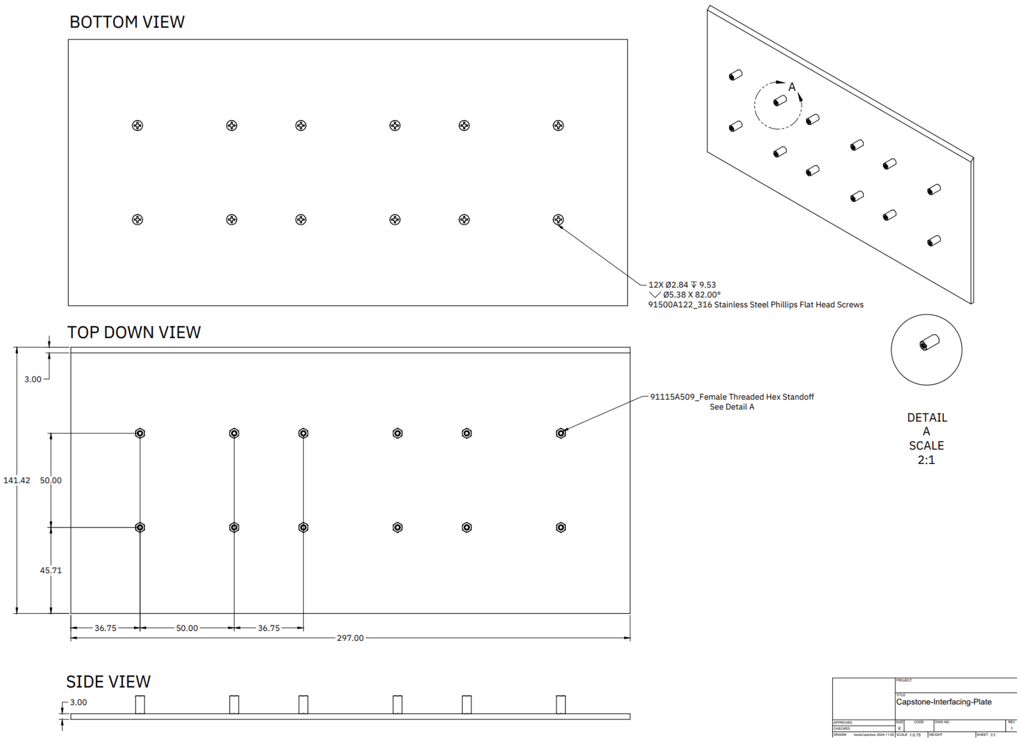

Figure 4 - RSOnar III drawing for Initial mounting points [7]

Please note that after several iterations, we have finalized the following models. Major changes to this design as compared to our initial design include;

- Mounting the OBC to the bracket mounted to the base
- Using a modular camera bracket for ease of manufacturing
- Using set screws to secure the camera instead of having a top mount
- Requiring more horizontal space than initially allocated to house a 90-degree power adapter

The following images allow for a side-by-side comparison of the initial and finalized versions of the NOVA payload

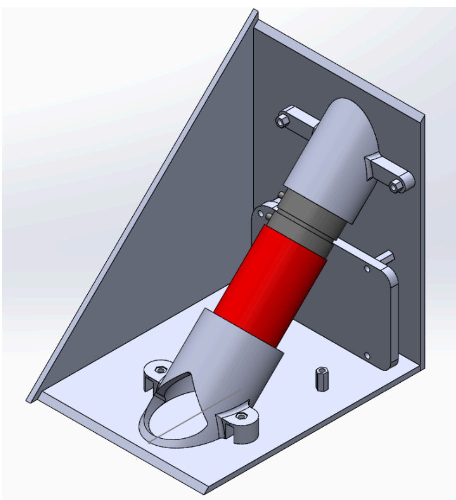

Figure 5 - Initial prototype for the NOVA Payload

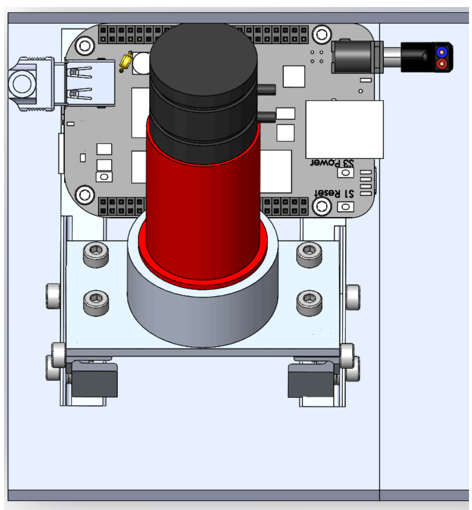

Figure 6 - Finalized NOVA payload Top View

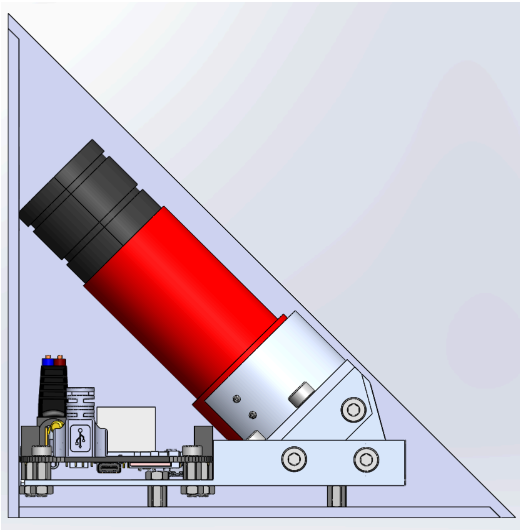

Figure 7 - Finalized NOVA payload side view

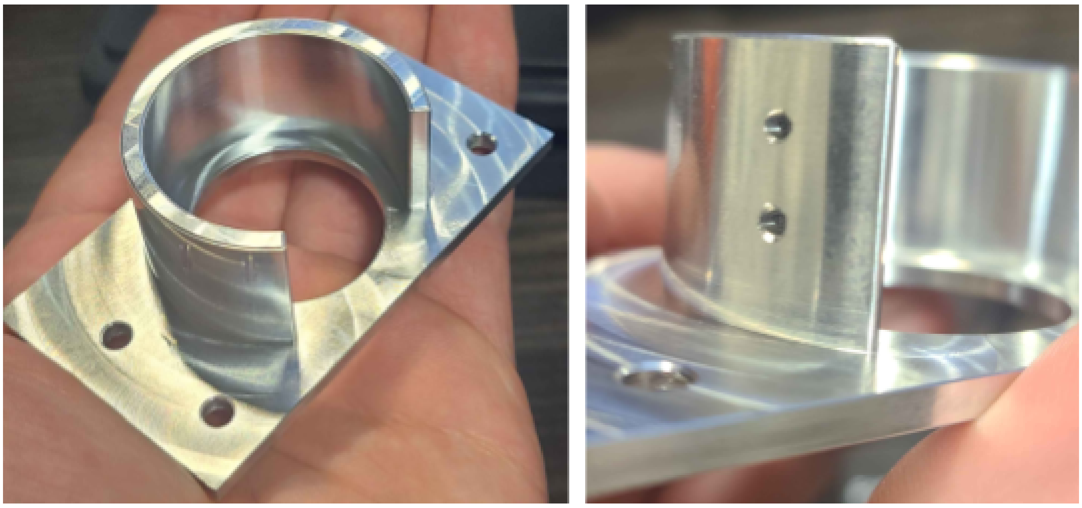

Figure 8 - Pictures of the Camera Mount

The component shown above was manufactured using a CNC machine to ensure precision. This approach allows us to produce the part accurately without requiring multiple iterations of the manufacturing process while also minimizing the risk of human error.

Computational Design Proposal

At the core of NOVA's computational system is the BeagleBoard BeagleBone Black Industrial, powered by a 1GHz ARM Cortex-A8 processor. Designed to operate within a temperature range of -40°C to +85°C, it offers the reliability and performance necessary to handle the computational demands and environmental conditions of the NOVA payload.

To ensure smooth running operations, the OBC would be undergoing conformal resin coating to ensure desired operation during extreme weather and radiation environments [6].

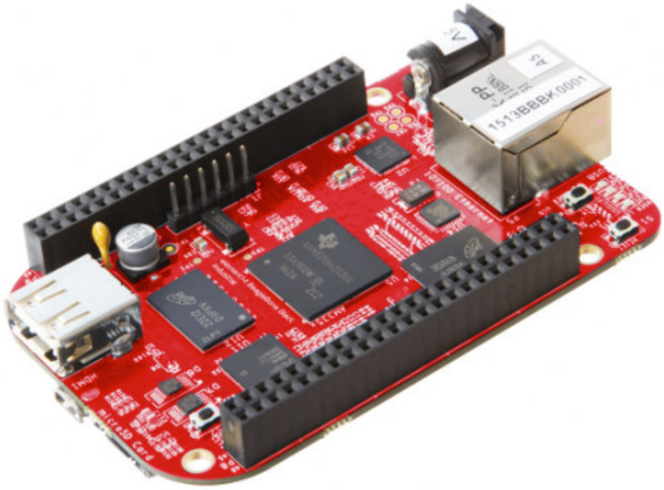

Figure 9 - Beagleboard BeagleBone Black Industrial OBC [8]

Scientific Studies

NOVA's scientific payload consists of the ZWO ASI120mm mini camera and the Raspberry Pi 6mm wide-angle lens.

Figure 10 - Camera and Lens [2] [3]

For our purpose of night sky brightness measurements, a high quantum efficiency and a low camera readout noise are key parameters. This makes the camera the driving factor in the scientific subsystem, with the lens choice being driven by our choice of camera. Test data by the manufacturer may be found in Appendix G - Manufacturer's test data for ZWO ASI120mm mini.

To ensure the camera-lens combination meets the mission requirements, the focal length of the lens was strategically chosen to closely match the Field of View (FOV) of the main payload optical system of 29.7 by 29.7 degrees as follows:

$$FOV = 2 \cdot \arctan\left(\frac{SensorDimension}{2 \cdot FocalLength}\right)$$

For the ZWO ASI120MM Mini camera, which has a sensor size of 4.8 mm × 3.6 mm, the vertical dimension of the sensor is 3.6 mm. Substituting the desired vertical FOV of 29.7◦ into the formula and solving for the required focal length:

$$FocalLength = \frac{SensorHeight}{2 \cdot \tan\left(\frac{VerticalFOV}{2}\right)} = \frac{3.6\,mm}{2 \cdot \tan\left(\frac{29.7^\circ}{2}\right)} \approx 6.78\,mm$$

This calculation shows that a lens with a focal length of approximately 6.78 mm is required to achieve the desired vertical FOV. However, commercially available lenses include a 6 mm lens, which is the closest option that maintains the required vertical FOV. Using a 6 mm lens results in the following vertical FOV:

$$VerticalFOV = 2 \cdot \arctan\left(\frac{3.6\,mm}{2 \cdot 6\,mm}\right) = 2 \cdot \arctan(0.3) = 33.4^\circ$$

This slightly exceeds the required vertical FOV, which is acceptable for the mission. Consequently, the horizontal FOV will be larger due to the sensor's rectangular shape. For a 6 mm lens, the horizontal FOV is calculated as:

$$HorizontalFOV = 2 \cdot \arctan\left(\frac{4.8\,mm}{2 \cdot 6\,mm}\right) = 2 \cdot \arctan(0.4) = 43.6^\circ$$

This larger horizontal FOV is a necessary compromise to maintain the vertical FOV alignment with the main payload. The 6 mm lens thus provides the closest practical solution, balancing the mission's scientific objectives and available hardware options. An alternative is to use adjustable lenses, which are considered in the trade study, although they come with other potential issues.

Software Design and Integration Assessment

The software architecture for the NOVA payload aimed to build upon the proven design from RSOnar II [1], but due to limited access to the previous mission, we made the choice to utilize Debian, a lightweight Linux distribution chosen specifically for its minimal resource requirements, power efficiency and compatibility with our OBC of choice. This choice is critical for maintaining our 4W power budget as per requirement 9.1.

The primary control software integrates the ZWO SDK [2] for camera operations with a custom data management system designed for continuous image capture and storage. We chose C++ as the primary programming language after a comprehensive trade study, leveraging its compatibility with the ZWO ASI120mm mini camera and its SDK [2], as well as its ability to handle complex image processing tasks more efficiently than traditional C.

Our software architecture employs a state-machine approach that provides predictable behaviour during operational mode transitions. This design ensures clear operational states for system monitoring, efficient resource management, and defined error recovery procedures. The system currently implements one exposure time of 5 seconds, but can be adjusted to different exposure times, depending on the needs of the RSOnar III team [4], enabling precise data collection for sky brightness measurements.

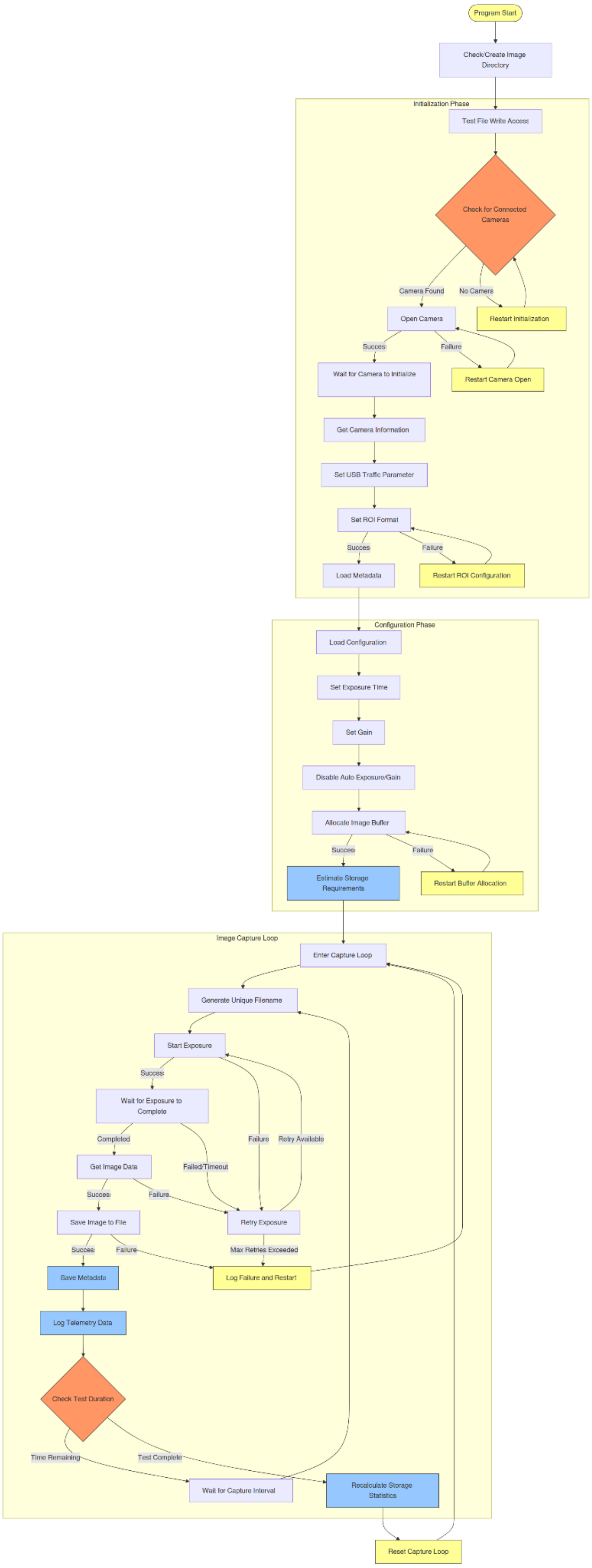

Figure 11 - Software Flowchart Diagram

Power management is a critical consideration in our software design. The application is explicitly structured to regulate power consumption, prioritizing critical functions to maintain total usage under 4W, as outlined in requirements 9.1 and 10.2 [1][6]. This is achieved through careful resource allocation, minimizing background processes, and implementing intelligent resource use efficiency between image captures.

Telemetry logging has been deliberately simplified to capture essential system parameters without introducing unnecessary computational overhead. As specified in requirement 10.3 [1], the logging mechanism records critical information such as camera connection status, image capture success or failure, storage capacity usage, and any error conditions [1]. These logs are time-stamped and stored in a human-readable format, facilitating straightforward post-mission analysis while maintaining low computational and storage requirements.

Error handling is implemented through a basic retry mechanism. The system is designed to attempt image captures continuously in case of initial failure, with each attempt logged for post-mission review. This approach balances mission reliability with software simplicity, avoiding the computational complexity of more elaborate error correction strategies. We also decided to ensure that the images are saved in two locations for data redundancy, as per requirement 8.1 [6].

The use of the BeagleBone Black Industrial OBC [8], with its industrial-grade specifications, provides initial confidence in the software's potential to operate consistently across the expected temperature range of -30°C to +50°C [6]. Planned integration testing will further validate the software's performance and reliability under the mission's challenging environmental conditions.

By prioritizing simplicity, efficiency, and targeted functionality, our software design aims to ensure that the NOVA payload can reliably capture the high-quality sky brightness measurements critical to the mission's scientific objectives.

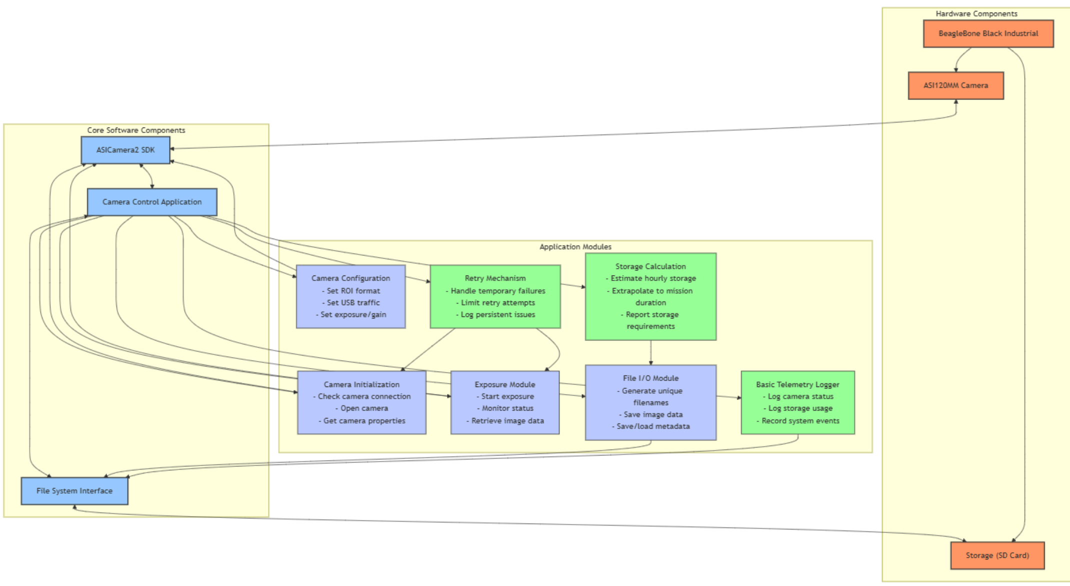

Figure 12 - Component Diagram of the Payload

Test Status Review

To ensure the NOVA payload meets all mission requirements, a structured and systematic testing approach has been implemented [6]. The test plan follows a logical progression, addressing both component-level and full-system verification. Testing has been organized into mechanical, electrical, software, and environmental evaluations, ensuring compliance with CSA regulations.

Environmental Verification and Validation

This section outlines the testing and simulations that NOVA used to verify that all requirements relating to performing reliably under the expected environmental conditions. The primary challenge within this subsystem is managing the extreme temperature variations encountered between 0 and 40 km in altitude [7]. An extensive thermal management and testing plan has been developed to ensure the payload meets all mission requirements [6]. Collaboration with the RSOnar team has confirmed that the entire payload, including all sub-payloads, will be encased in Mylar and coated with resin for thermal protection.

The payload will also be undergoing intense vibrations from launch to landing. To ensure that the mechanical design is reliable, extensive FEM testing was conducted. Given the nature of stratospheric balloon missions, the most suitable dynamic analysis is the random vibration analysis. This will most accurately evaluate how our payload responds to random, non-deterministic loads, such as atmospheric turbulence and wind gusts, which are common in balloon missions [11].

The mechanical design of NOVA prioritizes structural integrity, precise alignment, and reliability under extreme conditions while adhering to mass and spatial constraints [6]. The use of Aluminum 6061 ensures a lightweight yet robust structure, meeting the strength requirements necessary for the mission.

The ZWO ASI120MM Mini camera has been mounted at a 45-degree angle from the base, a critical placement for maintaining imaging accuracy. The camera mount is designed to mitigate vibrations during launch and descent, restricting movement across multiple axes to preserve a consistent field of view [1].

To ensure proper manufacturing and assembly, machine shop training has been provided, aligning fabrication processes with DFM standards. Vibrations experienced during launch and descent remain a key consideration and will be simulated pre-launch through vibration analysis. [11]

Table 3: Frequency vs PSD for simulations [11]

Frequency(Hz)	**PSD (g^2/Hz)**
0	0.01
20	0.01
40	0.02
80	0.04
160	0.04

320	0.04
500	0.04
1000	0.03
2000	0.01

The frequency vs PSD table below is meant to represent a very harsh rocket launch vibrational analysis. This provides an extremely large safety margin, ensuring our payload can most definitely withstand the vibrational and shock environment present during the balloon mission, provided the calculated strains are below the max of 8% for aluminum [11].

The results of the test are as follows;

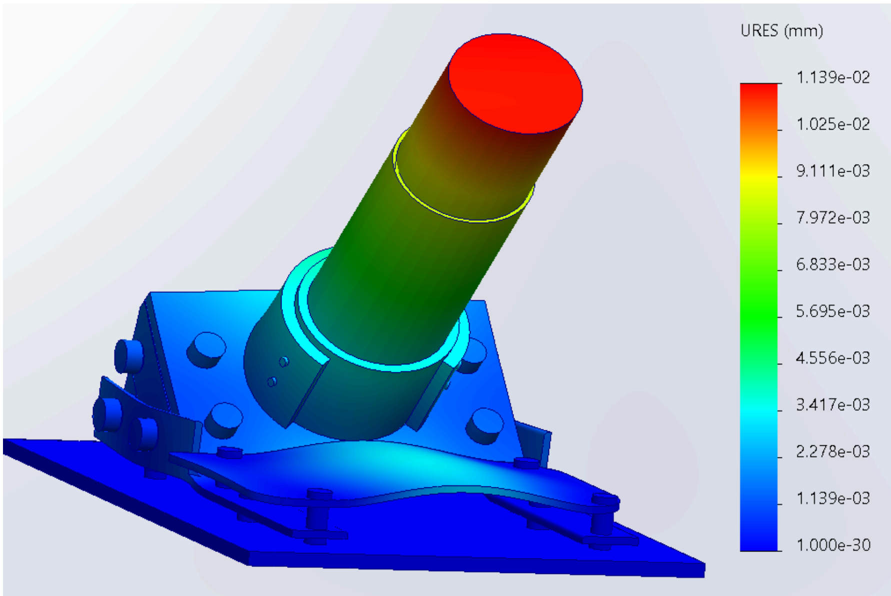

Figure 13 - Vibrational Displacement Analysis

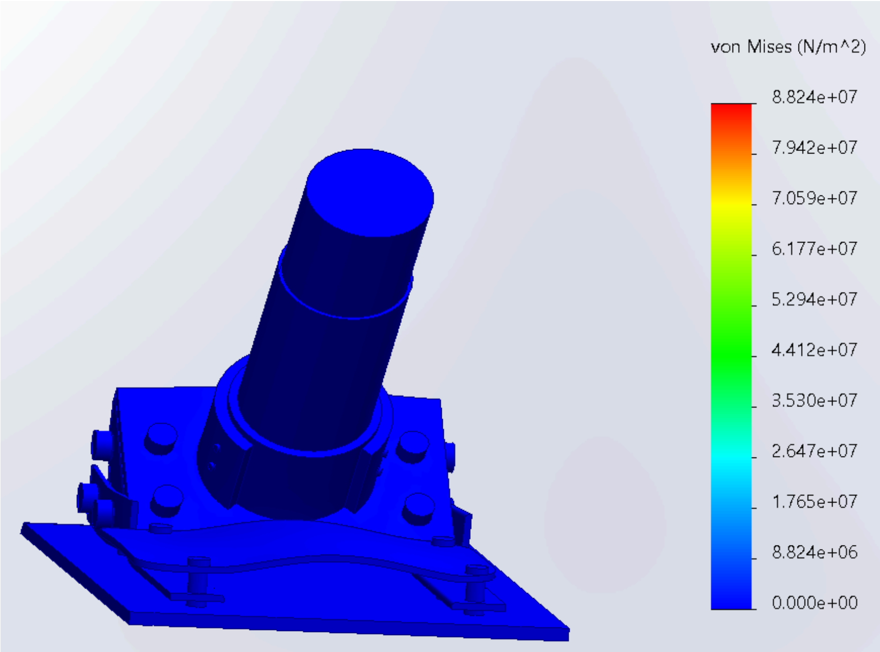

Figure 14 - Vibration Stress Analysis

Table 4: FEM Material descriptions

Material	**Density (Kg/M^3)**	**Poisson's Ratio**	**Tensile Yield Strength (Pa)**	**Young's Modulus (Pa)**
Aluminum 6061	2713	0.33	2.592e8	6.9e10
AISI 304 Stainless steel	7750	0.31	2.07e8	1.93e11
Fr-4	1944	0.1649	2.98e8	2.437e10
Camera	1038.5	0.33	2.592e8	6.9e10
Lens	2473.3	0.33	2.592e8	6.9e10

Since the camera and lens are made up of many different materials internally that are unknown, some assumptions had to be made. Since they are both encased in aluminum, their material was defined as such, but the density of both was changed to reflect their actual mass. Since we are not interested in analyzing the structural integrity of the camera and lens, but rather the mounting system and the thin OBC, this assumption works well for the purposes of our simulation. It will also allow us to define a fixed connection between the 4 set screws and the camera in order to understand any stresses that may occur on them as they are key potential failure points.

All parts were meshed as shown in the image below:

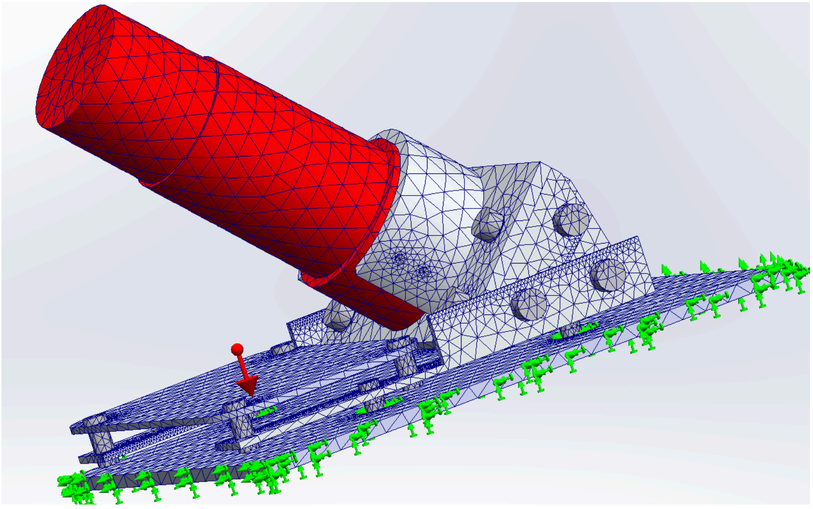

Figure 15 - Contact Points of the Assembled Payload

The contact points were defined as bonded connections between all hardware and parts. For the camera holder and camera, a frictional bond was applied. A key failure point is the set screws, so a conservative (low estimate) aluminum-on-aluminum coefficient of friction of 0.3 is applied. This allows us to effectively simulate the set screw placement, and determine whether the set screw camera holder design is valid.

The bottom plate is given a fixed constraint (highlighted in blue) as shown below:

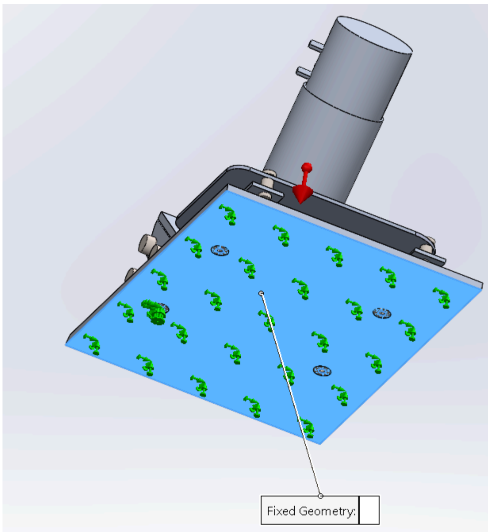

Figure 16 - Constrained Plane of the payload

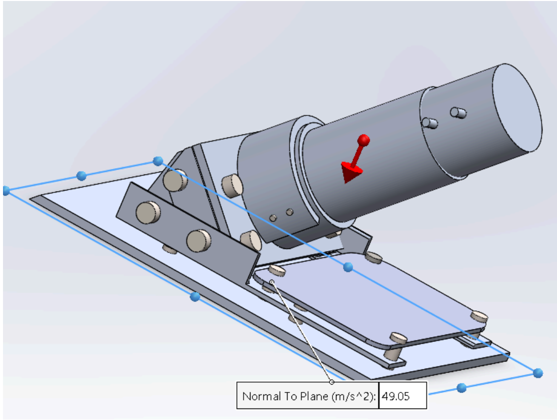

Figure 17 - Gravity direction Vector on the Payload

An acceleration of 10G (-98.1m/s^2) was applied for the first analysis. This is much higher than the expected load to provide a large safety margin.

As you can see, even with a 10G load, the expected displacements are well below 0.1mm.

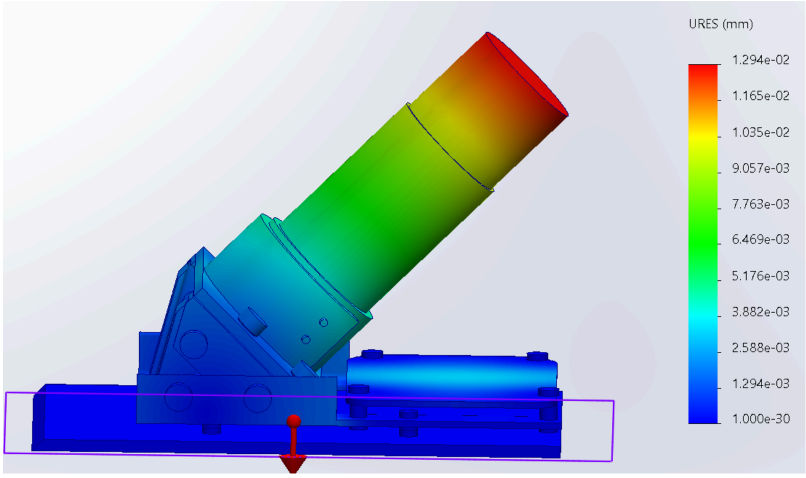

Figure 18 - Displacement analysis

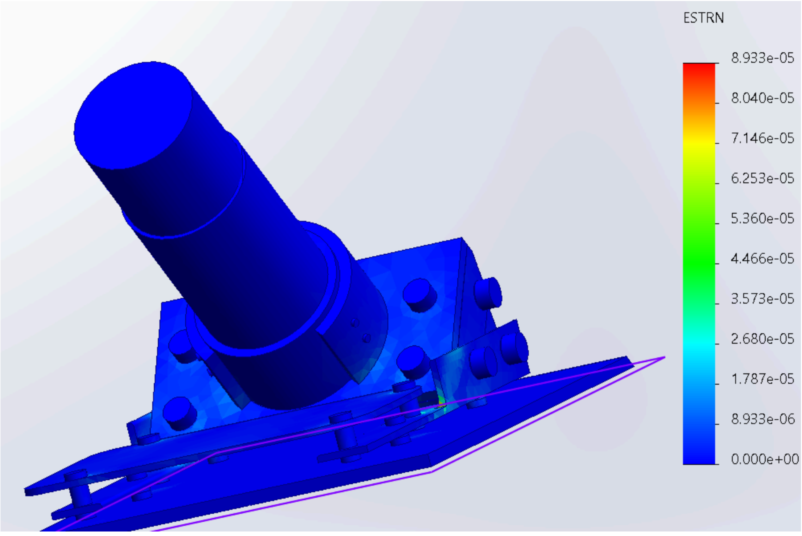

Figure 19 - Strain Analysis

The maximum computed strain value of 0.00893% is well below the allowable limit, indicating no structural concerns related to stress.

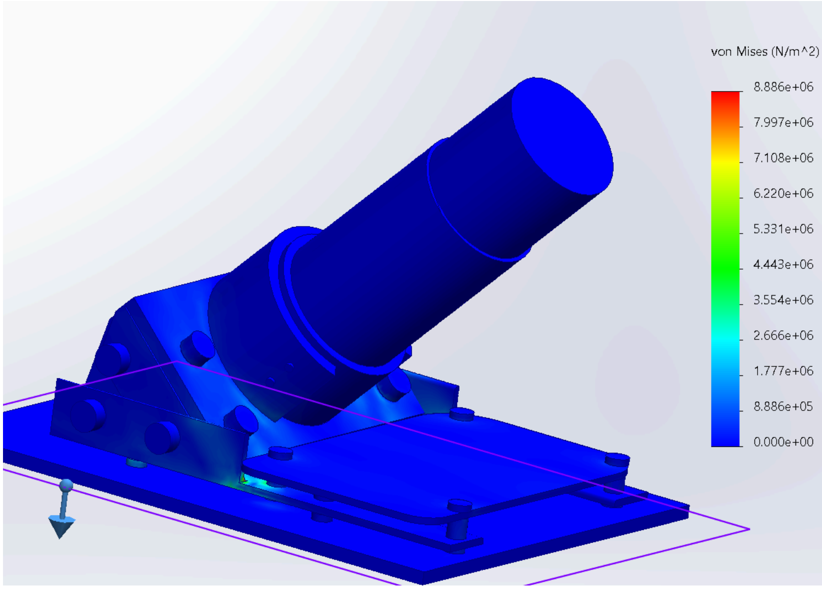

Figure 20 - Stress Analysis

Given the yield strengths of aluminum and stainless steel, we are well below these values at our maximum stress points.

Aluminum 6061- 2.76 × 10^8 N/m^2

AISI 304 Stainless Steel - 2.4 × 10^8 N/m^2

Table 5: Verification of Mechanical Requirements

Req. ID	**Abbreviated Requirement Statement**	**Verification Method**	**Status**
2.2	Withstand 30°C to +50°C (no thermal test, but rated components + resin)	Component specs, design review of insulation.	**Verified** (Design Review)
2.6	Function under UV/low pressure typical of the stratosphere	Resin coating, data on Mylar reflectivity.	**Verified** (Design Review)
2.7	Anti-condensation measures	Resin sealing & enclosed design	**Verified** (Design Review)
3.2	Maintain 45° camera alignment	FEM-based alignment checks under load and vibration.	**Verified** (FEM)

3.3	Withstand vibrational loads (random vibration analysis)	FEM simulation @ 10 G, high PSD margin	**Verified** (FEM)
3.4	Structural stability with minimal weight (Aluminum 6061)	Mass measurement + FEA stress < yield	**Verified** (FEM)

Electrical and Computational Testing

The NOVA payload's electrical and computational testing has been combined into a single category due to the high interconnectedness, as the OBC is powering all components. It is designed to ensure reliable operation under the mission constraints of 5V and 4W. Based on our research and component specifications, we anticipate the BeagleBone Black Industrial [8] will draw approximately 2.3W during peak processing and storage operations, and the camera will draw 1.5W, which would keep us below our 4W threshold.

For storage capacity verification (requirement 4.1) [1], we have designed a testing procedure that will involve a 1-hour continuous image capture test, with data size extrapolation to the full mission duration. This approach replaces our initial requirement for a full 780-minute test while providing equivalent verification with reduced testing time. Based on camera specifications and image size calculations, we expect to utilize approximately 24GB of our 256GB storage capacity over the full mission, providing a comfortable margin, as well as providing enough extra memory to save backups of each image taken by our camera.

To validate non-volatile storage reliability (requirement 4.2) [6], we will conduct simulated power failure testing. This will involve multiple power interruption tests during active write operations, followed by a system restart and data integrity verification. These tests will ensure our storage system is resilient to unexpected power loss situations that might occur during the mission.

Our trade studies and component selection process, approved by mission supervisors, indicate the BeagleBone Black Industrial [8] should meet all computational requirements. The industrial-grade OBC is rated to operate within our mission's temperature range of -30°C to +50°C without additional fault tolerance mechanisms, which supported our decision to remove requirement 4.4 as unnecessary.

Additional risk mitigation strategies include plans for resin coating of the computational components and proper vibrational testing to ensure data integrity in the event of thermal shock upon landing. These protective measures will further enhance the reliability of our computational subsystem under mission conditions [6].

Power Delivery and Regulation

Initial Issue Resolution: Early testing revealed that the USB power source prevented consistent imaging with the camera. By rerouting the power delivery to the 5V barrel jack port, the electrical design now functions reliably, as confirmed by subsequent measurements.

Power Consumption Testing: Using a digital multimeter, we verified that the system draws approximately 3.7 W during peak processing and storage, leaving a small margin below the

4 W maximum. Image testing has confirmed stable power delivery and reliable operation during continuous operation for 15 hours in each operating mode.

Extended Duration Operation

The entire system was tested continuously for >15 hours while being powered by the external power supply. The test demonstrated that the imaging system maintains steady performance, with no power spikes or unexpected behaviour.

BeagleBone Black Industrial Performance

The OBC was tested under full imaging load to verify that it consistently operates within the expected power budget of 4 W during peak processing. Extended testing for 15 hours in each mode was executed, with steady performance and consistent data processing observed throughout.

Storage and Data Integrity

A 1-hour continuous imaging test was conducted. The storage size of the resulting images was then extrapolated to confirm that only 22.4GB of the available 256GB will be used, leaving 233.6GB of extra storage space in case of an extended mission duration of 24 hours.

Power Loss Reliability

Power loss tests were carried out during active imaging and write operations. The payload successfully restarted the image collection sequence and retained all data, confirming the robust and reliable data protection and storage.

Table 6: Verification of Electrical and Computational Requirements

Req. ID	**Requirement Statement (Abbrev.)**	**Verification Method & Test Duration**	**Status**
1.1 / 9.1	Operate at 5 V ± 0.5 V with total consumption ≤ 4 W	Power draw measurements using a digital multimeter; confirmed during 15-hour tests.	**Verified**
4.1	Sufficient storage for continuous image capture for 780 minutes	1-hour capture test with extrapolation; confirmed projected usage of 22.4GB	**Verified**
4.2	resiliency under power interruptions	Power interruption tests during active writes and images; data integrity was confirmed.	**Verified**

Endurance Test	The main operational mode functions continuously for 15 hours	Continuous 15-hour for 5-second exposure mode; steady power and performance observed	**Verified**
Telemetry	Accurate logging of critical parameters with < 50 ms deviation	Analysis of time-stamped logs during mode operation and switching tests	**Verified**

Scientific Testing

The main purpose of the NOVA payload is to capture high signal-to-noise ratio (SNR) images for accurate sky brightness measurements to improve RSO detection. To verify that mission requirements regarding the expected science, the following verification tests have been executed or planned. These tests include field and laboratory imaging, calibration algorithm validation, and an indirect evaluation of mount stability.

Night Sky Imaging Verification

The camera system was used for imaging outdoors under actual nighttime conditions. The NOVA team went to Gilford Beach, just outside of Toronto light pollution. Test images were captured to demonstrate that: Stars were clearly visible, and background brightness measurements vary with artificial light variations (outdoor light). Given the extremely wide field of view and the small aperture, the expected outcome is very dim stars. As shown in the image field test image below, we were able to capture stars even under a portal 4 sky brightness level, showcasing the robust capabilities of the NOVAS camera sensor.

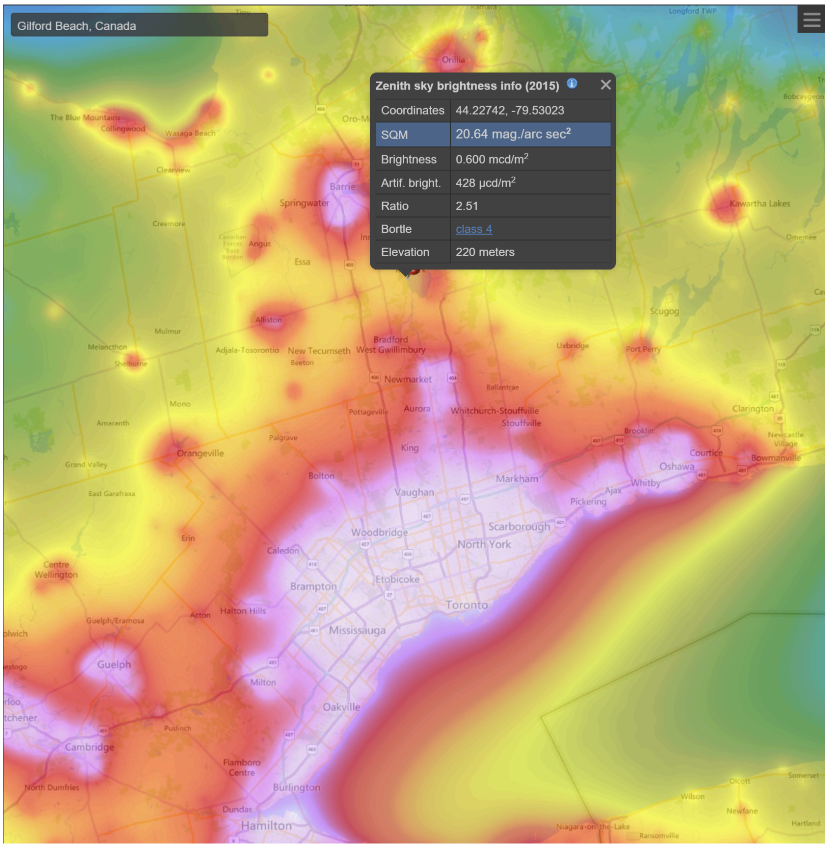

Figure 21 - Field Test Location

Figure 22 - Field Test Image

Flat-Field and Bias Image Testing

Bias frames were captured with the camera shutter closed on the lowest exposure time (0.01s) to measure sensor dark current and inherent noise levels. Flat field images were also captured using a uniformly illuminated white wall to Calibrate pixel-to-pixel sensitivity differences, and enable software calibration for post-mission processing to remove sensor noise effectively. These images ensure that subsequent image processing will reliably reduce noise and enhance the SNR.

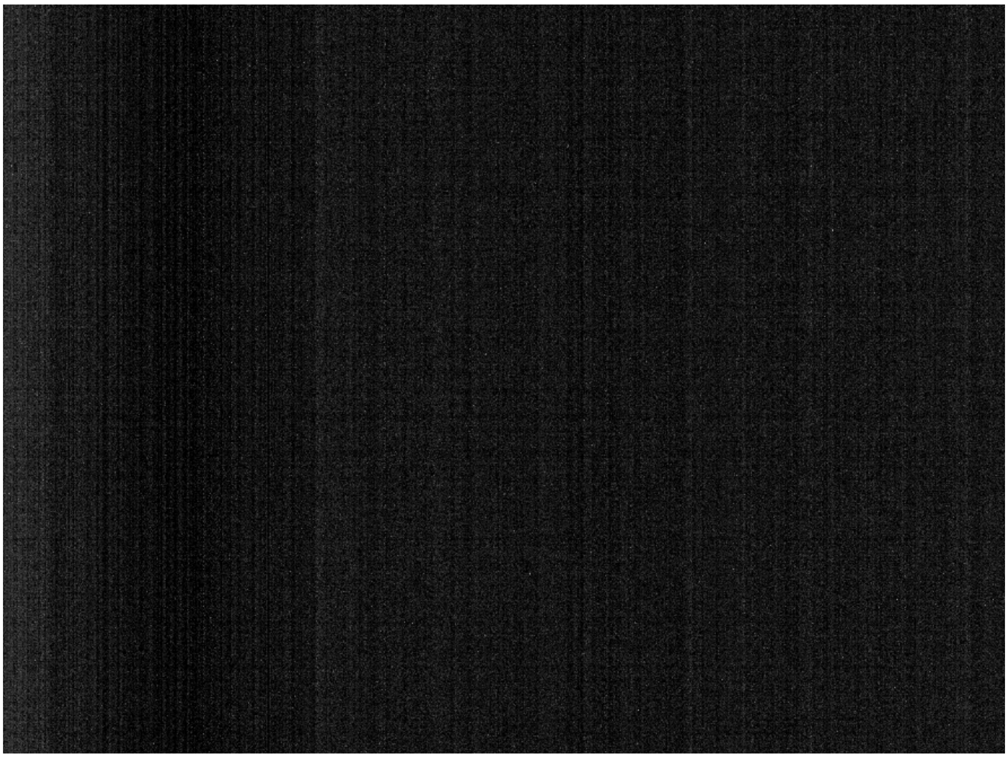

Figure 23 - Bias Image

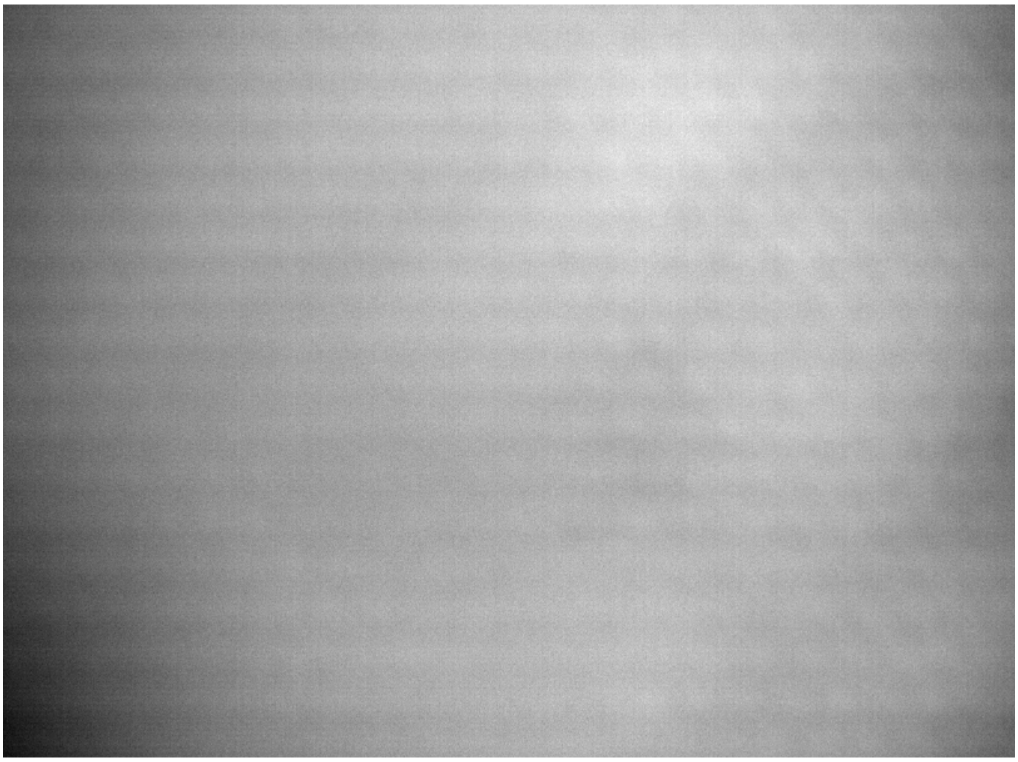

Figure 24 - Flatfield Image

Mount Stability Verification

The stability of the camera mount is critical for maintaining the proper 45° alignment. This has been verified through FEM load and vibrational displacement testing that ensures no vibrational nodes will cause excessive blurring.

Table 7: Verification of Image Capture Capabilities

Req. ID	**Test Area**	**Test Description**	**Verification Method**	**Status**
5.4	Night Sky Imaging	Capture nighttime images to verify that stars are visible.	Outdoor imaging field test	Verified (Field Test)
5.5	Bias Frame	Acquire dark frames with the shutter closed to measure sensor dark current and inherent noise.	Laboratory images of bias frames	Verified (Lab Test)

5.5	Flat-Field Calibration	Capture uniformly illuminated images to calibrate sensor sensitivity and correct pixel non-uniformity.	Laboratory flat-field image frames	Verified (Lab Test)
5.2	Calibration Algorithm Validation	Process field test images using background subtraction and noise reduction algorithms.	Compare the star SNR levels before and after calibration	Verified (Software)
3.2	Mount Stability (Indirect)	Confirm that the camera mount maintains a 45° alignment and a stable field-of-view under vibration or load.	FEM analysis	Verified (Field Test)

Software Justification

The selection of Linux as our operating system was justified through many factors. As it has many variations, it yields the necessary drivers and tools for our hardware while minimizing overhead processes. This is critical for maintaining our 4W budget as per requirement 9.1 [1], with an expected power draw of approximately 1.8W during normal operations based on similar implementations in stratospheric missions [4][5].

The implementation of one exposure time of 5 seconds supports our mission's scientific objectives by making sure we can maintain consistent data collection intervals, ensure synchronization with the main payloads' imaging, and provide flexibility for varying light conditions. We must also enable direct comparison with RSOnar III's primary camera data collection [4]. Our state-machine architectural approach is designed to provide predictive behaviour during mood transitioning, clear operational states for system monitoring, efficient resource management, and defined error recovery procedures.

The ZWO SDK implementation is due to its compatibility with our camera hardware [2] and its ability to provide efficient image data handling, direct access to camera parameters, and built-in error-checking capabilities. This is also the reason we are using C++ as our coding language of choice, as the SDK is written in this language, and it has the most benefits when it comes to image-capturing software implementation.

Project Management Updates

Project Task Management Status (WBS Update)

Please note that the boxes highlighted in green have been completed, whereas the boxes highlighted in purple define our plan for the upcoming weeks. This work breakdown structure provides us with a well-defined plan that allows us to successfully finish a working solution for our capstone project.

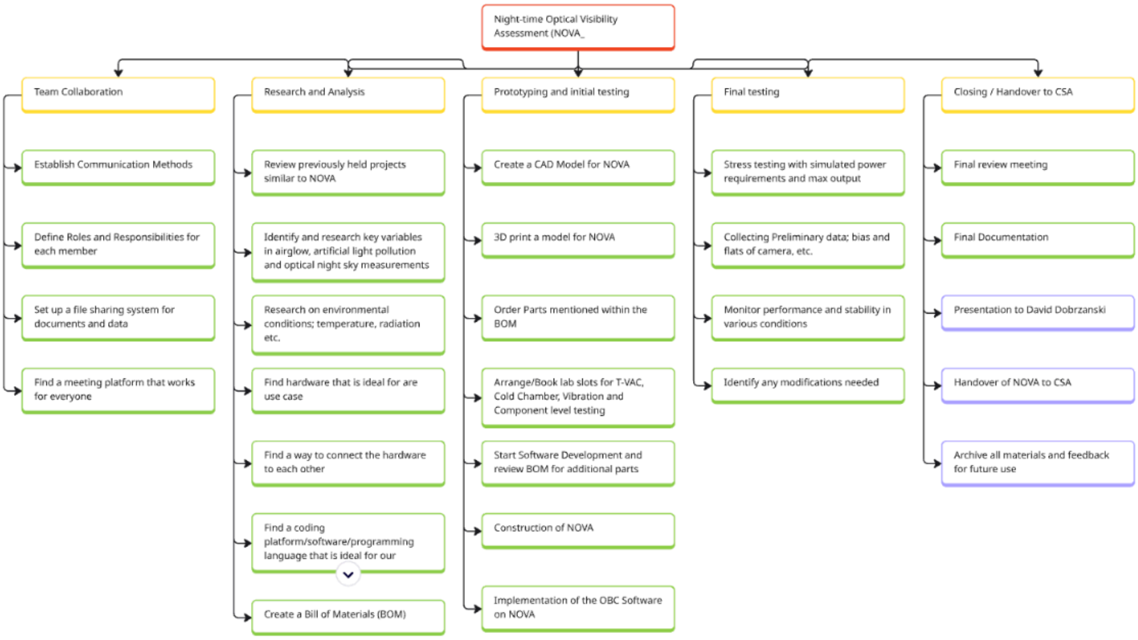

Figure 25 - Work breakdown structure outlining the finished work packages

Project Schedule (Gantt Chart Update)

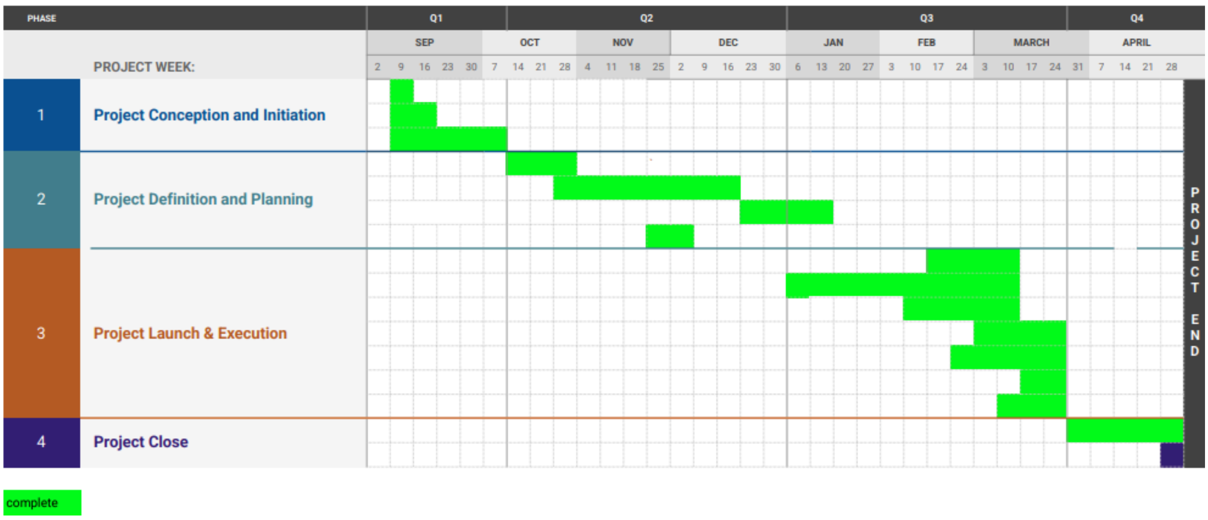

Figure 26 - Updated Gantt Chart

The phases, as mentioned above in comprise of the following sub-sections:

Phases:

1. Project Conception and Initiation
    a. Establish Communication Methods
    b. Define Team Roles and Responsibilities
    c. Preliminary Research and Planning
2. Project Definition and Planning
    a. Hardware Selection
    b. Integration and Calibration Planning
    c. Research Key Variables
    d. Budget/Create BOM
3. Project Launch and Execution
    a. Component Testing-
    b. Implementation of Software
    c. Subsystem Testing
    d. System Testing
    e. Interface Testing
    f. Final Integration
    g. Construction of NOVA
4. Project Close
    a. Final Review and Preparation
    b. Handover NOVA to the RSOnar Team

The Gantt Chart has been updated to reflect the project's progress. Phases 1, 2, and 3 have been completed (marked in bright green). The final review and preparation are underway. The last remaining task for this project is the handover of NOVA to the RSOnar Team and CSA.

Resource Allocation

Name	April 2025- Software Dev (	April 2025- Mechanical De	April 2025- Testing and Val	April 2025- Project Manag	April 2025- Documentation	Total Hours
Harrish Elango	18	3	10	0	10	125
Katia Kassabov	1	2	5	2	10	121
Prajakta Lal	1	2	5	3	10	121
Gaurav Charan Moturi	20	7	10	0	10	127
Sarthak Sahai	10	8	10	0	10	127
Aiden Weatherbee	20	8	10	1	10	131

Figure 27 - Resource Allocation Matrix

A resource allocation matrix has been developed with all of the team members' hourly contributions over the duration of the course. Above are the logged hours by the team for April, as well as the total hours per member over the course of the project.

As we reached the end of the project, a lot more time had to be put into the software development and testing, as well as the mechanical assembly. More documentation than previously was required for the final review.

Reimbursement Status	Expense details	Category	Cost	# of Units	Total Cost	Transaction date	Paid by	Notes	Remaining Budget
☐	BeagleBoard BeagleBone Black Industrial	OBC	113.59	1	113.59	19/01/2025	Aiden Weatherbee	https://www.digikey.	386.41
☐	ZWO ASI120MM	Camera	225	1	225	01/03/2025	Gaurav Charan Moturi	https://all-startelesc	161.41
☐	Raspberry Pi 6 mm Wide Angle Lens	Lens	52.07	1	52.07	05/02/2025	Gaurav Charan Moturi	https://www.pishop.	109.34
☐	Micro SD card	Other/Miscellaneous	49.99	1	49.99	19/01/2025	Aiden Weatherbee	https://www.bestbuy	59.35
☐	Aluminum Angle	Chasis	1.63	2	3.26	17/03/2025	Gaurav Charan Moturi	https://www.mcmas	57.72
☐	Bolt - m4 x 0.7 mm thread	Fasteners	##	10	0	17/03/2025		Already have	57.72
☐	Washers, metal, for m4 screws	Fasteners	3.57	1	3.57	17/03/2025	Gaurav Charan Moturi	https://www.mcma:	54.15
☐	M4 hex nut, 0.7 mm thread pitch	Fasteners	##	10	0	17/03/2025		Already have	54.15
☐	Bolt- M3 x 0.5mm thread	Fasteners	11.11	1	11.11	17/03/2025	Gaurav Charan Moturi	https://www.mcma:	43.04
☐	Hex nuts, m3 thread	Fasteners	##	8	0	17/03/2025		Already have	43.04
☐	Flat head m3	Fasteners	3.96	1	3.96	17/03/2025	Gaurav Charan Moturi	https://www.mcma:	39.08
☐	M3 Male-Female Threaded Hex Standoff	Fasteners	3.56	1	3.56	17/03/2025	Gaurav Charan Moturi	https://www.mcma:	35.52
☐	Set screws, m2 x 0.4 mm thread	Fasteners	5.66	1	5.66	17/03/2025	Gaurav Charan Moturi	https://www.mcma:	29.86
☐	Loctite	Other/Miscellaneous	##	1	0	17/03/2025		Already own	29.86
☐	Type A to C Charging Cable	Other/Miscellaneous	18.95	1	18.95	21/04/2025	Gaurav Charan Moturi	https://www.amazon	10.91

Figure 28 - Budget Tracker

The budget tracker has been revised to account for the team's purchases to date and the updated list of required materials needed to successfully complete the project. The team is still awaiting reimbursement on purchases, but all items have been received, and the project stayed within budget.

Risk Register

Table 8: Risk Register

ID	Risk	Impact	Likelihood	Mitigation Strategy	Status
1	**Thermal Failure**	High	High	Mylar, foam insulation, resin coating, thermal coupling, heatsink, cold chamber testing.	Retired
2	**Vibration Damage**	High	High	Vibration testing. Use of durable materials. Rigid harnessing of the project to the payload. Resin coating	Retired
3	**Radiation Interference**	High	High	Use of error-correcting algorithms in the SD card when saving the data.	Retired
4	**Schedule Delays**	High	High	Gantt Chart, Time buffers, Critical task prioritization, and ensuring fast delivery times of components.	Retired

5	**Power Constraint of 4W**	High	Medium	Parts chosen for the project with power usage in mind. Discuss with project leads if more power is required.	Retired
6	**Payload Integration**	High	Medium	Work closely with the primary payload team. Use of the Interface Control Document for specifications.	Retired
7	**Component Failure**	High	Medium	Use of robust and highly reliable equipment and modules	Retired
8	**Data Loss**	High	Medium	Use of non-volatile solid-state storage. Have a data loss protocol in place.	Retired
9	**Over Budget**	Medium	Low	Budget reviews. Consider cheaper alternatives when possible while maintaining functionality.	Retired
10	**Regulatory Compliance**	High	Low	Working closely with CSA to adhere to regulatory and safety compliance.	Retired
11	**Camera Calibration Error**	High	Low	Will be using “Flats” and “Biases” to ensure that the camera is calibrated well before flight. Testing will be done prior as well.	Retired

Deviations from Plan

Some of the difficulties we encountered were not having enough image processing power due to the combination of our camera and OBC when working together.

Image Format and Resolution

- Planned: Capture images in 16-bit format at 1280 × 960 resolution to allow detailed brightness analysis.
- Deviation: The camera failed to function reliably in 16-bit mode at high resolution.
- Response: Temporarily used 8-bit images at full resolution, then reverted to 16-bit format with reduced resolution (640 × 480) to ensure scientific validity.
- Impact: Slightly reduced spatial detail, but allowed brightness-based star differentiation. Enabled the mission’s scientific goals to remain achievable.

Exposure Time Limitations

- Planned: Capture long-exposure images (5 seconds) to enhance low-light sensitivity.
- Deviation: The camera was unable to operate reliably at 5 seconds due to hardware and processing limits.
- Response: Exposure was reduced to 0.9 seconds (manufacturer-supported), then reverted to 5 seconds after resolution was lowered.
- Impact: Final configuration balanced exposure and resolution to restore high-SNR imaging.

Thermal Management Material Switch

- Planned: Use multilayer Mylar insulation to regulate payload temperature.
- Deviation: Switched to conformal resin coating based on discussions with the RSOnar III team.
- Response: Re-evaluated the thermal strategy and opted for resin due to improved durability and lower outgassing.
- Impact: Enhanced thermal stability and reduced risk of condensation without exceeding mass limits.

Delays in Hardware Procurement

- Planned: Begin integration and software testing in January 2025.
- Deviation: Delayed due to the late arrival of the OBC and camera units.
- Response: Conducted software development on laptops as an interim measure and shifted hardware-specific testing to February.
- Impact: Tightened testing schedule, but the team compensated with extended working hours and prioritized mission-critical tests.

Limited Dark Sky Testing

- Planned: Conduct star imaging under Bortle 2–3 skies.
- Deviation: Only able to reach a Bortle 6 location (Gilford Beach) due to time and travel constraints.
- Response: Increased exposure time during field testing to simulate ideal conditions and validate image quality.
- Impact: Validated imaging pipeline under less-than-ideal conditions, but the full sensitivity range may not have been tested.

6. Software Integration Challenges

- Planned: Full camera operation using OBC by February.
- Deviation: Faced delays integrating the camera SDK with the BeagleBone Black Industrial.
- Response: Used laptops for initial camera validation and transitioned to OBC once integration was stable.
- Impact: Minor delay in OBC-based testing, but the final system achieved stable, continuous operation.

Failure Report

This section outlines the key technical and operational issues encountered during the NOVA project, along with the corrective actions taken. Each entry reflects deviations from the original plan and the team's response to ensure mission success.

Change in Image Resolution

Objective:

The NOVA team aimed to capture images in 16-bit format to accurately measure the brightness of stars observed by the payload camera. The 16-bit format provides a brightness range from approximately -32,000 to +32,000, which is essential for astronomical imaging and scientific analysis.

Issue Encountered:

During system integration, the team encountered technical difficulties while attempting to capture images in 16-bit format that matched the field of view (FOV) of the primary payload camera. These compatibility challenges prevented reliable image acquisition in the intended format.

Temporary Solution:

To maintain imaging capabilities, the team temporarily switched to capturing images in 8-bit format at a resolution of 1280 × 960 pixels. Although this allowed continued testing and data collection, the reduced bit depth did not provide sufficient brightness data for meaningful analysis.

Final Adjustment:

To address this limitation, the team restored the use of the 16-bit image format to enable effective brightness measurement. To accommodate processing and storage constraints, the resolution was lowered to 640 × 480 pixels. While this resulted in reduced spatial detail, the camera can now differentiate and compare star brightness levels as required for the mission.

Conclusion:

This configuration allows the mission to achieve its primary objective of accurate brightness analysis of celestial bodies. The team will continue to refine image processing strategies in future payloads to support higher resolution and improved data quality.

Change in Image Exposure Time

Objective:

The NOVA team initially aimed to capture long-exposure images with a 5-second exposure time to maximize light collection from faint celestial objects. Longer exposure times are typically preferred in astronomical imaging to enhance star visibility and contrast.

Issue Encountered:

During initial testing, the camera failed to operate correctly at a 5-second exposure time. This malfunction was attributed to the camera's hardware limitations, as it was not originally designed to handle such long exposures at the set resolution and processing configuration.

Interim Solution:

To ensure image capture could proceed, the exposure time was reduced to 0.9 seconds, which aligned with the camera's native design specifications. This change allowed the system to function reliably, but the shorter exposure time resulted in reduced sensitivity and limited the ability to detect dimmer stars and distant objects.

Final Adjustment:

After further testing, the team restored the 5-second exposure time. To accommodate this change, the image resolution was reduced, which eased the camera's processing load and resolved previous operational failures. With the lower resolution in place, the camera successfully captured long-exposure images without performance issues.

Conclusion:

The adjustments made to exposure time and resolution allowed the NOVA payload to balance sensitivity and system stability. The ability to use a 5-second exposure significantly improves the quality of star observations, ensuring that the mission objectives related to brightness measurement and object detection can be met effectively.

Lessons Learned

The NOVA team learned many different lessons from their failures throughout this semester. One of the biggest things is the value of obtaining flight hardware as early as possible. One of the key enablers of successful stratospheric balloon payloads is thorough testing. Obtaining key flight hardware like the camera and OBC early is required to start development of flight software, therefore allowing key testing to take place. Key testing that the NOVA team was unable to perform due to financial and time constraints includes:

1. **Cold Chamber Testing-** The on-campus testing chamber was damaged. The cost of creating a mock test with liquid nitrogen is out of our cost range.
2. **Vacuum Testing-** There were delays with the main payload and 3 sub-payloads in delivering the payloads in a timely manner, therefore, vacuum testing has not been conducted.
3. **Dark Sky Testing-** Due to the team's busy schedule, the darkest sky location we were able to make it to for field testing, Gilford Beach in Innisville, Ontario, a level 6 on the Bortle scale. This gave us issues with effectively imaging stars, so the exposure time had to be increased to a 1-minute exposure to effectively capture stars.
4. **Board Image Testing-** We took longer than expected to effectively make our OBC take images in a 16-bit format. This meant that for field testing, we had to use a laptop for imaging. We then did outdoor testing with the OBC, but not at a dark sky location.

5. **Proven Hardware = Best-** This is the third RSOnar mission. With 2 proven flights, it would likely have been a better idea to try and secure extra funding for the proven camera hardware. This would likely have mitigated our problems with hardware integration between the camera and OBC and enabled larger and longer exposure images.

Self-Evaluation

This section provides a critical assessment of the NOVA team's performance across technical, collaborative, and project management domains. It reflects on our adherence to requirements, problem-solving strategies, and overall execution, using evidence from the final report to support each evaluation.

Table 9: Self-Evaluation Table

Criterion	Self-Evaluation Ranking	Justification
Clarity and completeness of project objectives	Exceeding	Objectives are clearly stated in Section 2: Mission Objectives, aligning directly with the calibration needs of the RSOnar III payload and broader SSA goals. Each objective is specific, measurable, and rooted in practical mission applications.
Alignment of final design with requirements	Meeting	The design reflects all defined electrical, mechanical, environmental, and scientific requirements, as shown in Section 3: Requirements and Section 4: As-Built Design. Each subsystem was validated against its respective performance criteria.
Subsystem integration and system-level thinking	Exceeding	The payload’s electrical, thermal, computational, and structural elements were successfully integrated, as shown throughout Section 4. Power and data flows are mapped in Figures 1 and 2, showing deep attention to interdependency and system-level planning.
Demonstrated technical feasibility through simulations and testing	Meeting	FEM analysis, vibrational testing, and thermal mitigation strategies are outlined in Section 5: Test Status Review, and Figures 12–19. These demonstrate that the payload is capable of surviving the mission environment.
Robustness of environmental and thermal design	Meeting	The payload was designed to operate between 30°C and +50°C using resin coatings and passive thermal regulation. See Section 4.2: Environmental Subsystem and Figure 3 for insulation strategies and trade studies.

Power and data system reliability under mission constraints	Exceeding	The system operated within the 4W power limit and used a robust 5V power supply configuration, as tested in Section 5.2: Power Delivery and Regulation. The OBC, camera, and SD card worked continuously for over 15 hours.
Software design efficiency and error handling	Meeting	The C++ software implemented a state-machine architecture with retry mechanisms and logging, described in Section 4.6: Software Design. Telemetry was simplified to reduce overhead, satisfying power and storage constraints.
Scientific rigor in imaging and data collection strategy	Meeting	The imaging approach used 16-bit depth and various exposure settings for accurate brightness measurement, validated by Section 5.3: Scientific Testing and Section 5.4: Bias and Flat Field Testing.
Use of trade studies and component selection logic	Meeting	Trade studies on thermal materials, lenses, and software architecture are discussed in Appendix G. Selections prioritized mission fit, cost, and performance, with clear rationale.
Quality and depth of the final written report	Exceeding	The report is 90+ pages, highly structured, and supported by diagrams, simulations, and test results. It includes a full BOM, testing rationale, trade studies, and appendices for transparency and completeness.
Effectiveness of testing and validation methods	Meeting	Testing included long-duration operation, thermal design validation, power reliability, and FEM vibration analysis. These are documented in Section 5: Test Status Review and Appendices.
Project management and timeline adherence	Meeting	The team maintained and followed a detailed Gantt chart (Figure 21) and WBS (Figure 20) with weekly progress reflected in meeting minutes. Project phases were completed on time with contingency built in.
Adaptability in response to challenges and failures	Exceeding	The team responded to hardware failures by modifying image resolution and exposure time, documented in Section 6: Change in Image Resolution and Change in Image Exposure Time. These changes were validated by retesting.
Communication and collaboration within the team	Exceeding	Team reflections in Section 7: Team Reflections demonstrate high levels of collaboration, cross-functional support, and shared accountability, with team members stepping outside their roles as needed.

Engagement with mentors and external stakeholders	Meeting	The team regularly engaged with mentors, including Prof. Bazzocchi and Dr. Ryan Clark, and coordinated integration with the RSOnar III team and CSA advisors. This is referenced in both the acknowledgements and technical integration sections.
Overall mission readiness and completeness of deliverables	Meeting	The payload meets all outlined functional, safety, and testing requirements, with completed integration and readiness for flight. All deliverables, including code, report, CAD, and testing data, are included.

Preliminary Business Case

The NOVA sub-payload addresses a critical need in the field of space situational awareness (SSA): improving the detection and tracking of resident space objects (RSOs) through accurate night sky brightness calibration. With over 200,000 RSOs currently in Low-Earth Orbit (LEO), and increasing risks posed to operational satellites, there is growing demand for reliable, cost-effective, and high-precision calibration systems for optical payloads.

NOVA presents a low-cost, scalable solution that enhances the performance of field-of-view (FOV) space surveillance systems. By providing high signal-to-noise ratio (SNR) brightness measurements and a redundant imaging system aligned with the main payload's camera, NOVA enables more accurate background subtraction and discrimination between try RSO signals and noise sources such as cosmic rays. This improves the reliability of space-based object tracking, especially in stratospheric environments where traditional ground-based systems are limited.

From a development perspective, NOVA demonstrates strong cost-efficiency by using commercially available off-the-shelf (COTS) components and modular subsystem design. This reduces both development time and hardware costs, making it an attractive option for future balloon or CubeSat missions. The thermal management and compact mechanical design also make NOVA adaptable to a range of altitudes and mission profiles.

Table 10: SWOT Analysis

Strengths	Weaknesses	Opportunities	Threats
High SNR, low-cost imaging system	Limited resolution due to cost	Integration into future CubeSats and satellite calibration missions.	Environmental exposure risks
Redundant calibration for optical payloads	Dependent on the host payload for power	Applications in outreach and research	Potential delays in component availability or launch readiness

Proven thermal and mechanical robustness	Mission duration is restricted by balloon flight time		

Overall, NOVA delivers clear stakeholder value by advancing stratospheric SSA capabilities with a reliable, efficient, and mission-ready sub-payload. It lays the groundwork for future adaptations in orbital platforms. Additionally, it offers critical data to support collision avoidance and satellite operations in the increasingly congested LEO environment.

Team Reflections

The following outlines the team members responsibilities as well as other factors that may influence their performance within the capstone project. It also serves as a summary of the ITP Feedback they have received and their future motives.

Harrish Elango

Role: Integration Lead

Responsibilities:

- Oversee software architecture, coding, and debugging processes collaboratively with the Software Lead.
- Ensure seamless integration and compatibility among all components.
- Coordinate integration testing to validate system performance under mission conditions.

Skills and Qualifications:

- Strong problem-solving abilities.
- Quick learner who applies new knowledge effectively.
- Proficient in troubleshooting integration issues and optimizing system performance.
- Adaptable team player, skilled in diverse technical environments.
- Familiar with coding practices across various software, hardware, and operating systems.

Motivation:

- Passionate about contributing to space exploration and technology advancement.
- Merge personal interests in technology and space into meaningful outcomes.

Fulfilling Team Gaps:

- Offer a holistic technical perspective to bridge gaps across disciplines and subsystems.
- Leverage a broad skill set to align the system with mission goals and team success.
- Support the team dynamically in any capacity to ensure collective achievement.

ITPMetrics Feedback

The feedback I received highlights my commitment, communication, and technical skills as key strengths that benefit the team. My dedication, positive attitude, and ability to fill knowledge gaps, keep things organized, and support well-informed decisions are appreciated. I'm glad my efforts to document decisions and maintain high standards have been valuable. I also see room to grow by taking on more leadership, such as facilitating brainstorming sessions and ensuring everyone has opportunities to contribute. This feedback motivates me to build on my strengths, step into more leadership roles, and continue driving high-quality, team-focused results.

Katia Kassabov

Role: Thermal and Environmental Lead

Responsibilities:

- Thermal management strategy
- Design and implementation of thermal protection solutions
- Conduct environmental tests and simulations
- Analyze environmental data

Skills and Qualifications:

- Experience with thermal and environmental simulation tools
- Knowledge of stratospheric conditions
- Experience with data analysis

Motivation:

- Passionate about space exploration and the challenge of designing space systems.

Fulfilling Team Gaps:

- Brings experience with data analysis and risk mitigation

ITPMetrics Feedback

The feedback I received was incredibly encouraging and reinforced my confidence in my contributions to the project. It highlighted my strong work ethic, reliability, and contributions to documentation. I was particularly pleased to hear that my attention to detail and commitment to maintaining high standards have been recognized as valuable assets. Moving forward, I aim to continue building on these strengths by maintaining clear communication and staying organized.

Prajakta Lal

Role: Testing Lead / Scientific Analyst

Responsibilities:

- Documentation and Compliance
- Testing
- Data Analysis for atmospheric

Skills and Qualifications:

- Collaborative Approach
- Data Analysis and Interpretation

Motivation:

- Blending scientific exploration with practical solutions
- The challenge of conducting broader research in space science and designing a payload to capture data.

Fulfilling Team Gaps:

- Ensure we meet high standards for the quality of data during measurements and bridge any technical gaps in space science.

ITPMetrics Feedback

The feedback from my team is very encouraging, and I'm glad my organization and creative ideas are helpful. It's great to know my dependability and problem-solving skills are valued, as I genuinely enjoy supporting our success. I'm also glad that my team members enjoy working with and and feel that I am doing a good job with my responsibilities.

Gaurav Charan Moturi

Role: Software Lead

Responsibilities:

- Finding and choosing appropriate software solutions for project objectives with the integration lead
- Performance optimization of software solution
- Collaborate with other team members to align software development with mission requirements and constraints
- Documentation of code for project objectives

Skills and Qualifications:

- Experience working with FPGA and hardware connections
- Extensive knowledge of coding principles
- Great communication skills

Motivation:

- Passion for solving problems with technology and software solutions
- Bridges the gap in technical knowledge related to software integration and development

Fulfilling Team Gaps:

- Bring technical experience in FPGA
- Enhances team cohesion by promoting effective communication and collaboration

ITPMetrics Feedback

The feedback I received from my teammates was positive, emphasizing my willingness to contribute and my ability to create a collaborative and inclusive environment. I was commended for ensuring that everyone felt involved, effectively organizing the team, and proactively seeking external help when needed. Following my team's earlier suggestions, I took the initiative to delve deeper into the selected OBC's operations, conducting additional research and becoming more familiar with its software. As a result, my team's feedback has now shifted towards encouraging me to improve my focus on the implementation of the software for this project, highlighting this as an area for further growth.

Sarthak Sahai

Role: Project Lead / Systems Lead

Responsibilities:

- Act as the point of contact between the NOVA team and the Project Manager of R3
- Documentation and organization of all materials and resources.

Skills and Qualifications:

- 3D Modeling
- Experience with data analysis, prototyping and fabrication of materials

Motivation:

- Passionate and curious about Space engineering applications
- Eager to see the final outcome of the project

Fulfilling Team Gaps:

- Coordinating skills and resources
- Facilitating Communication
- Support

ITPMetrics Feedback

Reviewing through the ITPMetrics Feedback, I understand that I've been a great help to my peers and have done a great job in researching and providing my team members with what they need. I have been told I tend to take on more tasks than I should which may negatively affect my mental health and I need to emphasize the need to delegate tasks over taking more tasks upon myself.

Aiden Weatherbee

Role: Space Systems Engineer

Responsibilities:

- Camera and lens Trade study
- Thermal management plan.
- Mass, volume, and power budget.
- OBC trade study

- Mechanical design and CAD model
- Fem analysis

Skills and Qualifications:

- Experience with several cameras for astronomical brightness measurements and telescope imaging.
- Experience employing vision camera code on multiple space-grade microcomputers.
- Experience on ESSENCE cubesat mission mechanical team (primary payload is a camera).

Motivation:

- Passion for space missions and astronomical imaging.

Fulfilling Team Gaps:

- Astronomical brightness measurement and camera knowledge.
- Space mission analysis and design skills.

ITPMetrics Feedback

After reading the new ITP metrics, it is clear that the team is even happier with my work than before. All of my feedback mentioned that the team is happy with how we are collaborating. I plan to continue with my current efforts. This is reflected in the 5/5 rating.

Conclusions

The NOVA (Night-time Optical Visibility Assessment) sub-payload was developed to improve space situational awareness (SSA) through high signal-to-noise ratio (SNR) optical measurements of night sky brightness and resident space object (RSO) detection. Technically, NOVA integrates a ZWO ASI120MM Mini CMOS camera paired with a 6 mm wide-angle lens to achieve a field of view aligned with the main payload. The system is supported by a BeagleBone Black Industrial onboard computer, 256 GB of non-volatile storage, and a custom software stack developed in C++ using the ZWO SDK, enabling an exposure of 5 seconds with a resolution of 640x480 pixels, synchronized data acquisition, and error handling. The software includes redundant image logging and telemetry capture for system diagnostics.

Thermal performance is maintained using conformal resin coatings, chosen over Mylar after a detailed trade study, ensuring operation between 30°C to +50°C in a low-pressure, high-radiation stratospheric environment. Mechanical integrity was verified through extensive finite element method (FEM) simulations, random vibration analysis, and material stress tests, showing compliance with structural and alignment requirements under 10G loads. The electrical system operates within a 5V ±0.5V DC range and maintains a maximum power draw of 4W, sourced from the primary payload and distributed through the onboard computer.

Throughout the course, the NOVA team demonstrated strong adaptability, technical problem-solving, effective communication, and collaboration across engineering disciplines. Close coordination between space engineers and software engineers was critical in hardware capabilities with imaging, power regulation, and data storage logic. The integration of the structural, thermal, and computational subsystems required continuous communication and refinement to ensure full functionality under flight conditions. NOVA is a successful example of a mission-ready, cost-effective optical payload and offers a solid foundation for future iterations of high-altitude balloon missions.

Acknowledgement

As we reach the final pages of this project, we find ourselves looking back not just on technical milestones but on the moments that made this journey unforgettable. NOVA was never just a payload. It was built from long nights, quiet determination, laughter in the lab, and the unspoken promise that we would carry each other through, no matter what.

To our mentors, Professor Michael Bazzocchi and Dr. Ryan Clark, thank you for standing beside us through uncertainty, challenges, and breakthroughs. Your encouragement gave us room to fail, but also the belief that we could rise stronger each time. You taught us that engineering is not only about calculations and hardware, but about integrity, patience, and trust in the process.

To the Lassonde staff, especially Ms. Claudia V. Bennet, Professor Costas, Professor Edris Hassan, TA Damuth, TA Milena, and a special thank you to Tamjeed Shariff, thank you for being the steady hands and open hearts behind this journey. Your support extended far beyond lectures and logistics. You listened when we were overwhelmed, guided us when we were lost, and celebrated even the smallest wins with us. You reminded us that behind every project are people who care deeply, and that made all the difference.

To the Canadian Space Agency and the Strato-Science Campaign, thank you for making it possible for students like us to reach for the stars. You gave our ideas a place in the sky, and that kind of support changes the course of young engineers' lives.

To the RSOnar III and the RSOnar II team, thank you for being more than collaborators. You were our sounding boards, our backup when things went sideways, and our partners in making this mission real. Working with you turned pressure into pride and deadlines into memories.

To our families and friends, you may not have seen the payload firsthand, but you helped carry it just as much as we did. Every ride to campus, every meal left on the table, every time you told us "you've got this" when we were ready to give up, we felt it. And we are so grateful.

And to each other, thank you for being more than teammates. You became a second family. Together, we laughed through bugs in the code, shared awe at the stars in our test photos, and held onto hope when things looked uncertain. We learned that real engineering is built on trust, patience, kindness, and love, for the work, for the mission, and for the people beside you.

This project was never just about what we built. It was about who we became because of it. And that is something we will carry with us, always.

Thank you for being part of our journey.

With love and light,

The NOVA Team

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Appendix

The following is a collection of all data that was collected during the planning, execution and testing phase of the NOVA payload. Please note that the appendices are divided into several sections as follows;

- Appendix A - Meeting Minutes
- Appendix B - McMaster Carr Part Drawings
- Appendix C - Links to important complementary resources
- Appendix D - Bill of Materials
- Appendix E - Off the shelf parts used for the NOVA payload
- Appendix F - Manufacture test data for ZWO ASI120mm mini
- Appendix G - Trade Study for Components
- Appendix H - System Code
- Appendix I - NOVA Progress Images

Appendix A - Meeting Minutes

Please note that this is a collection of meeting minutes recorded post submission of the fall term report (December 5th, 2024). To access all meeting minutes, please refer to Appendix C

January 10th, 2025

Name	Role	Student Number (if applicable)	Email
Sarthak Sahai	Team Member	218743401	sahai@my.yorku.ca
Prajakta Lal	Team Member	218610964	prajakta@my.yorku.ca
Katia Kassabov	Team Member	219182682	Katiak@my.yorku.ca
Gaurav Charan Moturi	Team Member	218093526	Gaurav77@my.yorku.ca
Harrish Elango	Team Member	218187781	elangoha@my.yorku.ca
Aiden Weatherbee	Team Member	216879520	aidenweatherbee@hotmail.com
Prof. M. Bazzocchi	Faculty Supervisor	N/A	mbazz@yorku.ca
Ryan Clark	Partner Contact	N/A	ryan.clark@mda.space
Updates:			
R0: - Mechanical design and mounting section are complete.			

- Request for approval has been sent.
- Running simulations to meet requirements.
- Preparing to send the boards for manufacturing.

R1:
- Two designs completed (40g and 80g versions).
- Prototype ready.
- Finishing PCB routing.
- Assembly and testing is expected to take 1-2 weeks.
- Electrical schematics are finalized.

R2:
- Specifying tolerances.
- Starting the testing process.
- Finalizing the size of bolts.
- Exploring simpler, cost-effective ideas to save time and money.
- Reducing material waste by saving a tube of material.
- Consulting with the machine shop for recommendations.
- Focusing on making the manufacturing process cheaper.
- Planning for field testing, timing confirmation, and functionality checks.
- Preparing for overnight Thermal Vacuum (TVAC) testing.

2. Upcoming Dates
- CAD and Mass Budget Submission: January 14th
- Final CAD, Load, and Mass Submission: February 14th
- Thermal Vacuum Testing: March 10th
- Hardware Delivery Deadline: April 25th

3. Hardware Qualification Testing
- Ongoing refinement of the design to ensure system functionality.
- Demonstration planned in a flight-like environment.
- Testing includes vibration and thermal vacuum tests.
- Differentiating between Acceptance Testing and Qualification Testing:
  - Acceptance Testing: Ensures the product functions within its intended range.
  - Qualification Testing: Demonstrates the product works under extreme conditions.

Key Test Components:
- LFFT (Low-Frequency Functional Testing) and SFFT (Standard Frequency Functional Testing).
- Functional test list being finalized.
- Environmental test campaign scheduled.
- Expected thermal conditions: -70°C to 50°C.

Action Items:
- Create assembly instructions separate from the report (in an IKEA-style format).
- Schedule a demo session for functionality and assembly verification.
- Establish a timeline for data collection.
- Plan for potential extenuating circumstances (e.g., power outages, data overwrites).
- Ensure no exposed surfaces:

- Cover all plastic components, particularly on the lens, with insulation materials.

4. Key Considerations
- Optimize manufacturing processes to save costs and time.
- Consult with the machine shop for process improvement suggestions.
- Ensure all testing and assembly processes are clearly documented and accessible to all team members.

January 21st, 2025

Name	Role	Student Number (if applicable)	Email
Sarthak Sahai	Team Member	218743401	sahai@my.yorku.ca
Prajakta Lal	Team Member	218610964	prajakta@my.yorku.ca
Katia Kassabov	Team Member	219182682	Katiak@my.yorku.ca
Gaurav Charan Moturi	Team Member	218093526	Gaurav77@my.yorku.ca
Harrish Elango	Team Member	218187781	elangoha@my.yorku.ca
Aiden Weatherbee	Team Member	216879520	aidenweatherbee@hotmail.com
Prof. M. Bazzocchi	Faculty Supervisor	N/A	mbazz@yorku.ca
Ryan Clark	Partner Contact	N/A	ryan.clark@mda.space

Updates:

Camera Mount and Onboard Computer (OBC)

- Redesign of Camera Mount:
  - New design ready today/tomorrow.
  - Order OBC and manufacture the mount by next week.
- Procurement and Testing:
  - ETA for OBC: Explore alternative procurement strategies.
  - Last possible date to order OBC as a backup to avoid a mad scramble in the final weeks.
- New Camera:
  - Ordering a new camera, using Aiden’s as a backup.
- Testing:

    - Coordinate timing/data with other teams working on the payload.

Delivery and Milestones

- Key Dates:
    - Mechanical (CAD) Drawing Delivery: February 14th.
    - Test Readiness Review: Critical milestone for the launch.
    - TVAC Testing: March 10th.
    - Hardware Delivery: April 25th.
    - Testing Deadline: Extended to the end of March.
- Test Plans and Documentation:
    - Write full test plans and results:
        - Essential for accountability and client agreement.
        - Provides a safety net if issues arise.

Software Development

- Process and Interface:
    - Use modular software development with clear interface documentation.
    - Integrate modules into a master code that runs in a loop to maintain system operation.
- Debugging Strategy:
    - Reevaluate current bugs—are they causing new ones?
    - Break down issues to pinpoint specific bugs.
    - Use this pause to improve and refine.

Procurement Challenges and Contingencies

- Procurement Uncertainty:
    - Ensure thorough documentation throughout the process.
    - Assess how delays would impact the project and outline contingency plans.
    - Major issues anticipated if procurement fails—plan accordingly.

General Status

- Project Position:
    - Overall, the project is in a strong position.
    - Address uncertainties proactively to maintain momentum.

January 31st, 2025

Name	Role	Student Number (if applicable)	Email
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Prajakta Lal	Team Member	218610964	prajakta@my.yorku.ca
Katia Kassabov	Team Member	219182682	Katiak@my.yorku.ca
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Harrish Elango	Team Member	218187781	elangoha@my.yorku.ca
Aiden Weatherbee	Team Member	216879520	aidenweatherbee@hotmail.com
Prof. M. Bazzocchi	Faculty Supervisor	N/A	mbazz@yorku.ca
Ryan Clark	Partner Contact	N/A	ryan.clark@mda.space

Updates:

1. Materials Update
   - OBC and Aluminium received (Aluminium was donated, lowering costs by around $150).
2. Upcoming Meetings
   - Meeting with Amanda: Thursday, February 6th.
   - Action Item: Send meeting minutes from this meeting before February 7th (Meeting with Ryan and Bazzocchi).
3. Test Documentation Requirements
   - Built Requirements:
   - Define how each requirement is verified (e.g., mechanical size and weight verified through design).
   - Link each requirement to a verification activity (design, testing, etc.).
   - Provide a test/design procedure for each requirement.

* Test Procedure:
   - 1-to-1 Mapping: Each requirement must be linked to a specific test (e.g., TVAC is verified through the TVAC procedure).
   - Test Readiness Review (Before Testing): Confirm the procedure is complete.
   - Test Review (Post-Testing): Analyze results, identify failures, and document what didn't work.
   - Bi-Directionality:

- If a requirement exists → it needs a corresponding test.
- If a test is performed → it must be linked to a specific requirement.

* Stakeholder Requirements:

- Need written confirmation if a certain test is not required (e.g., shock testing) as proof if issues arise.
- Clarify stakeholder expectations regarding required testing.

4. Test Readiness Review Structure
- Test ID: Assign a unique identifier to each test.
- Estimated Work Hours: Document the estimated time required.
- Team Member Assignment: Assign a responsible team member for execution and documentation.
- Expected Outcome: Define what the test is verifying.
- Actual Procedure Execution: Perform and document the test process.
- Test Results & Compliance:
- Outcome: Categorize results as compliant, partially compliant, or non-compliant.
- Stakeholder Discussions: If partial or non-compliant, discuss with stakeholders (to be filled after testing).

<u>February 7th, 2025</u>

Name	Role	Student Number (if applicable)	Email
Sarthak Sahai	Team Member	218743401	sahai@my.yorku.ca
Prajakta Lal	Team Member	218610964	prajakta@my.yorku.ca
Katia Kassabov	Team Member	219182682	Katiak@my.yorku.ca
Gaurav Charan Moturi	Team Member	218093526	Gaurav77@my.yorku.ca
Harrish Elango	Team Member	218187781	elangoha@my.yorku.ca
Aiden Weatherbee	Team Member	216879520	aidenweatherbee@hotmail.com
Prof. M. Bazzocchi	Faculty Supervisor	N/A	mbazz@yorku.ca
Ryan Clark	Partner Contact	N/A	ryan.clark@mda.space
Updates:			
General Updates - Discussed meeting with Amanda. - No connection from [clarify missing connection].			

Hardware Updates

- Currently working on remaking the part - Discussed with Amanda
- Looking at creating part from bending metal.
  - Need to ensure the part is rigid with proper supports.
  - Considering purchasing pre-bent metal instead.
  - Need to evaluate vibration effects.
- Assessing cost trade-offs.

Software Updates

- Minor issues with Beaglebone.
- Using Bullseye version instead of Buster.
- Issues downloading STK onto the board.
  - Problems transferring data from the computer → SD card → board.
- Software is downloaded, but facing issues installing it onto the board.
- Searching for a barrel connector to power the board.
- Ensure testing is done in the same version planned for flight.
- Exploring ways to modify the board's startup sequence.

<u>February 14th, 2025</u>

Name	Role	Student Number (if applicable)	Email
Sarthak Sahai	Team Member	218743401	sahai@my.yorku.ca
Prajakta Lal	Team Member	218610964	prajakta@my.yorku.ca
Katia Kassabov	Team Member	219182682	Katiak@my.yorku.ca
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Prof. M. Bazzocchi	Faculty Supervisor	N/A	mbazz@yorku.ca
Ryan Clark	Partner Contact	N/A	ryan.clark@mda.space
Updates:			

- Redesigned model
    - Hoping to finish it today
    - Looking to raise plate
- Doing FEM analysis over reading week
- Received lens- it fits!
- Move software code from computer to board
    - Refining and tweaking code over reading week
    - Working on getting our code to run on startup
- Working on test documentation over reading week: Send to Dr Clark

February 28th, 2025

Name	Role	Student Number (if applicable)	Email
Sarthak Sahai	Team Member	218743401	sahai@my.yorku.ca
Prajakta Lal	Team Member	218610964	prajakta@my.yorku.ca
Katia Kassabov	Team Member	219182682	Katiak@my.yorku.ca
Gaurav Charan Moturi	Team Member	218093526	Gaurav77@my.yorku.ca
Harrish Elango	Team Member	218187781	elangoha@my.yorku.ca
Aiden Weatherbee	Team Member	216879520	aidenweatherbee@hotmail.com
Prof. M. Bazzocchi	Faculty Supervisor	N/A	mbazz@yorku.ca
Ryan Clark	Partner Contact	N/A	ryan.clark@mda.space
Updates:			

- FEM analysis updates
- CNC - structure done for free
- types of connector
- software: coding delay

March 21, 2025

Name	Role	Student Number (if applicable)	Email
Sarthak Sahai	Team Member	218743401	sahai@my.yorku.ca
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Gaurav Charan Moturi	Team Member	218093526	Gaurav77@my.yorku.ca
Harrish Elango	Team Member	218187781	elangoha@my.yorku.ca
Aiden Weatherbee	Team Member	216879520	aidenweatherbee@hotmail.com
Prof. M. Bazzocchi	Faculty Supervisor	N/A	mbazz@yorku.ca
Ryan Clark	Partner Contact	N/A	ryan.clark@mda.space
Updates:			
- All parts in - Beginning Assembly - Getting power figured out - Talking to RSonar2 Team- next week Wednesday - Trying to figure out TVAC testing alternatives - Working on debugging - Changed code to use exposure vs video capture - Changed code to switch image file format from RAW to Fitz - Problems with images being all white			

March 28, 2025

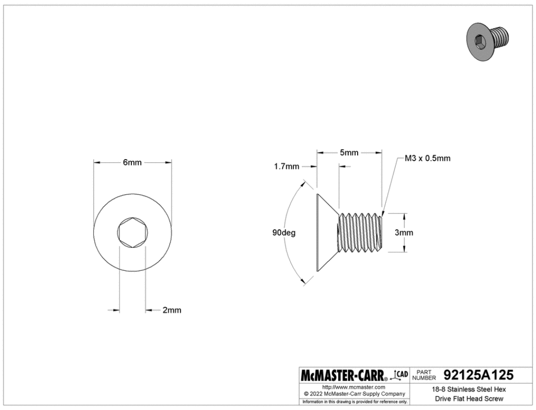
Name	Role	Student Number (if applicable)	Email

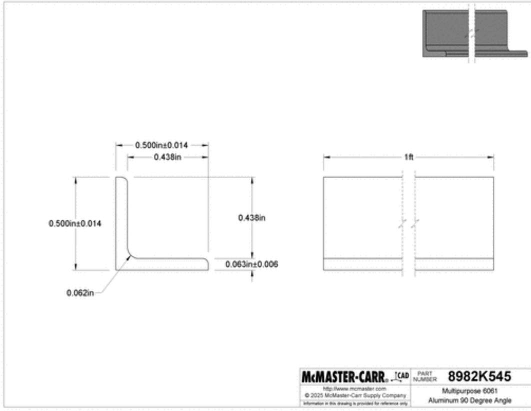
Sarthak Sahai	Team Member	218743401	sahai@my.yorku.ca
Prajakta Lal	Team Member	218610964	prajakta@my.yorku.ca
Katia Kassabov	Team Member	219182682	Katiak@my.yorku.ca
Gaurav Charan Moturi	Team Member	218093526	Gaurav77@my.yorku.ca
Harrish Elango	Team Member	218187781	elangoha@my.yorku.ca
Aiden Weatherbee	Team Member	216879520	aidenweatherbee@hotmail.com
Prof. M. Bazzocchi	Faculty Supervisor	N/A	mbazz@yorku.ca
Ryan Clark	Partner Contact	N/A	ryan.clark@mda.space

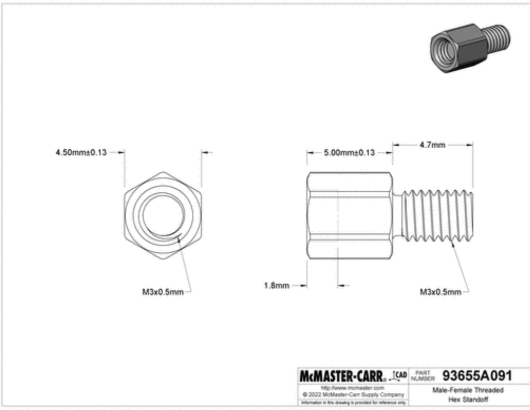
Updates:

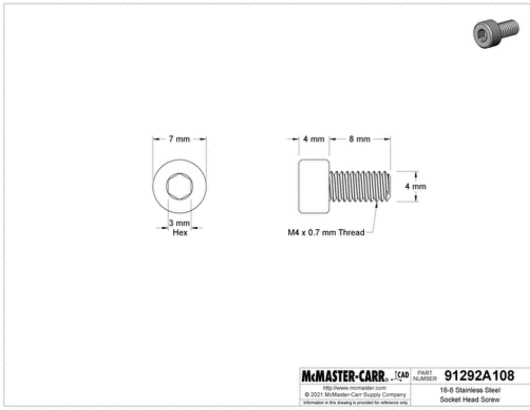
- Met with the R2 team to fix issues
- Fixed camera issues
- Pointed out exposure time timing was off (5, 10, 15 second values too high)
- The camera is now able to take and save photos
- Software is working, and development complete
- Need to work on testing
- Need to take flats and biases prior to test flight
- Have a follow-up meeting with the R2 team to update and work on final refinements
- Need to assemble mechanical design
- Need to do testing and documentation
- End of term next week
- Need to schedule meetings during exam period
- Dr. Clark away from April 9-22nd

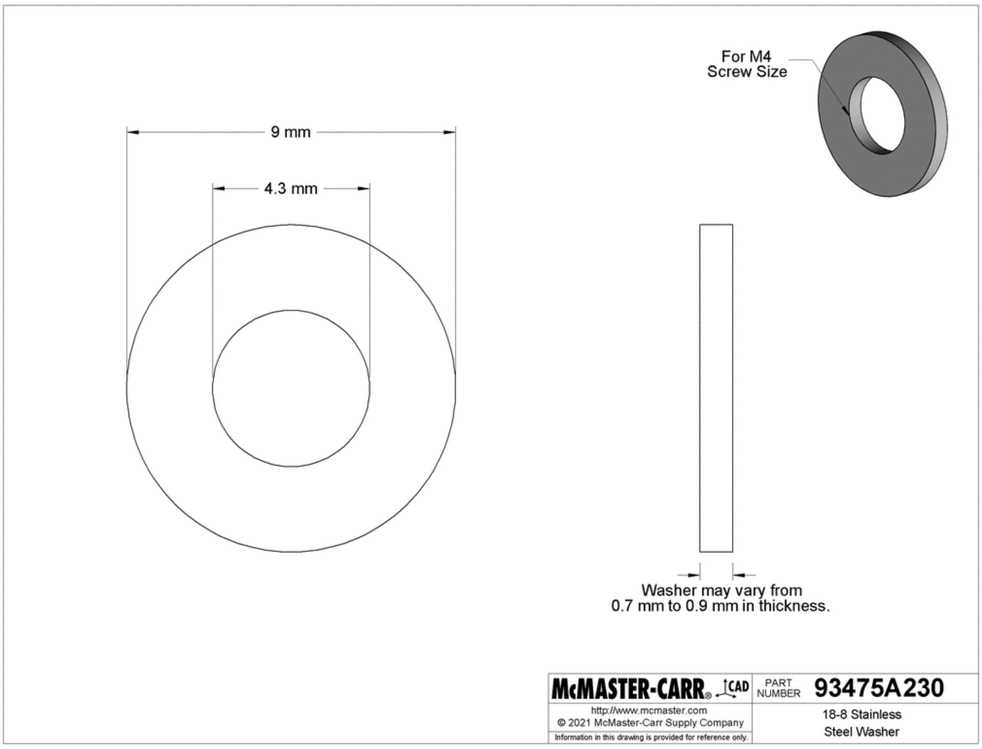
<u>Appendix B - McMaster-Carr Part Drawings</u>

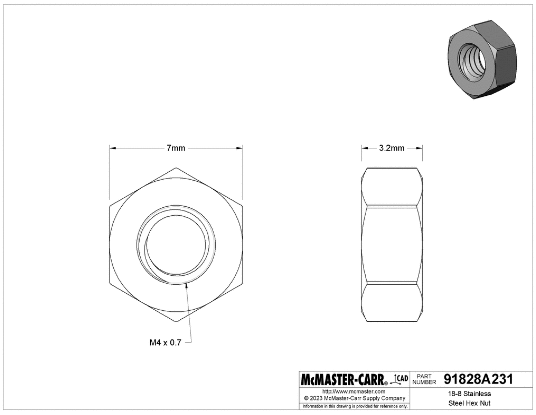


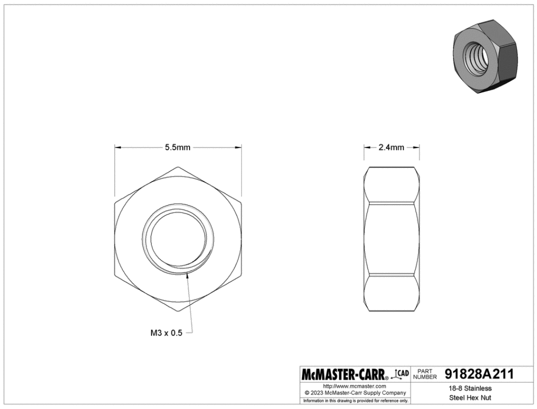


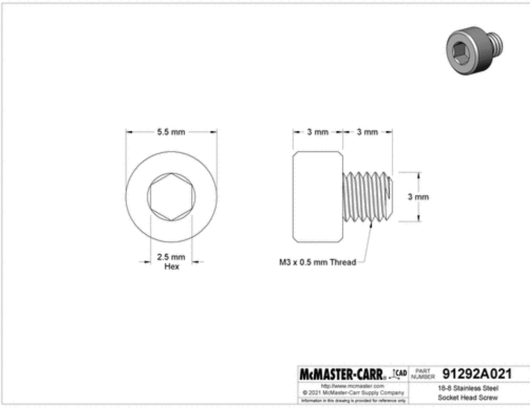


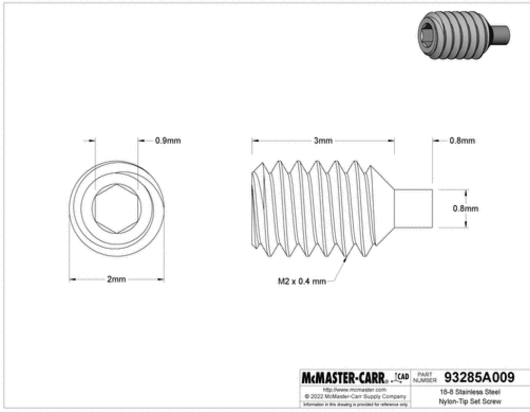












Appendix C - Links to Important Complementary Resources

Meeting Minutes: Meeting Notes

CAD Models: CAD Models

Gantt Chart: Capstone Gantt Chart

Resource Allocation Matrix: Resource Allocation Matrix

Budget Tracker: Bill of Materials

Software Flowchart: Software Flowchart Diagram.png

Appendix D - Bill of materials

Component	**Estimated Cost (CAD)**	**Manufacturer**	**Notes**
BeagleBone Black Industrial	~$110	BeagleBoard.org	Onboard Computer (OBC) for processing and control; industrial temperature range.

ZWO ASI120MM Mini Camera	~$225	ZWO	High quantum efficiency and low readout noise; meet scientific requirements for sky brightness measurements
Camera Lens	~$50	Raspberry Pi 6mm widefield	The camera needs some sort of lens to focus/ take images
Micro SD Card	~$50	SanDisk / Kingston	Needs to provide sufficient storage for image data; standard grade for cost reduction
Wiring Harnesses	~$20	undetermined	For powering components and data connections between components.
Insulation	~$20	undetermined	For keeping components within operational temperatures if needed
Aluminum 6061	~$50	undetermined	For the internal OBC and camera mount
Contingency	~$125	N/A	To account for fluctuating costs and currency conversions. These funds would be used as emergency cash and proper receipts will be provided upon usage.
Total	$ 650	N/A	This implies that we would be requiring approval of the budget from our faculty supervisor, Professor Michael Bazzocchi.

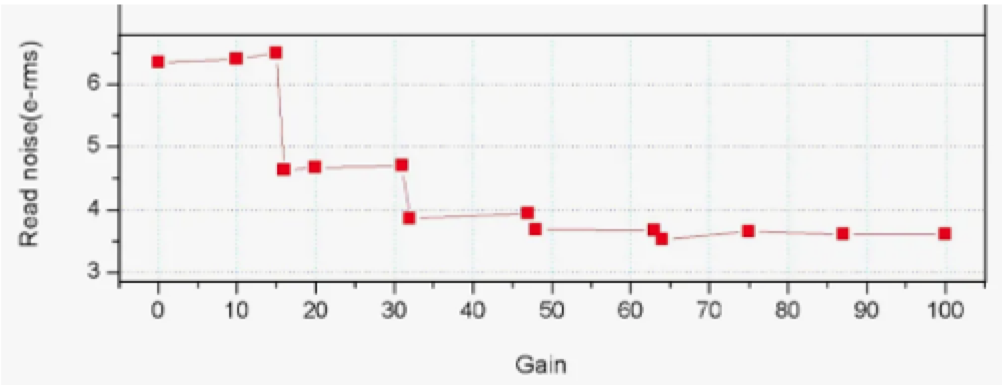
Appendix E - Off-the-Shelf Parts Used for the NOVA Payload

Part	McMaster-Carr Number/link	Total number	Cost $	Additional notes
Aluminum angle	https://www.mcmaster.com/8982K54-8982K545/	2 at one foot length	1.63 x 2= 3.26	For making the camera mount
Bolt - m4 x 0.7 mm thread	https://www.mcmaster.com/91292A108/	10	N/A	For making the camera mount, we have these so **no need to buy.**
Washers, metal, for m4	https://www.mcmaster.com/93475A230/	4	3.57 per pack of	For spacing the aluminum angles in the camera mount. **The part Mcmaster carr**

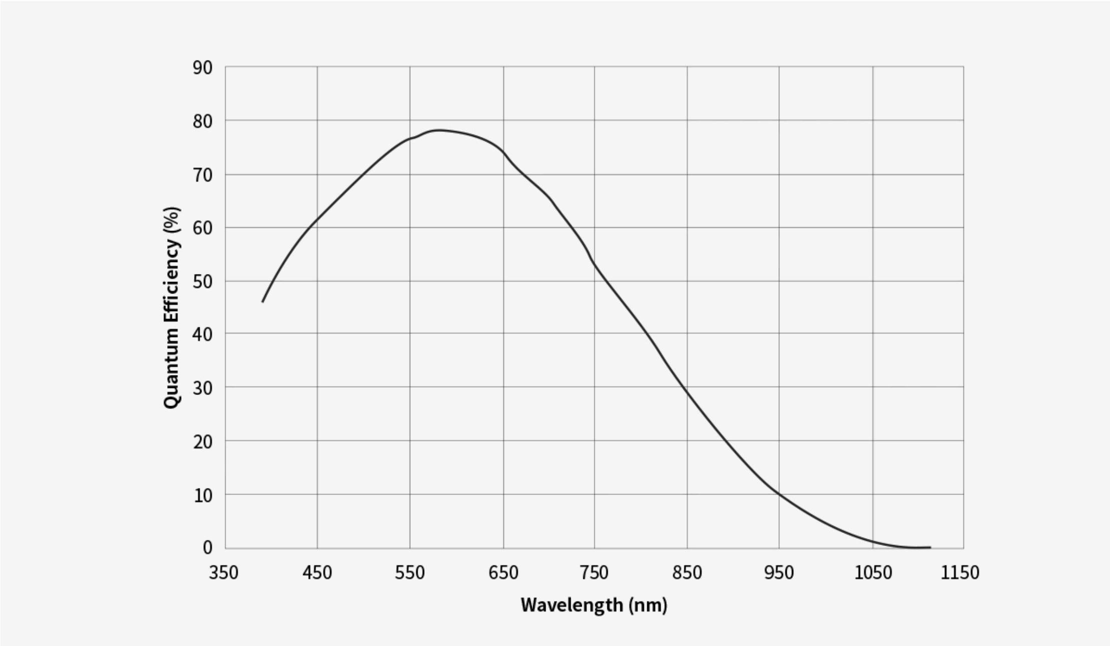
screws			100	**part number in the solidworks assembly is wrong, use the link here**! I just used another one because there was no cad available for the 18-8 stainless steel.
M4 hex nut, 0.7 mm thread pitch	https://www.mcmaster.com/91828A231/	10	N/A	For making the camera mount, we have these so **no need to buy**. **The part McMaster-Carr part number in the solidworks assembly is wrong, Ignore it and refer to the link here. (were already have these anyways)**
Bolt- M3 x 0.5mm thread	https://www.mcmaster.com/91292A021/	4	11.11 per pack of 25	For connecting the obc to the standoffs
Hex nuts, m3 thread	https://www.mcmaster.com/91828A211/	8	N/A	For connecting to standoffs. We have these so **no need to buy.**
Flat head m3	https://www.mcmaster.com/92125A125/		3.96 per pack of 100	For connecting to R3 through the standoffs
M3 Male-Female Threaded Hex Standoff	https://www.mcmaster.com/93655A091/	8	3.56 x 10 = 35.60 8 needed but discount at 10	To connect the OBC to our mount
Set screws, m2 x 0.4 mm thread	https://www.mcmaster.com/93285A009/	4	5.66 x 4 = 22.64	Set screws forholding the camera in place- the nylon tip makes them expensive
Loctite	https://www.amazon.ca/Loctite-Locking-Compound-Removable-303379/dp/B019GIS13O/ref=sr_1_2?sr=8-2	1	N/A	To secure important bolts and avoid vibration issues. **We have this so no need to buy**.
Total	Contingency Fund		60.14	A lot of leftover hardware in case of mistakes

Appendix F - Manufacture Test Data for ZWO ASI120mm Mini

The camera gain vs Read Noise is as follows:



The Camera's Quantum efficiency compared to the wavelength being observed is as follows:



Appendix G - Trade Study for Components

Electrical

Trade studies were not conducted on Electrical design. This was a predefined portion of our mission before capstone, and we were required to use a pre-designed power distribution unit from within the main RSOnar payload. Providing our power unit that meets the rigorous standards of the CSA is not within the budget of our mission, hence receiving power from the main payload is the best and only viable option. We are to provide them with the connection type, and they are to provide the proper connections that meet CSA standards and provide 5V at a maximum of 4W for our OBC, which will be powering the camera.

Environmental

The purpose of this thermal case study is to evaluate and recommend effective thermal insulation and regulation methods tailored to the NOVA payload. By analyzing established practices in the aerospace industry, including the use of foam insulation, Mylar, and resin conformal coatings, this study seeks to provide a comprehensive strategy for managing internal and external payload temperatures. This framework will enhance the durability and efficiency of the NOVA payload's electronic components, ensuring mission success while maintaining compliance with environmental requirements.

Defining Temperatures and Impact:

1. External Temperature Range: Between -30°C and +50°C, requiring robust insulation to prevent external conditions from adversely affecting payload functionality.
2. Internal Temperature Regulation: Maintaining a controlled range critical for the operation of electronics, particularly the camera and OBC. Proper regulation prevents performance degradation due to temperature fluctuations.

Applications to NOVA Payload: These methods ensure sensitive electronics such as the ZWO ASI120MMMini camera and BeagleBone Black Industrial OBC operate efficiently. Thermal coupling, insulation, and coatings will maintain the necessary internal temperature stability, directly supporting mission objectives.

<u>Candidate Thermal Solutions</u>

<u>Foam Insulation</u>

Description: Foam insulation provides thermal resistance by minimizing heat transfer. Common materials include closed-cell polyethylene foam.

- Advantages:
  - Excellent thermal resistance.
  - Lightweight and offers vibration damping.
- Disadvantages:
  - High outgassing potential in vacuum environments, risking contamination.
  - Degrades under UV exposure, reducing long-term reliability.
- Specific Details:
  - Thermal Performance: ~0.03 W/(m·K) thermal conductivity.
  - Mass: Lightweight (<5 g/cm³ depending on thickness).

<u>Resin Coating</u>

Description: Resin coatings, such as Parylene or silicone-based, are applied directly to electronic assemblies to protect against environmental stressors.

- Advantages:
  - Minimal outgassing; suitable for vacuum environments.
  - Durable under UV exposure and mechanical stress.
  - Enhances thermal coupling.
- Disadvantages:
  - Slightly heavier than foam insulation.
  - Requires precise application techniques.
- Specific Details:

- Thermal Performance: Conductivity depends on the material (e.g., 0.1–0.2 W/(m·K)).
- Mass: Adds ~10–20 g per square meter of coverage.

Mylar Insulation

Description: Mylar, a polyester film, is used in multilayer insulation (MLI) systems to reflect radiant heat and shield against UV radiation.

- Advantages:
  - Extremely lightweight.
  - Proven performance in aerospace missions.
  - Low outgassing.
- Disadvantages:
  - Fragile under mechanical stress; requires secure mounting.
- Specific Details:
  - Thermal Performance: Reflectivity >95%; conductivity negligible due to multilayer design.
  - Mass: ~1.4 g/m² for 25-micron thickness.

Trade-Off Analysis

Criteria	Foam Insulation	Resin Coating	Mylar	Preferred Option
Thermal Performance	Excellent resistance to heat transfer.	Good; enhances heat dissipation with coupling.	Reflects radiant heat effectively.	Depends on purpose
Mass Impact	Lightweight.	Slightly heavier than foam (but marginal).	Extremely lightweight.	Mylar
Outgassing Risk	High; significant testing required.	Minimal; highly vacuum-compatible.	Minimal; proven vacuum performance.	Resin or Mylar
Durability	Degrades under UV and vibration stress.	Highly durable and resistant to UV and mechanical stress.	UV-resistant but fragile under vibration.	Resin
Ease of Integration	Moderate; requires careful placement.	Moderate; requires precision application.	Simple application but needs secure mounting.	Equal

Cost	Low material cost but testing adds expense.	Moderate upfront cost.	Low material cost; minimal additional testing.	Mylar

Evaluation and Scoring

Criteria	Weight	Foam Insulation	Resin Coating	Mylar Insulation
Thermal Performance	25%	4	4	4
Mass	15%	5	3	5
Durability	20%	2	5	3
Outgassing Risk	20%	2	5	5
Cost	20%	4	3	4
Total Score	100%	3.25	4.2	4.0

Recommended Solution

Given the mission's environmental conditions and CSA/MDA requirements:

1. Primary Solution: Resin Coating
    - Provides durability, vacuum compatibility, and protection against condensation and UV radiation.
    - Ensures structural reinforcement and thermal coupling for key components like the camera and onboard computer.
2. Supplementary Protection: Mylar
    - Applied as an external layer to enhance UV and radiant heat shielding.
    - Offers lightweight additional protection but requires careful integration to prevent tearing.
3. Avoid Foam Insulation:
    - Outgassing risks and UV degradation make foam unsuitable for this mission, despite its thermal resistance.

The recommended solution is a combination of resin coating and Mylar insulation, which aligns with CSA and MDA requirements for vacuum compatibility, UV resistance, and thermal management. This approach ensures the payload can operate reliably in the extreme environmental conditions of a stratospheric mission.

Computational

The OBC and storage are the core of NOVA's processing and data handling. Very careful consideration needs to be done when choosing these components. Many factors go into choosing the best OBC and this trade study aims to evaluate different choices based on the defined criteria. These will not only impact the reliability of the payload but also the quality and amount of data we obtain. The OBC must be capable of efficiently processing and storing large amounts of data while keeping a low power draw, and maintaining a stable temperature for a long duration of continuous imaging. To ensure the OBC design meets all of these requirements, the following parameters need to be considered:

Size and weight(10%)- Must be minimized to adhere to all payload constraints.

Cost(20%)- The chosen OBC must be as cost-effective as possible while still ensuring all operational requirements are met.

Power consumption(20%)- It must operate within the available power budget of 4W at 5V while providing power to the camera and storage device.

Temperature range(20%)- The OBC must be able to operate within the -30°C to +50°C with the help of the thermal subsystem. The wider this range, the more reliable.

Computational power(15%)- The OBC will need to be able to handle the throughput of image processing and error correction algorithms. This will be a continuous image file stream over a long duration.

Software/ Programmability(15%)- The OBC needs to be able to support custom software, as well as programming environments that our team is familiar with.

With these parameters in mind, a trade study was conducted where several different OBCs were compared.

OBC	Processor	Expected load Power Draw	Weight	Size (L x W x H)	Temp Range	Programmability	Cost
Beagle Bone Black Industrial	ARM Cortex-A8 @ 1 GHz	~3W	37g	86 x 54 x 12 mm	-40°C to +85°C	Linux (Debian), Python, C, C++	~$110
PIC32 MZ OBC	PIC32MZ M14K @ 200 MHz	~1.5W	120g	144 x 101 mm	-40°C to +85°C	C, C++, Assembly, FreeRTOS, Micrium OS	~$100
NanoPi Neo H3	ARM Cortex-A53 @ 1.5 GHz	~2W	22g	40 x 40 mm	-20°C to +70°C	Linux (Armbian), Ubuntu Core, FriendlyWrt	~$50

Each of the OBC’s considered above are rated on a scale from 1 to 5 for each of the 5 defined criteria to determine the best OBC choice.

Criteria	Weight (%)	BeagleBone Black Industrial	PIC32MZ OBC	NanoPi Neo H3

Size and weight	10	4	2	5
Cost	20	2	3	5
Power Consumption	20	3	5	4
Temperature range	20	5	5	3
Computational power	15	5	2	2
Software/ Programmability	15	4	1	3
Total	100	3.75	3.25	3.65

Although the PIC32MZ has the lowest power draw, it has the most complex programming environment, and it is much larger, heavier, and slower than the other options. So it was ultimately not chosen. With the reliable temperature range, low weight, and small size, the BeagleBone Black Industrial ended up just being the best choice. With the temperature range of the atmosphere being the most challenging failure point in this project, the extra price and power draw of the BeagleBone is a worthwhile tradeoff that ultimately led us to choose it for the OBC on the NOVA payload.

Scientific

This study focuses on 12-bit cameras available within a budget of 300 CAD. We prioritized astronomical guide cameras because they emphasize high quantum efficiency and low readout noise, which are key factors for detecting faint stars in low-light conditions. These cameras can detect subtle changes in brightness without the added cost of high-resolution sensors found in other high-end cameras, which are unnecessary for our purposes. These specifications aim to select a camera that maximizes scientific value for obtaining highly accurate sky brightness measurements while remaining cost-effective. For the lens choice, this study focuses on 6mm commercially available lenses under 125 CAD. The focal length of 6mm was chosen because it's the closest available focal length to match the 6.8mm focal length that achieves a FOV of 29.7mm without an adjustable lens. This is the FOV of the Main payload camera that we will be supporting with our brightness measurements for better calibration. Each criterion is weighted according to its importance with respect to the mission objectives and requirements, reflecting the level of priority each imposes on the camera design.

- Quantum Efficiency (QE) (20%) - A key scientific parameter influencing the camera choice.
- Readout Noise (15%) - The second key scientific parameter driving the camera choice.

- Power Consumption (15%) - With a low power budget of 4 watts, there is an important trade-off between computing power and camera power, making this a critical parameter.
- Physical Dimensions (5%) - Our physical dimensions provide ample room, so as long as the camera size is reasonable, this is a less important factor.
- Operating Temperature Range (10%) - While important, acceptable cameras that can operate in the expected atmospheric temperature range are generally outside our budget. We plan to mitigate this with thermal design to allow a cost-effective camera that provides useful scientific measurements.
- Mass (5%) - The total mass is expected to stay well below 500 g if the camera weight is reasonable, making this a lesser priority.
- Cost (25%) - The most important factor given the budget constraint. Key scientific features, such as high quantum efficiency and low readout noise, increase camera costs, making cost a primary factor.

The following cameras were assessed based on the evaluation criteria outlined above, ensuring traceability to the mission requirements:

Feature	ZWO ASI120MM Mini	ZWO ASI220MM Mini	QHY5L-II Mono
Quantum Efficiency (QE)	79%	92%	74%
Readout Noise	4.0 e to 6.5 e	0.6 e to 3.2 e	4 e to 6.5 e
Power Consumption	0.8W (160mA at 5V)	0.8W (160mA at 5V)	0.64W
Physical Dimensions	36mm x 61mm	36mm x 61mm	31mm x 70mm
Operating Temperature Range	-5°C to +45°C	-5°C to +45°C	-40°C to +50°C
Mass	60g	60g	51g
Cost (CAD)	200	350	200

Each camera is scored based on how well it meets each criterion in alignment with mission requirements (see Requirements Table). This scoring matrix reflects both the absolute suitability and the trade-offs necessary for each camera model.

Criteria	Weight	ZWO ASI120MM Mini	ZWO ASI220MM Mini	QHY5L-II Mono
Quantum Efficiency (QE)	20%	4	5	3
Readout Noise	15%	3	5	3
Power Consumption	15%	5	5	5
Physical Dimensions	5%	5	5	4
Operating Temperature	10%	3	3	4
Mass	5%	4	4	4
Cost	25%	5	0	5
Total Weighted Score	100%	**4.00**	**3.25**	**3.85**

Each criterion is weighted according to its importance with respect to the mission objectives and requirements, reflecting the level of priority each imposes on the lens design.

- Aperture (f-stop) (25%) - A key optical parameter that influences the lens's ability to gather light and maintain clear imaging in low-light conditions.
- Optical Quality (25%) - Ensures the lens provides sufficient resolution to distinguish stars and measure sky brightness accurately, which is critical for achieving scientific objectives. Adjustable lenses generally have a lower optical quality than fixed FOV lenses.

- Mass (10%) - The total mass of the payload is expected to stay well within the overall limit of 500 g.
- Physical Dimensions (10%) - The lens while attached to the camera must fit within the specified payload geometry. While spatial constraints are manageable, ensuring compatibility is still necessary.
- Cost (30%) - The most important factor given the budget constraint. Balancing optical quality with affordability is essential to meet both scientific and financial requirements.

The following lenses were assessed based on the evaluation criteria outlined above, ensuring traceability to the mission requirements:

Feature	Raspberry Pi 6mm Wide Angle Lens	FA 6mm Machine Vision	ZWO 2.8-12mm f/1.4 Adjustable Lens
Aperture (f-stop)	f/1.2	f/2.0	f/1.4
Focal Length	6 mm	Adjustable 6 mm	Adjustable (2.8 mm to 12 mm)
Lens Type	Fixed	Fixed	Varifocal
Compatibility	C-Mount	C-Mount	CS-Mount
Weight	53 g	34.5 g	55 g
Size	30 x 34 mm	26.8 x 23.5 mm	42 x 32 mm
Cost (CAD)	Approximately 45 CAD	Approximately 110 CAD	Approximately 50 CAD

Each lens is scored based on how well it meets each criterion in alignment with mission requirements (see Requirements Table). This scoring matrix reflects both the absolute suitability and the trade-offs necessary for each lens option.

Criteria	Weight	Pi 6mm Wide Angle Lens	FA 6mm Machine Vision	ZWO 2.8-12mm f/1.4 Adjustable Lens
Aperture (f-stop)	25%	5	2	4
Optical Quality	25%	4	5	2
Mass	10%	3	5	3
Physical Dimensions	10%	4	5	3
Cost	30%	5	2	5
Total Weighted Score	100%	**4.45**	**3.35**	**3.6**

This trade study determined that the ZWO ASI120MM Mini is the most suitable camera for our stratospheric balloon mission aimed at measuring optical night sky brightness. Although the ZWO ASI220MM Mini has higher quantum efficiency and lower readout noise, the price increase of 150 CAD for only a 13 percent improvement in quantum efficiency limits its suitability for our mission objectives. It was included to give stakeholders a clear idea of the key trade-offs between price and performance. The QHY5L-II Mono has a better operational temperature range but falls short in technical performance compared to the ASI120MM Mini. Overall, the ASI120MM Mini offers a balanced solution that meets the mission's primary requirements, balancing technical capability, cost-effectiveness, and environmental suitability.

For the lens choice, the Pi 6 mm wide-angle lens was the clear winner. Although it is the cheapest of the 3, it has a fixed focal length of 6 mm which means fewer moving parts compared to the adjustable lens. It also had the largest aperture for collecting light. Although it was not the smallest and lightest, we can avoid using the 5 mm spacer due to it being the only CS mount lens of the 3.

Based on this analysis, the ZWO ASI120MM Mini and Pi 6 mm wide angle lens are the recommended choice for our mission. To ensure reliable operation in the expected environmental conditions, thermal management solutions are required to mitigate the camera operating temperature limitations, as specified in Requirements ENV-02 and ENV-04. Likewise, Vibrational testing is recommended to ensure all adjustment screws on the lens will maintain focus for the full mission duration. Additionally, it is required that we take proper Flats and Bias images near the flight date to ensure the scientific team can properly calibrate the images for scientific use.

Software

The software case study was done in two parts so that there was enough research into the many software components we would be using for the NOVA project. The first thing we focused on was finding the appropriate operating system as this would need to be able to run on our OBC of choice and be able to work with the other hardware components in our system. We looked mainly at four different operating systems, Debian, Armbian, Pi Lite and FreeRTOS. Our main areas of concern were the compatibility of the operating system with our hardware and software, the power consumption of the OS and the learning curve related to operating systems due to us having not known them before.

Criteria	**Debian**	**Armbian**	**Pi Lite**	**FreeRTOS**
Hardware/Software Compatibility	4	**5**	3	4
Power Consumption	**5**	2	2	**5**
Learning Curve	3	4	**4**	3
Total Score	**12**	11	9	**12**

The case study revealed that it would be ideal for us to continue with either FreeRTOS or Debian as our OS of choice for this project. Although they seem to be the better choice, due to our familiarity with Linux kernels, we will be going with **Debian**, with a possibility to move towards FreeRTOS if time permits. If we can complete our requirements easily, we might take this leap to make our project more efficient and effective.

The second thing we needed to consider for our software case study was the language that we would be choosing to code our image-capturing software in. We had different criteria for these such as its data acquisition capabilities, compatibility with different OS and hardware, power efficiency, memory allocation efficiency and learning curve as again we are not completely familiar with all of these languages.

Criteria	**C**	**C++**	**Python**	**Java**
Data Acquisition	5	**4**	3	3
Compatibility with Hardware and OS	5	**5**	4	4
Power Efficiency	5	**4**	2	3
Memory Efficiency	5	**4**	2	3
Learning Curve	1	**4**	4	4
Total Score	21	**21**	11	13

From this case study, we were able to understand that C++ would be the best candidate for coding language for creating a much more capable and efficient image-capturing software. Although there is a tie between C++ and C, we have opted for C++ because the syntax is more familiar to our software engineers and is more compatible with our camera. It is also able to do more than regular C taking care of some of the hard work. Due to one of our group members being proficient in Python, we will be using that to create an example attempt at the software so we can get a feel for the way we want our final software to function and we can get preliminary testing on our other components as well.

Appendix H - System Code

```
// CapCamSW with optimized implementation for ASI camera control

#include <iostream>
#include <fstream>
#include <string>
#include <vector>
#include <chrono>
#include <thread>
#include <iomanip>
#include <ctime>
#include <filesystem>
#include <dirent.h>
#include <atomic>
#include "ASICamera2.h"

namespace fs = std::filesystem;

// Configuration - centralized for easy modification
struct CameraConfig
{
    const std::string saveDirectory = "/mnt/sdcard/";
    const int exposureTimeUs = 5000000; // 5 seconds
    const int gain = 100;
    const int captureIntervalSec = 1; //
    const int maxRetries = 3;
    const bool debugMode = false;
    const std::string fileExtension = ".fits";
    const int width = 640;
    const int height = 480;
    const ASI_IMG_TYPE imgType = ASI_IMG_RAW16;
    const int statsOutputIntervalMin = 2; // How often to write
stats to file (minutes)
} config;

// Statistics tracking
struct CameraStats
{
    std::atomic<int> totalAttempts{0};
    std::atomic<int> successfulCaptures{0};
    std::atomic<int> failedCaptures{0};
```

```
    std::atomic<int> cameraReinitializations{0};
    std::chrono::system_clock::time_point startTime;
    std::chrono::system_clock::time_point lastStatsOutput;

    // Constructor to initialize time-based fields
    CameraStats()
    {
        startTime = std::chrono::system_clock::now();
        lastStatsOutput = startTime;
    }

    // Get run duration in seconds
    double getRunDurationSeconds() const
    {
        auto now = std::chrono::system_clock::now();
        return std::chrono::duration<double>(now -
startTime).count();
    }

    // Get success rate as percentage
    double getSuccessRate() const
    {
        if (totalAttempts.load() == 0)
            return 100.0; // No attempts yet
        return (static_cast<double>(successfulCaptures.load()) /
totalAttempts.load()) * 100.0;
    }
} stats;

// Error handling helper
const char *getASIErrorString(ASI_ERROR_CODE code)
{
    switch (code)
    {
    case ASI_SUCCESS:
        return "Success";
    case ASI_ERROR_INVALID_INDEX:
        return "Invalid index";
    case ASI_ERROR_INVALID_ID:
        return "Invalid ID";
    case ASI_ERROR_INVALID_CONTROL_TYPE:
        return "Invalid control type";
```

```
    case ASI_ERROR_CAMERA_CLOSED:
        return "Camera closed";
    case ASI_ERROR_CAMERA_REMOVED:
        return "Camera removed";
    case ASI_ERROR_INVALID_PATH:
        return "Invalid path";
    case ASI_ERROR_INVALID_FILEFORMAT:
        return "Invalid file format";
    case ASI_ERROR_INVALID_SIZE:
        return "Invalid size";
    case ASI_ERROR_INVALID_IMGTYPE:
        return "Invalid image type";
    case ASI_ERROR_OUTOF_BOUNDARY:
        return "Out of boundary";
    case ASI_ERROR_TIMEOUT:
        return "Timeout";
    case ASI_ERROR_INVALID_SEQUENCE:
        return "Invalid sequence";
    case ASI_ERROR_BUFFER_TOO_SMALL:
        return "Buffer too small";
    case ASI_ERROR_VIDEO_MODE_ACTIVE:
        return "Video mode active";
    case ASI_ERROR_EXPOSURE_IN_PROGRESS:
        return "Exposure in progress";
    case ASI_ERROR_GENERAL_ERROR:
        return "General error";
    default:
        return "Unknown error";
    }
}

// Function declarations
std::string getCurrentTimestamp();
int getLastImageIndex(const std::string &directory);
void logMessage(const std::string &message);
void logError(const std::string &message, ASI_ERROR_CODE errorCode
= ASI_SUCCESS);
bool initializeCamera(int &cameraID);
bool configureCamera(int cameraID);
bool captureImage(int cameraID, int imageIndex);
void releaseCamera(int cameraID);
std::string padRight(const std::string &str, size_t length);
```

```
std::vector<std::string> createFITSHeader(int width, int height,
double exposureTime, int gain, ASI_IMG_TYPE Type);
void outputStatistics(bool forcedOutput = false);
std::string getFormattedDuration(double seconds);

int main()
{
    logMessage("Starting ASI Camera Capture Software");

    // Initialize statistics
    stats.startTime = std::chrono::system_clock::now();
    stats.lastStatsOutput = stats.startTime;

    // Ensure save directory exists
    if (!fs::exists(config.saveDirectory))
    {
        try
        {
            fs::create_directories(config.saveDirectory);
            logMessage("Created save directory: " +
config.saveDirectory);
        }
        catch (const fs::filesystem_error &e)
        {
            logError("Failed to create save directory: " +
std::string(e.what()));
            return 1;
        }
    }

     const std::string backupDirectory = config.saveDirectory +
"backup/";
     if (!fs::exists(backupDirectory)) {
           try {
                 fs::create_directories(backupDirectory);
                 logMessage("Created backup directory: " +
backupDirectory);
           } catch (const fs::filesystem_error &e) {
                 logError("Failed to create backup directory: " +
std::string(e.what()));
                 return 1;
           }
```

```
      }

    // Create or open statistics file with header
    std::ofstream statsFile(config.saveDirectory +
"camera_stats.csv", std::ios::app);
    if (statsFile.is_open())
    {
        if (statsFile.tellp() == 0)
        {
            statsFile <<
"Timestamp,RunTimeSeconds,TotalAttempts,SuccessfulCaptures,FailedC
aptures,"
                      <<
"SuccessRate,CameraReinitializations,LastImageIndex" << std::endl;
        }
        statsFile.close();
    }

    // Get the last image index to avoid overwriting
    int imageIndex = getLastImageIndex(config.saveDirectory) + 1;
    logMessage("Starting image capture from index: " +
std::to_string(imageIndex));

    // Camera initialization
    int cameraID = -1;
    if (!initializeCamera(cameraID))
    {
        logError("Camera initialization failed. Exiting
program.");
        return 1;
    }

    // Log initial statistics
    logMessage("Starting camera run. Statistics tracking
enabled.");
    outputStatistics(true);

    // Main capture loop
    while (true)
    {
        bool captureSuccess = false;
```

```
        // Increment total attempts counter
        stats.totalAttempts++;

        for (int retry = 0; retry < config.maxRetries; ++retry)
        {
            // Try to capture with retries
            if (captureImage(cameraID, imageIndex))
            {
                logMessage("Successfully captured and saved image
" + std::to_string(imageIndex));
                stats.successfulCaptures++; // Increment success
counter
                imageIndex++;
                captureSuccess = true;
                break;
            }

            logError("Capture attempt " + std::to_string(retry +
1) + " failed");

            // On second retry, try reinitializing the camera
            if (retry == 1)
            {
                logMessage("Reinitializing camera...");
                releaseCamera(cameraID);

std::this_thread::sleep_for(std::chrono::seconds(2));

                stats.cameraReinitializations++; // Track camera
reinitializations

                if (!initializeCamera(cameraID))
                {
                    logError("Camera reinitialization failed");
                }
            }

            // Short delay before retry
            std::this_thread::sleep_for(std::chrono::seconds(2));
        }

        // If all retries failed, move on to the next image
```

```
        if (!captureSuccess)
        {
            logError("Failed to capture image after maximum
retries. Moving to next image.");
            //stats.failedCaptures++; Do not increment failure
counter
        }


        // Check if it's time to output statistics
        outputStatistics();

        // Wait before next capture
        logMessage("Waiting " +
std::to_string(config.captureIntervalSec) + " seconds before next
capture");

std::this_thread::sleep_for(std::chrono::seconds(config.captureInt
ervalSec));
    }

    // Code will not reach here in normal operation
    releaseCamera(cameraID);
    return 0;
}

// Get current timestamp for logging and FITS headers
std::string getCurrentTimestamp()
{
    auto now = std::chrono::system_clock::now();
    auto time = std::chrono::system_clock::to_time_t(now);
    struct tm timeinfo;
    localtime_r(&time, &timeinfo);

    std::stringstream ss;
    ss << std::put_time(&timeinfo, "%Y-%m-%d %H:%M:%S");
    return ss.str();
}

// Log a message with timestamp
void logMessage(const std::string &message)
{
```

```
    std::string timestamp = getCurrentTimestamp();
    std::cout << "[" << timestamp << "] INFO: " << message <<
std::endl;

    // Also log to file
    std::ofstream logFile(config.saveDirectory + "camera_log.txt",
std::ios::app);
    if (logFile.is_open())
    {
        logFile << "[" << timestamp << "] INFO: " << message <<
std::endl;
        logFile.close();
    }
}

// Log an error with timestamp and optional error code
void logError(const std::string &message, ASI_ERROR_CODE
errorCode)
{
    std::string timestamp = getCurrentTimestamp();
    std::string errorMsg = message;

    // Add error code information if provided
    if (errorCode != ASI_SUCCESS)
    {
        errorMsg += " (Code: " + std::to_string(errorCode) + " - "
+
                    getASIErrorString(errorCode) + ")";
    }

    std::cerr << "[" << timestamp << "] ERROR: " << errorMsg <<
std::endl;

    // Also log to file
    std::ofstream logFile(config.saveDirectory + "camera_log.txt",
std::ios::app);
    if (logFile.is_open())
    {
        logFile << "[" << timestamp << "] ERROR: " << errorMsg <<
std::endl;
        logFile.close();
    }
```

```
}

// Pad a string to a fixed length (for FITS header)
std::string padRight(const std::string &str, size_t length)
{
    if (str.length() >= length)
    {
        return str.substr(0, length);
    }
    return str + std::string(length - str.length(), ' ');
}

// Get the highest image index from the save directory
int getLastImageIndex(const std::string &directory)
{
    int highestIndex = -1;

    DIR *dir;
    struct dirent *entry;
    dir = opendir(directory.c_str());

    if (dir != nullptr)
    {
        while ((entry = readdir(dir)) != nullptr)
        {
            std::string filename = entry->d_name;

            // Check if the file is a FITS image with our naming
pattern
            if (filename.size() > 10 &&
                filename.substr(0, 6) == "image_" &&
                (filename.substr(filename.size() - 5) == ".fits"
|| filename.substr(filename.size() - 4) == ".fit"))
            {

                try
                {
                    size_t dotPos = filename.find(".fit");
                    if (dotPos != std::string::npos)
                    {
                        std::string indexStr = filename.substr(6,
dotPos - 6);
```

```
                        int index = std::stoi(indexStr);
                        if (index > highestIndex)
                        {
                            highestIndex = index;
                        }
                    }
                }
                catch (...)
                {
                    // If conversion fails, just ignore this file
                }
            }
        }
        closedir(dir);
    }
    else
    {
        logMessage("Warning: Could not open directory " +
directory + " to check for existing images");
    }

    return highestIndex;
}

// Initialize the ASI camera
// Format duration in human-readable form (Xh Ym Zs)
std::string getFormattedDuration(double seconds)
{
    int hours = static_cast<int>(seconds) / 3600;
    int minutes = (static_cast<int>(seconds) % 3600) / 60;
    int secs = static_cast<int>(seconds) % 60;

    std::ostringstream oss;
    if (hours > 0)
    {
        oss << hours << "h ";
    }
    if (hours > 0 || minutes > 0)
    {
        oss << minutes << "m ";
    }
    oss << secs << "s";
```

```
    return oss.str();
}

// Output current statistics to log and CSV file
void outputStatistics(bool forcedOutput)
{
    auto now = std::chrono::system_clock::now();
    auto elapsedMin =
std::chrono::duration_cast<std::chrono::minutes>(now -
stats.lastStatsOutput).count();

    // Only output stats if forced or if the interval has elapsed
    if (!forcedOutput && elapsedMin <
config.statsOutputIntervalMin)
    {
        return;
    }

    // Calculate runtime duration
    double runTimeSeconds = stats.getRunDurationSeconds();
    double successRate = stats.getSuccessRate();

    // Output to log
    std::ostringstream logMsg;
    logMsg << "STATISTICS SUMMARY - Runtime: " <<
getFormattedDuration(runTimeSeconds) << "\n"
           << "  Total attempts: " << stats.totalAttempts << "\n"
           << "  Successful captures: " <<
stats.successfulCaptures << "\n"
           << "  Failed captures: " << stats.failedCaptures <<
"\n"
           << "  Success rate: " << std::fixed <<
std::setprecision(2) << successRate << "%\n"
           << "  Camera reinitializations: " <<
stats.cameraReinitializations;

    logMessage(logMsg.str());

    // Output to CSV file
    std::ofstream statsFile(config.saveDirectory +
"camera_stats.csv", std::ios::app);
```

```
    if (statsFile.is_open())
    {
        statsFile << getCurrentTimestamp() << ","
                  << std::fixed << std::setprecision(1) <<
runTimeSeconds << ","
                  << stats.totalAttempts << ","
                  << stats.successfulCaptures << ","
                  << stats.failedCaptures << ","
                  << std::fixed << std::setprecision(2) <<
successRate << ","
                  << stats.cameraReinitializations << ","
                  << (stats.totalAttempts > 0 ?
(stats.successfulCaptures + stats.failedCaptures - 1) : 0)
                  << std::endl;
        statsFile.close();
    }

    // Update last output time
    stats.lastStatsOutput = now;
}

bool initializeCamera(int &cameraID)
{
    logMessage("Initializing ASI camera");

    // Get the number of connected cameras
    int numCameras = ASIGetNumOfConnectedCameras();
    if (numCameras == 0)
    {
        logError("No ASI cameras detected");
        return false;
    }

    logMessage("Found " + std::to_string(numCameras) + "
camera(s)");

    // Get info for the first camera (index 0)
    ASI_CAMERA_INFO cameraInfo;
    ASI_ERROR_CODE errorCode = ASIGetCameraProperty(&cameraInfo,
0);
    if (errorCode != ASI_SUCCESS)
    {
```

```
        logError("Failed to get camera properties", errorCode);
        return false;
    }

    logMessage("Camera model: " + std::string(cameraInfo.Name));

    // Open and initialize in sequence as per SDK recommendations
    cameraID = cameraInfo.CameraID;

    errorCode = ASIOpenCamera(cameraID);
    if (errorCode != ASI_SUCCESS)
    {
        logError("Failed to open camera", errorCode);
        return false;
    }

    errorCode = ASIInitCamera(cameraID);
    if (errorCode != ASI_SUCCESS)
    {
        logError("Failed to initialize camera", errorCode);
        ASICloseCamera(cameraID);
        return false;
    }

    // Configure the camera
    if (!configureCamera(cameraID))
    {
        logError("Failed to configure camera");
        ASICloseCamera(cameraID);
        return false;
    }

    logMessage("Camera initialization complete");
    return true;
}

// Configure camera settings
bool configureCamera(int cameraID)
{
    logMessage("Configuring camera with ID " +
std::to_string(cameraID));
```

```
    // Stop any existing capture operations
    ASIStopVideoCapture(cameraID);
    ASIStopExposure(cameraID);

    if (config.debugMode)
    {
        // Get camera properties for debugging
        ASI_CAMERA_INFO cameraInfo;
        ASIGetCameraProperty(&cameraInfo, 0);
        logMessage("Camera details:");
        logMessage("  - Name: " + std::string(cameraInfo.Name));
        logMessage("  - Max Resolution: " +
std::to_string(cameraInfo.MaxWidth) + "x" +
                   std::to_string(cameraInfo.MaxHeight));
        logMessage("  - USB3: " +
std::string(cameraInfo.IsUSB3Camera ? "Yes" : "No"));

        // Log available controls
        int numControls;
        ASIGetNumOfControls(cameraID, &numControls);
        logMessage("Camera has " + std::to_string(numControls) + "
controls");

        for (int i = 0; i < numControls; i++)
        {
            ASI_CONTROL_CAPS controlCaps;
            ASIGetControlCaps(cameraID, i, &controlCaps);
            logMessage("  - " + std::string(controlCaps.Name) +
                       " (Min: " +
std::to_string(controlCaps.MinValue) +
                       ", Max: " +
std::to_string(controlCaps.MaxValue) +
                       ", Default: " +
std::to_string(controlCaps.DefaultValue) + ")");
        }
    }

    // Simplified settings application with combined error
reporting
    ASI_ERROR_CODE error = ASI_SUCCESS;

    // Set image format and core settings
```

```
    error = ASISetROIFormat(cameraID, config.width, config.height,
1, config.imgType);
    if (error != ASI_SUCCESS)
    {
        logError("Failed to set ROI format", error);
        return false;
    }

    // Set exposure
    error = ASISetControlValue(cameraID, ASI_EXPOSURE,
config.exposureTimeUs, ASI_FALSE);
    if (error != ASI_SUCCESS)
    {
        logError("Failed to set exposure", error);
        return false;
    }

    // Set gain
    error = ASISetControlValue(cameraID, ASI_GAIN, config.gain,
ASI_FALSE);
    if (error != ASI_SUCCESS)
    {
        logError("Failed to set gain", error);
        return false;
    }

    // Set USB bandwidth overload to 20% (lower for stability)
    error = ASISetControlValue(cameraID, ASI_BANDWIDTHOVERLOAD,
20, ASI_FALSE);
    if (error != ASI_SUCCESS)
    {
        logError("Failed to set bandwidth overload - continuing
anyway", error);
    }

    // Disable high speed mode for stability
    ASISetControlValue(cameraID, ASI_HIGH_SPEED_MODE, ASI_FALSE,
ASI_FALSE);
    if (error != ASI_SUCCESS)
    {
        logError("Failed to set high speed mode - continuing
anyway", error);
```

```
    }

    // Get and log camera temperature if available
    long temperature;
    ASI_BOOL isAuto;
    if (ASIGetControlValue(cameraID, ASI_TEMPERATURE,
&temperature, &isAuto) == ASI_SUCCESS)
    {
        logMessage("Camera temperature: " +
std::to_string(temperature / 10.0) + "°C");
    }

    logMessage("Camera configuration complete");
    return true;
}

// Create FITS header
std::vector<std::string> createFITSHeader(int width, int height,
double exposureTime, int gain, ASI_IMG_TYPE type)
{
    auto bits = (type == ASI_IMG_RAW16) ? 16 : 8;

    std::vector<std::string> header;

    // Standard FITS header
    header.push_back(padRight("SIMPLE  =                    T /
Standard FITS format", 80));
    header.push_back(padRight("BITPIX  =                    " +
std::to_string(bits), 80));
    header.push_back(padRight("NAXIS   =                    2 /
Number of dimensions", 80));
    header.push_back(padRight("NAXIS1  = " + std::to_string(width)
+ " / Width", 80));
    header.push_back(padRight("NAXIS2  = " +
std::to_string(height) + " / Height", 80));
    header.push_back(padRight("BZERO   =                  0.0 /
Offset", 80));
    header.push_back(padRight("BSCALE  =                  1.0 /
Scale factor", 80));
    header.push_back(padRight("EXPTIME = " +
std::to_string(exposureTime) + " / Exposure time in seconds",
80));
```

```
    header.push_back(padRight("GAIN     = " + std::to_string(gain)
+ " / Camera gain", 80));
    header.push_back(padRight("DATE     = '" +
getCurrentTimestamp() + "' / Date of observation", 80));
    header.push_back(padRight("INSTRUME= 'ZWO ASI120MM Mini' /
Camera model", 80));
    header.push_back(padRight("END", 80));

    // Pad header to 2880 bytes (36 lines of 80 characters)
    while (header.size() < 36)
    {
        header.push_back(std::string(80, ' '));
    }

    return header;
}

// Capture and save an image
bool captureImage(int cameraID, int imageIndex)
{
    // Generate filename with padding
    std::ostringstream filenameStream;
    filenameStream << config.saveDirectory << "image_" <<
std::setw(4) << std::setfill('0')
                   << imageIndex << config.fileExtension;
    std::string filename = filenameStream.str();

    logMessage("Starting capture for image " +
std::to_string(imageIndex));

    // Start exposure
    ASI_ERROR_CODE errorCode = ASIStartExposure(cameraID,
ASI_FALSE);
    if (errorCode != ASI_SUCCESS)
    {
        logError("Failed to start exposure", errorCode);
        return false;
    }

    // Wait for exposure to complete with improved status
reporting
    ASI_EXPOSURE_STATUS exposureStatus;
```

```
    auto startTime = std::chrono::steady_clock::now();
    int statusCheckCount = 0;

    while (true)
    {
        errorCode = ASIGetExpStatus(cameraID, &exposureStatus);
        statusCheckCount++;

        if (errorCode != ASI_SUCCESS)
        {
            logError("Failed to get exposure status", errorCode);
            ASIStopExposure(cameraID);
            return false;
        }

        // Check exposure status
        if (exposureStatus == ASI_EXP_SUCCESS)
        {
            logMessage("Exposure completed successfully after " +

std::to_string(std::chrono::duration_cast<std::chrono::millisecond
s>(

std::chrono::steady_clock::now() - startTime)
                                          .count()) +
                       "ms");
            break;
        }
        else if (exposureStatus == ASI_EXP_FAILED)
        {
            logError("Exposure failed with status
ASI_EXP_FAILED");
            ASIStopExposure(cameraID);
            return false;
        }
        else if (exposureStatus == ASI_EXP_WORKING)
        {
            // Still working, check for timeout
            auto elapsedMs =
std::chrono::duration_cast<std::chrono::milliseconds>(
                                 std::chrono::steady_clock::now()
- startTime)
```

```
                                  .count();

            // Log progress every second in debug mode
            if (config.debugMode && (statusCheckCount % 10 == 0))
            {
                logMessage("Exposure in progress: " +
std::to_string(elapsedMs) + "ms elapsed");
            }

            // Set timeout at 3x the expected exposure time
            if (elapsedMs > (config.exposureTimeUs / 1000 * 8))
            {
                logError("Exposure timed out after " +
std::to_string(elapsedMs) + "ms");
                ASIStopExposure(cameraID);
                return false;
            }

            // Wait before checking again (100ms)

std::this_thread::sleep_for(std::chrono::milliseconds(100));
        }
    }

    // Get image dimensions
    int width, height, bpp;
    ASI_IMG_TYPE imgType;
    errorCode = ASIGetROIFormat(cameraID, &width, &height, &bpp,
&imgType);
    if (errorCode != ASI_SUCCESS)
    {
        logError("Failed to get ROI format", errorCode);
        return false;
    }

    // Calculate image size
    int imageSize = width * height * (config.imgType ==
ASI_IMG_RAW16 ? 2 : 1);

    if (config.debugMode)
    {
        logMessage("Image specs: " + std::to_string(width) + "x" +
```

```
std::to_string(height) +
                    ", Type: " + std::to_string(imgType) + ", Size:
" + std::to_string(imageSize) + " bytes");
    }

    // Allocate buffer for image data
    std::vector<unsigned char> imageData(imageSize);

    // Get image data
    errorCode = ASIGetDataAfterExp(cameraID, imageData.data(),
imageSize);
    if (errorCode != ASI_SUCCESS)
    {
        logError("Failed to get image data", errorCode);
        return false;
    }

    // Create FITS file
    std::ofstream outFile(filename, std::ios::binary);
    if (!outFile.is_open())
    {
        logError("Failed to open output file: " + filename);
        return false;
    }

    // Create FITS header
    std::vector<std::string> header = createFITSHeader(
        width, height, config.exposureTimeUs / 1000000.0,
config.gain, config.imgType);

    // Write header
    for (const auto &line : header)
    {
        outFile.write(line.c_str(), 80);
    }

    // Write image data
    outFile.write(reinterpret_cast<char *>(imageData.data()),
imageSize);

    // Pad data to a multiple of 2880 bytes (FITS standard)
    int padding = (2880 - (imageSize % 2880)) % 2880;
```

```
    if (padding > 0)
    {
        std::vector<char> padData(padding, 0);
        outFile.write(padData.data(), padding);
    }

    outFile.close();

                // Backup the image file
            std::string backupPath = config.saveDirectory +
"backup/" + fs::path(filename).filename().string();

            try {
                fs::copy_file(filename, backupPath,
fs::copy_options::overwrite_existing);
                logMessage("Backed up image to: " + backupPath);
            } catch (const fs::filesystem_error &e) {
                logError("Failed to back up image to " +
backupPath + ": " + std::string(e.what()));
            }


    // Update metadata CSV
    std::ofstream metadataFile(config.saveDirectory +
"metadata.csv", std::ios::app);
    if (metadataFile.is_open())
    {
        if (metadataFile.tellp() == 0)
        {
            // Write header if file is new
            metadataFile <<
"ImageIndex,Filename,Timestamp,ExposureTime_us,Gain,Width,Height,F
ormat" << std::endl;
        }

        metadataFile << imageIndex << ","
                     << "image_" << std::setw(4) <<
std::setfill('0') << imageIndex << config.fileExtension << ","
                     << getCurrentTimestamp() << ","
                     << config.exposureTimeUs << ","
                     << config.gain << ","
                     << width << ","
```

```
                     << height << ","
                     << "FITS" << std::endl;
        metadataFile.close();
    }
    else
    {
        logError("Failed to open metadata file");
    }

    return true;
}

// Release camera resources
void releaseCamera(int cameraID)
{
    logMessage("Releasing camera resources");

    // Stop any active operations
    ASIStopExposure(cameraID);
    ASIStopVideoCapture(cameraID);

    // Close camera
    ASI_ERROR_CODE errorCode = ASICloseCamera(cameraID);
    if (errorCode != ASI_SUCCESS)
    {
        logError("Failed to close camera", errorCode);
    }
    else
    {
        logMessage("Camera resources released successfully");
    }
}
```

Appendix I - NOVA Progress Images