SpartanSat: Design and Validation of a CubeSat Imaging System for Lunar Navigation

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by

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ABSTRACT

SPARTANSAT: DESIGN AND VALIDATION OF A CUBESAT IMAGING SYSTEM FOR LUNAR NAVIGATION

by Jose Jaime Esquivel Patricio

Imaging on small satellites is moving from observation toward navigation, and the Moon is a useful reference point for spacecraft operating where GPS signals are too weak to rely on. Previous SJSU work on TechEdSat-8 and TechEdSat-10 used an NVIDIA Jetson TX2 to record and compress video onboard from the ISS, but that module has been discontinued for new designs and newer Jetson variants require different carrier boards and interfaces. This project builds on that imaging heritage and extends it toward lunar navigation, with the goal of capturing the crescent Moon as a navigational reference using affordable hardware. The work covers mission requirements, a trade study of compute boards and cameras, hardware selection, prototype integration, and ground testing. The Jetson Orin Nano (8 GB) was selected for its compute headroom, low power draw, and direct compatibility with the Arducam IMX219 camera module. The integrated payload was tested in a darkened laboratory with a monitor target and in a vacuum chamber. In both tests, the system captured video and identified the lit lunar edge across all five moon phases in the test sequence using the same crescent detection pipeline. These results demonstrate that the imaging hardware needed for lunar navigation can be built and validated with low-cost commercial hardware.

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LIST OF ABBREVIATIONS

Symbol	Definition	Units (SI)
V	Volume	mm^3 (L)
m	Mass	kg (g)
U	CubeSat unit (1U = 10 cm $\times$ 10 cm $\times$ 10 cm)	——-
Subscripts		
$(\,)_{\text{Jetson}}$	NVIDIA Jetson Orin Nano	——-
$(\,)_{\text{Camera}}$	ArduCam IMX219 camera module	——-
$(\,)_{\text{max}}$	Maximum allowable	——-
Acronyms		
AE	Aerospace Engineering	——-
AGX	NVIDIA Jetson AGX product line	——-
AI	Artificial Intelligence	——-
ASU	Arizona State University	——-
CAPS	Cislunar Autonomous Positioning System	——-
CAPSTONE	Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment	——-
CLPS	Commercial Lunar Payload Services	——-
CMOS	Complementary Metal Oxide Semiconductor	——-
ConOps	Concept of Operations	——-
COTS	Commercial Off The Shelf	——-
CSI	Camera Serial Interface	——-
CSI-2	Camera Serial Interface 2	——-
CubeSat	Cube Satellite	——-
DC	Direct Current	——-
DPI	Dots Per Inch	——-
DSN	Deep Space Network	——-
ESA	European Space Agency	——-
FFC	Flat Flexible Cable	——-
FOV	Field of View	——-
FPC	Flexible Printed Circuit	——-
GB	Gigabyte	——-

Symbol	Definition	Units (SI)
GNC	Guidance, Navigation, and Control	——-
GNSS	Global Navigation Satellite System	——-
GPS	Global Positioning System	——-
GPU	Graphics Processing Unit	——-
GTU	Ground Test Unit	——-
I2C	Inter Integrated Circuit (serial bus)	——-
IM-1	Intuitive Machines 1 mission	——-
IM-2	Intuitive Machines 2 mission	——-
IMX219	Sony image sensor model used in the camera module	——-
ISS	International Space Station	——-
JPL	Jet Propulsion Laboratory	——-
LEO	Low Earth Orbit	——-
LONEStar	Lunar flashlight Optical Navigation Experiment with a Star tracker	——-
LPDDR	Low Power Double Data Rate (memory)	——-
LuGRE	Lunar GNSS Receiver Experiment	——-
LUMIO	Lunar Meteoroid Impacts Observer	——-
MB	Megabyte	——-
MIPI	Mobile Industry Processor Interface	——-
ML	Machine Learning	——-
MP	Megapixel	——-
N2	N-squared interface diagram	——-
NASA	National Aeronautics and Space Administration	——-
NRCSD	NanoRacks CubeSat Deployer	——-
NX	NVIDIA Jetson NX product line	——-
PCB	Printed Circuit Board	——-
PCIe	Peripheral Component Interconnect Express	——-
PO	Project Objective	——-
PR	Project Requirement	——-
RAD750	Radiation hardened spacecraft processor	——-
ROI	Region of Interest	——-
SDRAM	Synchronous Dynamic Random Access Memory	——-
SJSU	San José State University	——-
SO-DIMM	Small Outline Dual In line Memory Module	——-

Symbol	Definition	Units (SI)
SR	System Requirement	——-
SS	Subsystem Requirement	——-
SSH	Secure Shell	——-
SWAP	Size, Weight, and Power	——-
TFLOPS	Trillion Floating Point Operations Per Second	——-
TOPS	Trillion Operations Per Second	——-
TRN	Terrain Relative Navigation	——-
TX1	NVIDIA Jetson TX1	——-
TX2	NVIDIA Jetson TX2	——-
UHS-I	Ultra High Speed I (SD card class)	——-
USB	Universal Serial Bus	——-
VGA	Video Graphics Array	——-
VR	Virtual Reality	——-

1 INTRODUCTION

Imaging is a core capability for modern space missions, both for science and for navigation. The TechEdSat-8 [1] and 10 missions [2] demonstrated one of the first flight uses of a COTS graphics GPU (NVIDIA TX2) on board, intended to record and compress video onboard. These CubeSats were deployed from the NanoRacks CubeSat Deployer (NRCSD).

The TechEdSat-8 mission used NVIDIA's TX2 for onboard processing, but a power anomaly meant the imaging data was never recovered. This project builds on the TechEdSat imaging payload heritage with a greater emphasis on defining the mission concept, system requirements, and the architecture of space systems for lunar navigation. In particular, the work documented in AE 295B focuses on understanding how an onboard imaging system could support lunar navigation. Specifically, the goal is to recognize the crescent Moon as a navigational reference and to determine the hardware to complete its tasks.

One problem is that the Jetson TX2 module flown on TechEdSat-8 is no longer sold in its original form. Newer Jetson versions require different carrier boards and interfaces, which introduces additional integration considerations for a small CubeSat prototype. The hardware change means going back to the original design and picking a newer Jetson that can handle image capture, storage, and eventually navigation algorithms. This project therefore aims to identify a realistic path for a flight-ready imaging payload built around the Jetson Orin Nano (8 GB).

1.1 Motivation

This project builds on the imaging work done for TechEdSat-8 by looking at how a small satellite imaging payload could support lunar navigation. The main goal is to figure out what hardware and interfaces would actually work for this kind of payload before any flight unit gets built. Working through the requirements and trade studies up front saves time later and gives future teams a starting point.

For AE 295B specifically, the motivation is to clearly define what a visual navigation payload must do, how much data it must handle, and what processing capabilities are required on board. Understanding these requirements is important before implementing the final hardware in the CubeSat. Because the original Jetson TX2 configuration has become obsolete for flight, it is important to document why it is no longer optimal, how newer Jetson variants differ, and why the Jetson Orin Nano (8 GB) provides a better fit for this project. This analysis creates a technical record that explains the updated hardware direction and supports future design decisions. Having a detailed record will help future teams understand the reasoning behind the selected architecture and avoid similar hardware integration problems.

The work done here also gives future teams a starting point. The same hardware approach can be reused for other small satellite missions, including spacecraft heading to the Moon or Mars that need a low-cost backup to star trackers for navigation. The crescent Moon is hard to locate from position data, so a camera-based system adds another way to navigate.

1.2 Project Proposal and Objectives

The primary goal of this project is to define a practical imaging system architecture that could support lunar navigation within the constraints of a small satellite. This includes

selecting appropriate hardware, integrating the imaging components, and validating basic image capture and storage performance under vacuum and laboratory testing conditions. The challenge is not only choosing capable components, but also organizing them in a way that is realistic for a student design.

For AE 295B, the work centers on defining the system requirements, selecting the baseline hardware, establishing the prototype architecture, and validating the imaging subsystem under representative test conditions. This includes integrating the selected components, confirming image capture and storage, and evaluating system performance through laboratory and vacuum testing.

- To formalize the mission concept and system-level requirements for a visual navigation payload
- To compare the original Jetson TX2-based design with newer Jetson variants and alternative compute modules
- To select a candidate camera based on imaging needs and SWaP considerations
- To develop and validate a prototype imaging subsystem through laboratory and vacuum testing

1.3 Methodology Overview

The project will be executed in three main phases. The first phase focuses on defining the mission concept, system requirements, and baseline architecture for the visual navigation payload. During this phase, the work identifies the major functional needs of the system and evaluates suitable hardware options for the compute board and camera. The second phase focuses on prototype integration, including component selection, physical mounting, interface setup, and basic image capture and storage verification. The third phase focuses on environmental and functional validation through laboratory testing and vacuum chamber testing. An emphasis is placed on systems engineering, hardware selection, system integration, and validation of the prototype under different test conditions.

The methodology for AE 295B combines requirements development, trade-study evaluation, baseline hardware selection, prototype integration, and environmental validation. The work begins with mission and performance requirements, continues through evaluation of compute-board and camera options, and concludes with integration of the selected architecture and validation under laboratory and vacuum conditions. In this way, the project combines systems engineering with practical testing of the proposed imaging subsystem.

This three phase approach is based on standard systems engineering practices for space mission development. Wertz et al. describe a similar mission engineering process in Space Mission Engineering: The New SMAD (2011) [3]. Using a known process keeps the design organized and easier for the next team to pick up.

2 LITERATURE REVIEW

2.1 Small Satellites in Space and Their Challenges

Traditional satellites used for networking and broadcasting require significant power to operate, but in modern day smaller satellites are achieving similar capabilities with less room [4]. An example is the CubeSat, a type of nanosatellite typically built with a standard volumetric size of 1U (10 cm × 10 cm × 10 cm). Many CubeSats orbit in sun-synchronous or low inclination orbits, which are common for Earth observation because of the consistent lighting and lower launch costs [5]. To operate a CubeSat in space, the critical hardware systems include its power supply, scientific instruments, radio communication, guidance, navigation, and control (GNC), memory storage, and a computer. Due to their low cost and size, small satellites have been widely adopted in universities for research purposes and providing students with a wide range of skills. Also, advances in artificial intelligence (AI) have made it possible to have compact satellites handle the same tasks that previously required much bigger and more expensive spacecraft. Small satellites usually have two main objectives: testing and collecting data, but a new trend is emerging where they are increasingly being designed for deep space missions [6]. The next space race will be driven by leveraging data from smaller satellites for agriculture, defense, and disaster recovery [5].

All CubeSat designs must follow the CubeSat Design Specification maintained by Cal Poly San Luis Obispo. The current version, Revision 14.1, defines the physical dimensions, mass limits, deployment switch requirements, and testing procedures that launch providers require before accepting a CubeSat as a secondary payload [7]. The hardware decisions in this project were made with these requirements in mind, even though full launch qualification is outside the current scope.

One of the biggest challenges in small satellite design is Size, Weight, and Power (SWaP). SWaP constraints shape every hardware decision and can increase the cost of a mission. Since CubeSats are limited by volume, engineers must carefully balance processing capability against physical size and power used. This gets more difficult when imaging payloads need compute hardware for onboard processing because that hardware tends to be heavier and uses more power. Handling these trade-offs early is what keeps the system buildable and ready to fly [5].

Thermal management is another challenge that is often underestimated in student projects. In low Earth orbit, a satellite can cycle between extreme heat when sunlit and very cold temperatures in eclipse, sometimes within minutes. Commercial off-the-shelf (COTS) components were not originally designed for the space environment, so understanding their operating limits and potential failure modes is an important step when selecting hardware for a CubeSat prototype [8]. For this project, the operating temperature ranges of the Jetson Orin Nano and Arducam IMX219 were checked during the hardware selection process. On-orbit thermal testing is outside the scope of this work, but these considerations were still part of how the hardware was chosen.

Another challenge for CubeSats is reliability. Langer and Bouwmeester analyzed data from 178 CubeSat missions and found that most failures happen early, with many satellites never reaching a working state after deployment [9]. Among the identified subsystems, the

electrical power system is the common cause of failure [9]. That points to the value of structured development processes. For a student project like this one, clear requirements and a testing plan will help make it achievable. A NASA study by Jacklin found that about 41 % of small satellites launched between 2000 and 2016 failed or partially failed. That number went up to about 49 % between 2009 and 2016 [10]. The growing number of CubeSat launches has not automatically led to fewer failures, which is why structured development and testing still matter. Because of these strict size and power limitations, many current CubeSat missions are now pairing imaging hardware with onboard processing to make the most of limited resources.

2.2 Imaging and Autonomous Navigation Technologies for Small Satellites

Global Positioning System (GPS) signals are designed for users near Earth and become very weak beyond Earth orbit, which is a problem for any spacecraft heading to the Moon. One proposed solution is the Cislunar Autonomous Positioning System (CAPS), which lets satellites determine their positions by exchanging radio signals with each other [11]. However, CAPS requires multiple satellites to work together, so a single spacecraft cannot use it alone. Image processing offers an alternative. Image processing can identify nearby satellites and detect hazardous debris [12]. Additionally, image processing is emerging as a solution for autonomous lunar navigation. Wu et al. explore how small satellites can autonomously navigate in space without GPS or ground control, by using images of the Moon with mathematical models and algorithms [13].

This capability is becoming more important because the number of satellites in space has grown, which puts more pressure on ground communication and makes navigation harder. According to the European Space Agency (ESA) and the Nanosats Database, about 2,800 nanosatellites have been launched, with around 1,900 more expected between 2024 and 2029, adding to the roughly 11,000 active payloads in orbit [14, 15]. With that many satellites in orbit, advances in AI combined with NVIDIA's hardware have made it possible to process raw data directly onboard instead of sending everything to the ground [12]. NVIDIA's Jetson modules pair high compute with low power, and the Jetson TX2 series has already flown in low Earth orbit on several missions [1, 16]. For onboard image processing, the three key steps are finding the area of interest, identifying the target, and picking the best images so the satellite does not have to downlink everything. This cuts down on how much raw data needs to be sent back to Earth.

Traditionally, raw image data was downlinked to Earth for analysis, but with limited bandwidth and more satellites competing for ground station time, that approach is getting harder to sustain. Autonomous onboard classification allows the satellite to filter and store only the most useful frames, which reduces the total volume of data that needs to be sent to the ground.

Furano et al. at ESA looked at how far behind spacecraft processors are compared to what is available on the ground. Their survey covered multiple commercial options, including GPU modules similar to the Jetson family, and found that the performance gains over traditional space computers can be tens to hundreds of times faster at a fraction of the cost [17]. That gap between ground and space computing is a big part of why this project uses a COTS board instead of older space rated hardware.

2.3 Why the Moon Needs Better Navigation Systems

The Moon has been getting more attention in recent years. Between the Artemis program, the Commercial Lunar Payload Services (CLPS) initiative, and missions from international partners, the number of spacecraft heading to the Moon has gone up significantly.

The Congressional Research Service notes that the Artemis program includes multiple missions planned through the 2030s and a commercial cargo delivery program called CLPS that has already contracted multiple lunar landers, but recent direction has shifted toward establishing a permanent lunar outpost while pausing the Gateway station [18]. A White House report from the National Science and Technology Council also identified cislunar space as a national priority and called for better ways to track and guide spacecraft between Earth and the Moon [19].

Two recent CLPS missions show what happens when navigation sensors fail. In 2024, the Intuitive Machines IM-1 mission achieved the first successful soft landing by a commercial lander, but during descent, the lander's laser rangefinder failed. Engineers reprogrammed the spacecraft to use an experimental NASA lidar onboard to land the spacecraft [20]. It landed off target and tipped over, but the backup sensor saved the mission. In 2025, the IM-2 lander Athena had a similar failure when its sensor readings affected its final descent. The lander tipped over and its batteries died shortly after landing [21]. Both commercial lunar landings had navigation sensor failures. Relying on a single sensor is clearly not enough. A camera-based system could serve as a backup that gives a spacecraft another way to estimate its position when the primary sensor fails.

The problem is that GPS does not work well beyond a certain altitude. Delepaut et al. conducted an ESA study on this and found that while GPS and Galileo signals can reach the Moon, they are much weaker at that distance and hard to pick up [22]. Even good receivers have a hard time getting a location at lunar orbit. Any spacecraft operating near the Moon needs its own way of figuring out where it is.

In 2025, the Firefly Blue Ghost lander carried a NASA–Italian Space Agency receiver called LuGRE that picked up GPS and Galileo signals on the Moon. This was the first time a navigation fix using Earth-based satellite signals had been done on the Moon [23]. But the signals were still weak. The Global Navigation Satellite System (GNSS) may eventually help with lunar navigation, but it does not replace the need for onboard systems that can work on their own.

Pereira et al. took a closer look at this problem by modeling what a dedicated lunar GPS-like system would need to look like. Their analysis found that the satellite geometry near the Moon is so much worse than in low Earth orbit that getting even a rough position would need at least about two dozen satellites in a lunar constellation built just for that, depending on the accuracy and coverage needed [24]. That infrastructure does not exist yet. Until it does, spacecraft heading to the Moon have to rely on ground tracking through the Deep Space Network or develop some form of onboard navigation.

Ground based tracking has its own problems. The Deep Space Network (DSN) is a shared resource and it is already stretched thin. Turan et al. reviewed 64 proposed deep-space small satellite missions and found that most of them planned to use the Deep Space Network for

navigation, but argued that this approach will not scale to the growing number of missions competing for limited tracking resources [25]. As traffic to the Moon increases, autonomous navigation will become a necessity.

2.4 CubeSats Are Already Going to the Moon

CubeSats are no longer just student experiments in low Earth orbit. They have become real mission platforms capable of operating in deep space. The 2022 Artemis 1 mission launched 10 CubeSats as secondary payloads, and some of them were designed for lunar science and navigation tasks [26].

Before Artemis 1 even launched, the CAPSTONE mission had already shown that a CubeSat could operate in a demanding cislunar orbit. CAPSTONE was a 12U CubeSat created by Advanced Space that became the first spacecraft to fly in the same orbit planned for the Lunar Gateway station. It also tested a navigation method that allowed it to estimate its distance from NASA's Lunar Reconnaissance Orbiter, without constant guidance from Earth [27]. The mission also tested ways to reduce how often the spacecraft needed to contact the DSN [11]. These results are the closest published example to what this project is working toward.

Other Artemis 1 CubeSats also showed meaningful capabilities near the Moon. LunaH-Map was a 6U CubeSat from Arizona State University designed to map hydrogen deposits using a miniature neutron spectrometer at the lunar south pole [28]. LunaH-Map had a propulsion issue that stopped it from reaching lunar orbit, but the fact that a university team built a CubeSat intended for real lunar science is significant on its own. Lunar Flashlight, another 6U CubeSat from NASA JPL, carried a laser reflectometer to detect water ice in permanently shadowed regions [29]. It also experienced a propulsion issue but contributed important lessons about CubeSat operations beyond Earth orbit.

Interest in lunar CubeSats goes beyond the United States. ArgoMoon was a 6U Italian CubeSat that launched on Artemis 1 and demonstrated close proximity operations in cislunar space. Lombardo et al. documented the navigation design for ArgoMoon in detail, noting that cislunar navigation for a CubeSat poses unique challenges because of limited onboard memory, miniaturized thrusters, and the difficulty of maintaining accurate orbit solutions with small antennas and low transmit power [30]. LUMIO, a 12U CubeSat designed by a European consortium to observe meteoroid impacts on the lunar far side, was also selected through ESA's lunar CubeSat competition [31]. Both ArgoMoon and LUMIO had to operate on their own at times, far from Earth. That is the same constraint that any future lunar imaging mission will face.

These missions show that CubeSats can reach the Moon and operate there with flight-proven COTS hardware. The next step is using a camera not just for imaging but for figuring out where the spacecraft actually is.

2.5 Using Cameras for Navigation: The Technical Foundation

Using a camera to figure out where a spacecraft is in space may sound unusual, but optical navigation has a long history in space navigation. JPL's AutoNav system, which flew on

missions including Deep Space 1, Deep Impact, and Stardust, used onboard images of stars and asteroids to estimate the spacecraft's position and velocity without waiting for input from the ground [32]. These missions demonstrated that optical navigation is accurate, reliable, and does not require continuous ground station contact. The key insight is that if the spacecraft knows what objects it is looking at and where those objects are supposed to be, it can work backward to figure out its own position.

Since AutoNav, NASA has been developing a technology called Terrain Relative Navigation (TRN) that uses a camera during descent to figure out where the spacecraft is relative to the surface. TRN was used on the Mars Perseverance landing in 2021 and performed well within the required accuracy [33, 34]. That system was built for a large spacecraft, but the concept of using a camera to determine position from surface features is the same idea this project is built on.

The Moon's surface has many visual reference points, especially craters, which are well documented in existing catalogs. Christian et al. developed the first mathematically rigorous framework for identifying lunar craters from a camera without knowledge of its position in space [35].The algorithm uses images of the crater rim that remain recognizable regardless of viewing angle, allowing the system to match what the camera sees to a catalog of known craters. Although this project focuses on capturing the crescent Moon rather than individual craters, the underlying concept of matching camera images to known visual references is the same.

Downes et al. at MIT and Draper Laboratory extended this concept by applying a convolutional neural network to crater detection and showed that the deep learning approach was better at finding craters across multiple images without losing track of them, and with fewer mistakes [36]. When they fed those detections into a navigation filter, the estimated position error dropped by about 60 % compared to the classical approach.

There is also research about horizon navigation, which uses the visible edge of the Moon or another body to determine the spacecraft's position and attitude. Christian provides a thorough tutorial on this technique, showing how the planetary limb visible in a camera image can be used to figure out the pointing direction and distance with very high accuracy using basic image processing [37]. Horizon-based navigation does not require a crater catalog, which makes it easier to implement on a first prototype. Since one of the mission objectives is to capture a clear image of the crescent Moon, and a crescent is just a partial limb, photographing it is already the first step toward horizon-based navigation.

The LONEStar experiment on NASA's Lunar Flashlight CubeSat took optical navigation one step further by demonstrating it in actual flight. The LONEStar payload repurposed the spacecraft's star tracker to capture images of planets and the Earth-Moon system and processed nearly 400 images to figure out where the spacecraft was in space by looking at planets [38]. LONEStar showed that an onboard camera can serve as a navigation sensor and not just an imaging instrument.

2.5.1 Why Not Just Use a Star Tracker

Star trackers are the standard method for spacecraft attitude determination. A star tracker uses a camera pointed at the star field that identifies bright spots, measures their angular

separations, and matches it with the catalog of known stars. This tells the spacecraft how it is oriented in all three axes, with very high accuracy [39]. Star trackers are reliable and used on nearly every serious space mission built in the last thirty years.

However, star trackers are expensive. The Cal Poly CubeSat Lab noted that commercial star tracker offerings cost around $30,000, which motivated their own research into a lower-cost alternative built from COTS parts for under $250 [40]. For reference, the entire camera and compute setup used in this project, the Arducam IMX219 module and the Jetson Orin Nano Developer Kit, costs roughly $275 total. That is roughly a hundred-to-one price difference. For a university team on a limited budget, that changes what is even possible to build.

There is also an important difference between what a star tracker does and what this project is trying to do. A star tracker tells a spacecraft its attitude and orientation in space. Camera-based limb navigation tells a spacecraft its position relative to the Moon. These are two different measurements, and a complete navigation solution would need both. This project focuses on the position side because that is where low-cost hardware can make the biggest difference.

2.5.2 What This Approach Cannot Do Yet

Camera-based lunar navigation has clear limitations. The biggest one is accuracy. Christian's tutorial shows that position accuracy from horizon-based navigation depends heavily on viewing geometry, the apparent size of the body in the image, and the precision of edge localization [37]. LONEStar found that the accuracy of each position estimate changed with the observation geometry and the lighting on the target, with performance degrading as the geometry became less favorable [38]. For applications requiring precision on the order of tens of meters, such as a spacecraft trying to land at a specific site, camera-based limb navigation alone is not sufficient.

The crescent phase also makes things harder rather than easier. When the Moon appears as a crescent, only a small arc of the limb is illuminated and visible. Fewer pixels on the edge means the curve-fitting algorithm has less data to work with, and errors grow. Research has shown that even a single-pixel error in edge detection can produce significant range errors at typical cislunar distances, which is why being able to find the edge with better-than-one-pixel accuracy is important [37, 38].

There are also hardware concerns specific to using COTS components in space. NASA's guideline expects a Raspberry Pi to freeze or restart at most about once every 100 days in low Earth orbit, and more often in lunar orbit, closer to one event every 40 to 120 days [41]. For a ground prototype, these risks do not prevent progress, but they would need to be addressed before any flight deployment.

2.6 Moving Image Processing Off the Ground and Onto the Satellite

As the number of satellites in orbit grows, sending raw data to the ground for processing is getting harder to sustain. More teams are moving toward onboard processing where the satellite handles its own data and only sends back what is useful. The most visible demonstration of this change was the PhiSat-1 mission, a 6U CubeSat launched by ESA in

2020 that was the first to run a deep neural network for image analysis directly on a dedicated onboard accelerator. The onboard network, called CloudScout, sorted images as they were captured and discarded the cloudy ones so they would not be downlinked [42]. Giuffrida et al. reported about 95% accuracy, which saved storage and reduced the downlink burden. The hardware that ran this network was an Intel Myriad 2 vision processing unit, a COTS chip not originally designed for space, operating inside a real CubeSat in low Earth orbit.

Arechiga et al. tested the NVIDIA Jetson TX2 for onboard image processing and showed it fits within the size, weight, and power budget of a small satellite [43]. The same TX2 flew on TechEdSat-8, and the Orin Nano, a later board in the same Jetson family, is the one chosen for this prototype [1]. Staying within the Jetson family makes sense because performance data shows these modules can handle the image processing loads that autonomous navigation would eventually need.

Since this project started, the Jetson Orin family has gone from being a ground platform to having flight experience. In 2024, the startup Aethero flew an edge computer built around an NVIDIA Jetson Orin NX on a SpaceX rideshare mission [44]. NVIDIA has also brought its Jetson hardware into satellite applications, working with satellite companies such as Kepler Communications to run Orin modules in orbit [45]. The same product family as the compute board in this project is now being used in space.

Another relevant example is SONATE-2, a 6U CubeSat built by the University of Würzburg that launched in March 2024 on a SpaceX rideshare mission. It carries a Jetson Xavier NX, which is part of the same Jetson product family as the Orin Nano used in this project. The Würzburg team tested it under radiation before flight and reported that the system is thermally stable and working in orbit [46].

Denby and Lucia describe Orbital Edge Computing as a new class of computing infrastructure rather than just a data collection platform [47]. Their analysis showed that moving image classification onboard can reduce the demand for ground station infrastructure by more than 24 times compared to the traditional approach where all data just gets sent straight to the ground. Being able to demonstrate image capture and storage now is the first step toward a satellite that can eventually decide on its own what data to keep and what to throw away.

2.7 How This Project Fits Into the Bigger Picture

The Moon is getting more attention than it has in decades, but the navigation infrastructure needed to support all those missions does not exist yet. CubeSats have already proven they can operate in cislunar space. Camera-based navigation has a solid technical foundation and is starting to show up on real missions. And processing images onboard using commercially available hardware is not just a concept anymore. But there are not many documented examples of a prototype that puts these pieces together using affordable hardware.

Most of the work covered has been done by large organizations like JPL, ESA, or research labs with big budgets. Those projects are important, but they do not give a student team a clear path to follow. SpartanSat takes the same ideas and applies them at a university scale. The Jetson Orin Nano and Arducam IMX219 together cost under $300, and the project goes

through a real testing process with requirements driving every decision. For comparison, a radiation hardened RAD750 processor board costs around $200,000 [48]. The goal is not to solve lunar navigation in one project but to build the imaging foundation that future teams can develop navigation algorithms on top of.

There are also not many documented examples of student projects that combine COTS hardware with environmental testing like vacuum and laboratory imaging. Andreis et al. built one of the few CubeSat systems that combine image processing with a navigation filter. They note that vision based navigation for deep space has only been tested so far but not flown on a real mission [49]. Langer and Bouwmeester found that a large share of CubeSats fail early in their missions, and that thorough system level functional testing before launch is one of the most effective ways to reduce those failures [9]. That is the approach taken here, with documented requirements, phased integration, and test results that future teams can build on.

3 TIMELINE AND PROJECT MANAGEMENT

The timeline below reflects the deliverables and tasks to be completed for developing a functioning small satellite imaging system for lunar navigation. This project was developed over four academic terms: AE 295A (Spring 2025) for initial research and trade studies, Summer 2025 for hardware acquisition, AE 295B (Fall 2025) for prototype integration, and AE 1290R (Spring 2026) for testing and final documentation.

3.1 Project Timeline and Milestones

Figure 3.1 shows a Gantt chart of each deliverable and task for AE 295A, Summer, and AE 295B/AE 1290R. The equipment and software were selected and tested during Spring 2025.

Tentative Schedule

		AE 295 A				Summer		AE 295 B/1290R				
		Feb	Mar	Apr	May	Jun	Jul	Jan	Feb	Mar	Apr	May
Research & Integration		M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
Task 1	First written report: Chapter 1 (Lit Review)											
Task 2	Second written report: Chapter 2											
Task 3	Compute platform & camera trade study											
Task 4	Hardware acquisition (Jetson Orin Nano, ArduCam)											
Task 5	Requirements derivation (Chapter 4)											
Task 6	Hardware integration & block diagrams											
Task 7	Interface specification & N2 diagram											
Testing & Results												
Task 1	Software/hardware integration											
Task 2	Initial imaging system bring-up											
Task 3	Indoor and vacuum chamber test plan											
Task 4	Indoor lab test (crescent Moon mock-up)											
Task 5	Vacuum chamber test execution											
Task 6	Indoor vs. vacuum comparison											
Task 7	Final report writing											

Figure 3.1 – Project schedule for research and testing.

4 SYSTEM DEFINITION AND REQUIREMENTS

4.1 Mission and Operational Requirements

This project aims to design, build, and test a small satellite imaging system for visual navigation. The satellite aims to capture video and extract still frames from it to address key challenges in space navigation, specifically, determining its position by recognizing the crescent Moon as a navigational reference. In the ideal mission scenario, a CubeSat is placed in ISS low Earth orbit equipped with a camera. During observation periods, the spacecraft will move into position toward the Moon and acquire images. For the scope of this project, on orbit operations are not demonstrated. Instead, the work focuses on developing and validating a visual navigation imaging system on Earth, built around the Jetson Orin Nano. This prototype will demonstrate the ability to capture and process images relevant to lunar navigation, such as identifying the crescent Moon.

1) Integrate the ground test unit imaging subsystem hardware
2) Demonstrate basic ground test unit image capture
3) Create the ground test unit system decomposition for the visual navigation payload
4) Validate the ground test unit imaging subsystem hardware through laboratory and vacuum chamber testing

For the mission objectives, the minimum success criteria are the acquisition and integration of imaging hardware to be placed inside a CubeSat spacecraft. The nominal mission success criteria include demonstrating basic image capture and producing a system architecture for the navigation payload. A basic image is defined as a single image that is in focus and has appropriate exposure such that the captured object is identifiable to a human observer. The final objective of the project is to validate the imaging hardware through laboratory and vacuum chamber testing.

4.2 Functional and Performance Requirements

After the primary mission objectives were set, the project, system, and subsystem requirements were derived by flowing down each objective into specific expectations for the imaging payload. This ensures that every requirement has a direct connection to meet the mission objectives. The requirements were limited to maintain a small budget on a limited timeline. This reduces complexity while allowing the imaging functionality to be validated. The traceability tables that follow describe the requirements at 4 levels. Level 1 contains the project objectives (PO), Level 2 contains the project requirements (PR), Level 3 contains the system requirements (SR), and Level 4 contains the subsystem requirements (SS). Each lower-level requirement traces directly to the level above it, ensuring full coverage of the mission objectives. Because the flight unit is outside the scope of this project, the Level 4 subsystem requirements are derived to a Ground Test Unit (GTU) configuration. The GTU represents the prototype hardware that was built and tested during this project.

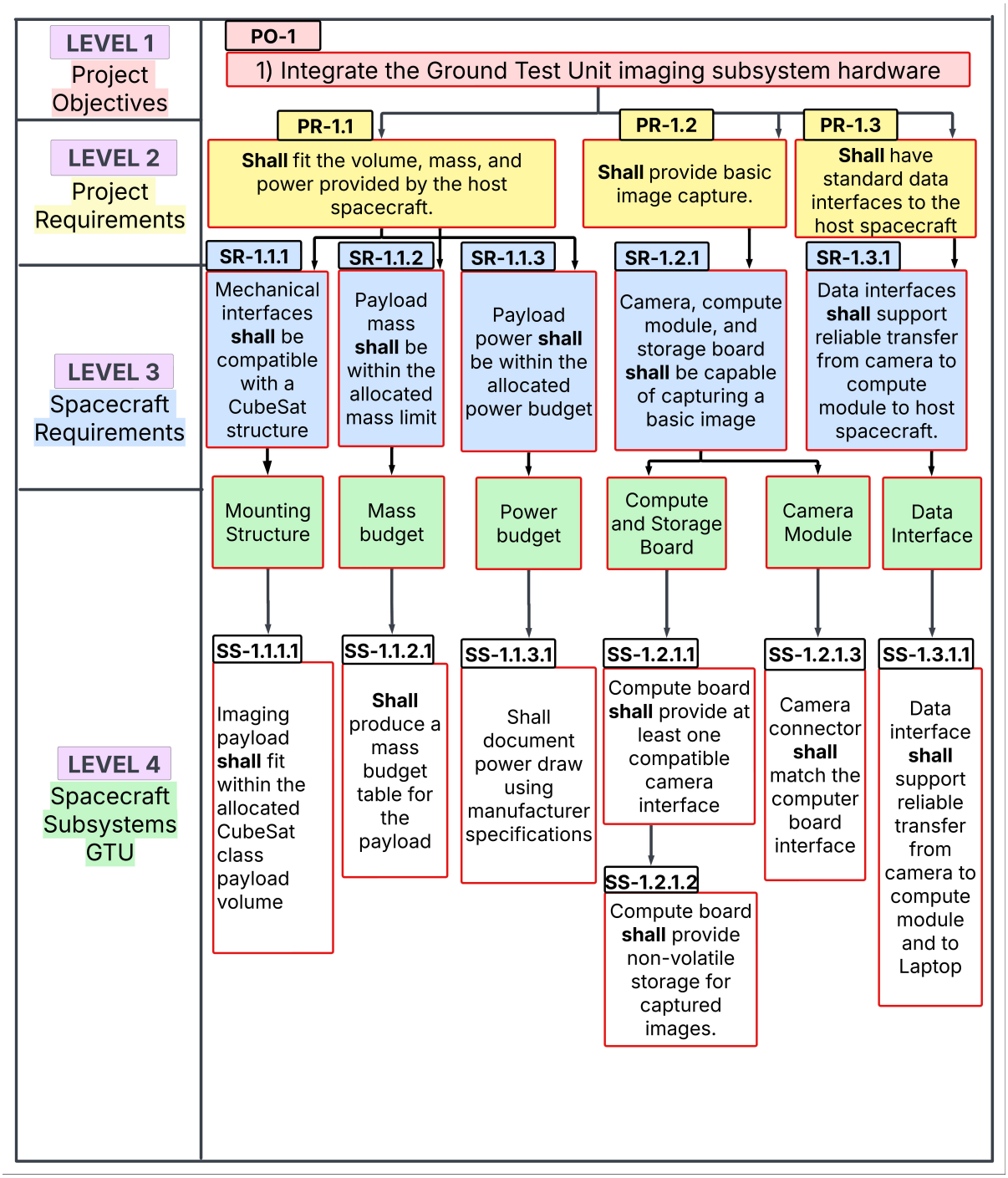


Figure 4.1 – Project objective 1: integrate the ground test unit imaging subsystem hardware.

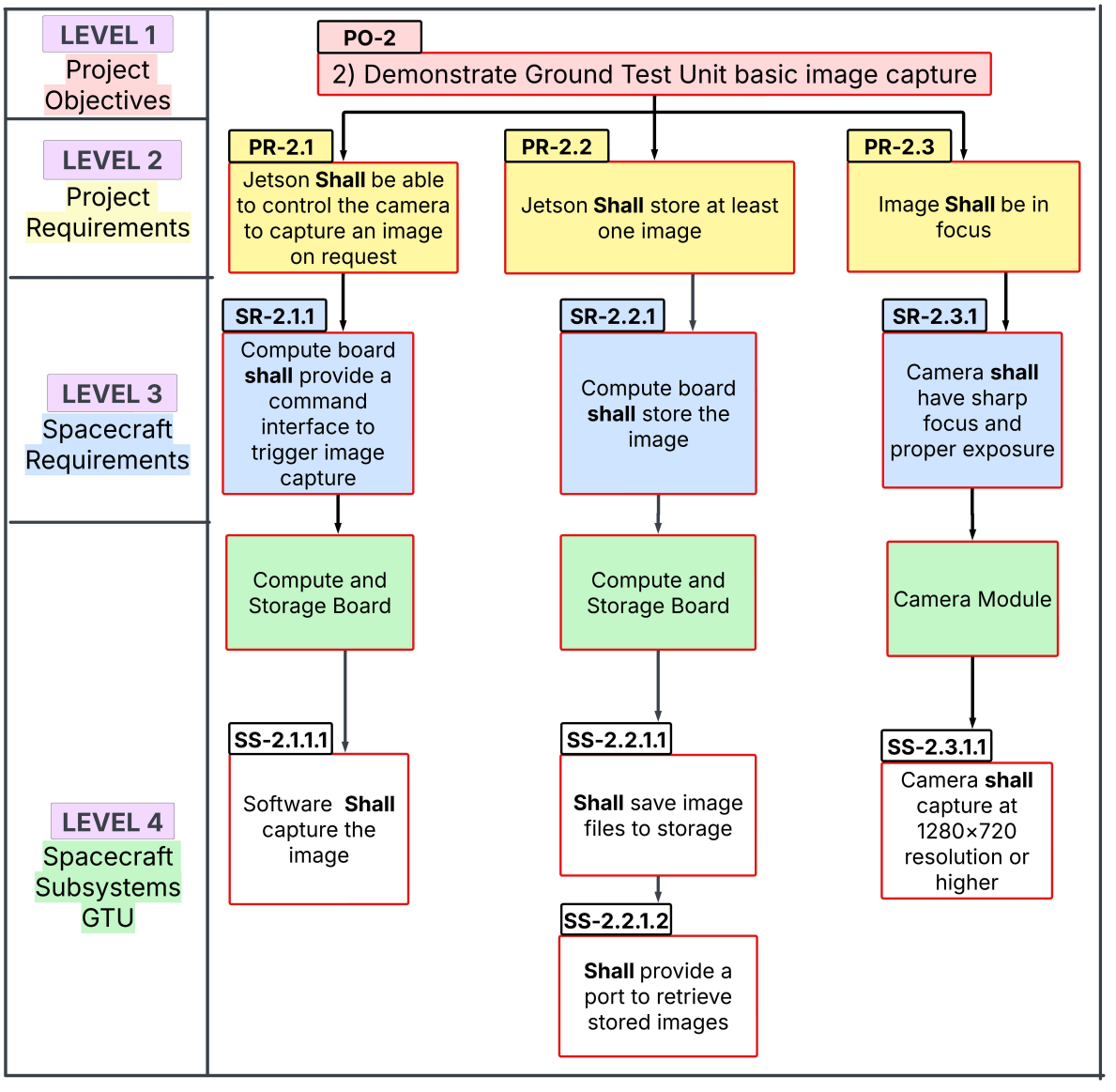


Figure 4.2 – Project objective 2: demonstrate basic ground test unit image capture.

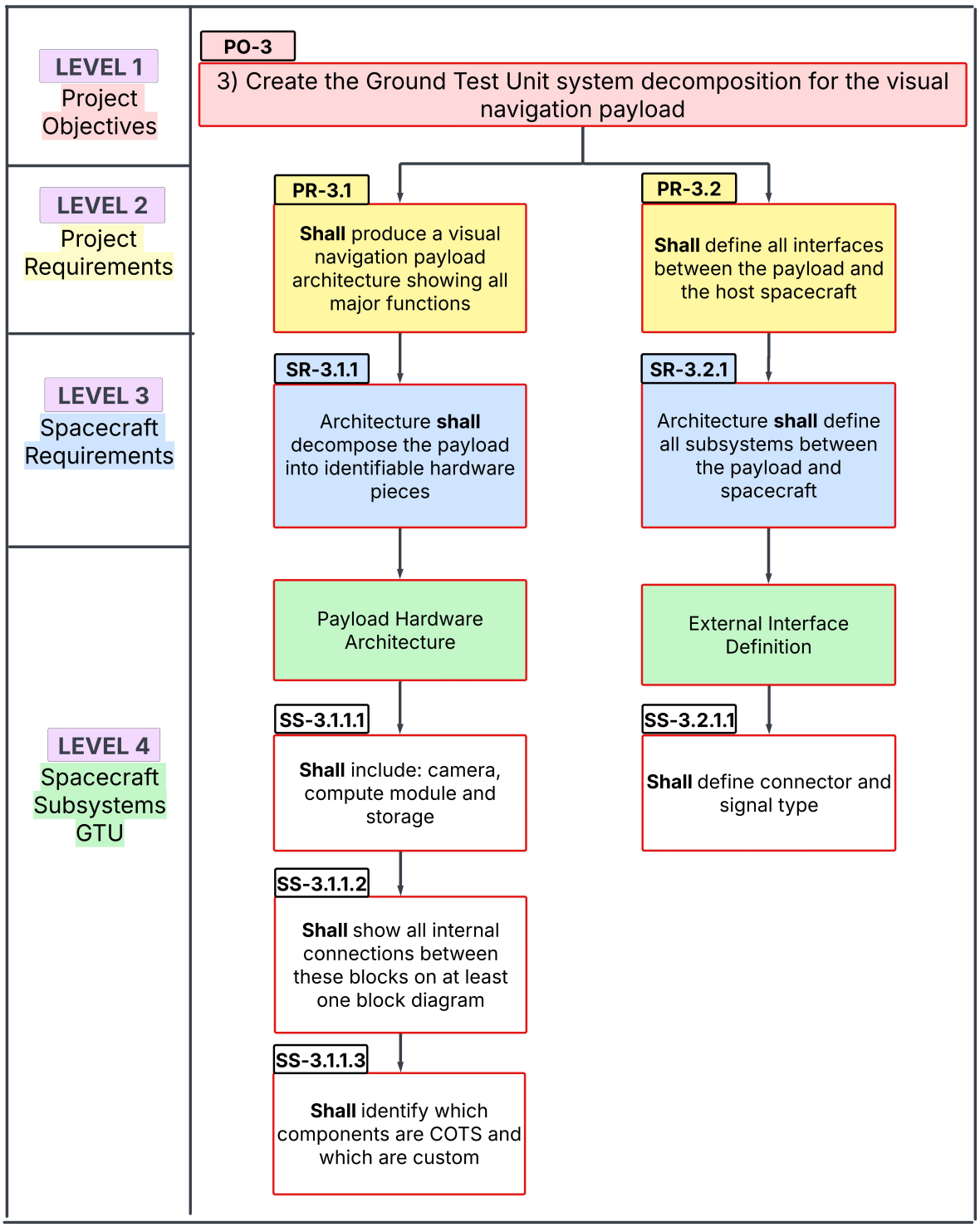


Figure 4.3 – Project objective 3: create the ground test unit system decomposition for the visual navigation payload.

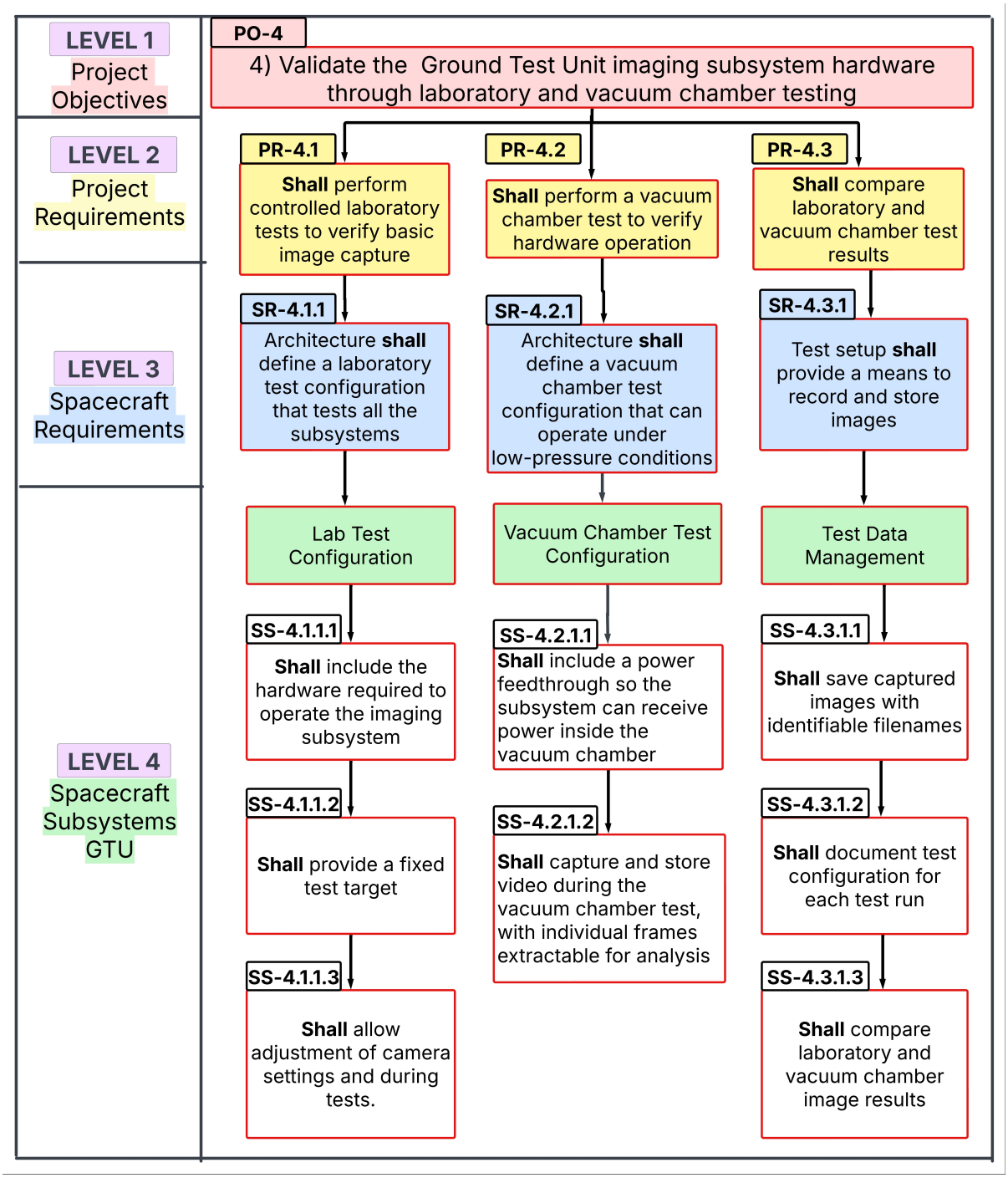


Figure 4.4 – Project objective 4: validate the ground test unit imaging subsystem hardware through laboratory and vacuum chamber testing.

Table 4.1 – Mission performance requirements for visual payload.

Category	Mission Success Criteria (Requirements)
Frame Resolution	Shall capture images at 1280 × 720 (720p) or higher resolution.
Image Visibility	Shall produce an image that is distinguishable by an observer with normal (20/20) vision.
Capture Function	Shall capture video, with individual frames extractable as still images for ground analysis.
Storage	Shall store at least one captured image that can be retrieved later.
Vacuum Operation	Shall operate inside the vacuum chamber without crashes or data loss during the test.

Table 4.1 summarizes the mission performance requirements for the visual payload. These requirements describe the capabilities needed for the imaging system to successfully accomplish the mission. The emphasis is placed on producing usable images because this helps ensure that the system is testable with the available resources.

4.3 Requirements Traceability

Table 4.2 – Requirements traceability – PO-1: integrate the ground test unit imaging subsystem hardware.

Req ID	Requirement	Paper Section	Status
PR-1.1	Shall fit the volume, mass, and power provided by the host spacecraft	Section 5.5, 5.6	Partially verified
PR-1.2	Shall provide basic image capture	Section 5.4, 7.1	Verified by test
PR-1.3	Shall have standard data interfaces to the host spacecraft	Section 6.2	Verified
SR-1.1.1	Mechanical interfaces shall be compatible with a CubeSat structure	Section 5.5	Partially verified
SR-1.1.2	Payload mass shall be within the allocated mass limit	Section 5.5	Verified by analysis
SR-1.1.3	Payload power shall be within the allocated power budget	Section 5.6	Verified by analysis
SR-1.2.1	Camera, compute module, and storage board shall be capable of capturing a basic image	Section 5.3, 5.4	Verified by test
SR-1.3.1	Data interfaces shall support reliable transfer from camera to compute module to host spacecraft	Section 6.2	Verified
SS-1.1.1.1	Imaging payload shall fit within the allocated CubeSat-class payload volume	Section 5.5	Verified by analysis
SS-1.1.2.1	Shall produce a mass budget table for the payload	Section 5.5	Verified
SS-1.1.3.1	Shall document power draw using manufacturer specifications	Section 5.6	Verified
SS-1.2.1.1	Compute board shall provide at least one compatible camera interface	Section 5.3	Verified
SS-1.2.1.2	Compute board shall provide non-volatile storage for captured images	Section 5.3	Verified
SS-1.2.1.3	Camera connector shall match the computer board interface	Section 5.4	Verified
SS-1.3.1.1	Data interface shall support reliable transfer from camera to compute module and to host spacecraft	Section 6.2	Verified

Table 4.3 – Requirements traceability – PO-2: demonstrate basic ground test unit image capture.

Req ID	Requirement	Paper Section	Status
PR-2.1	Jetson shall be able to control the camera to capture an image on request	Section 6.1, 7.1	Verified by test
PR-2.2	Jetson shall store at least one image	Section 6.3, 7.1	Verified by test
PR-2.3	Image shall be in focus	Section 7.1	Verified by test
SR-2.1.1	Compute board shall provide a command interface to trigger image capture	Section 6.1, 7.1	Verified by test
SR-2.2.1	Compute board shall store the image	Section 6.3	Verified by test
SR-2.3.1	Camera shall have sharp focus and proper exposure	Section 5.4,7.1	Verified by test
SS-2.1.1.1	Software shall capture the image	Section 7.1	Verified by test
SS-2.2.1.1	Shall save image files to storage	Section 7.1, 7.2	Verified by test
SS-2.2.1.2	Shall provide a port to retrieve stored images	Section 6.4	Verified
SS-2.3.1.1	Camera shall capture at 1280×720 resolution or higher	Section 5.4	Verified

Table 4.4 – Requirements traceability – PO-3: create the ground test unit system decomposition for the visual navigation payload.

Req ID	Requirement	Paper Section	Status
PR-3.1	Shall produce a visual navigation payload architecture showing all major functions	Section 5.1	Verified
PR-3.2	Shall define all interfaces between the payload and the host spacecraft	Section 6.2, 6.4	Verified
SR-3.1.1	Architecture shall decompose the payload into identifiable hardware pieces	Section 5.1	Verified
SR-3.2.1	Architecture shall define all subsystems between the payload and spacecraft	Section 6.2, 6.5	Verified
SS-3.1.1.1	Shall include: camera, compute module, storage, and power	Section 5.1	Verified
SS-3.1.1.2	Shall show all internal connections between these blocks on at least one block diagram	Section 6.3	Verified
SS-3.1.1.3	Shall identify which components are COTS and which are custom	Section 5.3, 5.4	Verified
SS-3.2.1.1	Shall define connector and signal type	Section 6.4	Verified

Table 4.5 – Requirements traceability – PO-4: validate the ground test unit imaging subsystem hardware through laboratory and vacuum chamber testing.

Req ID	Requirement	Paper Section	Status
PR-4.1	Shall perform controlled laboratory tests to verify basic image capture	Section 7.1	Verified by test
PR-4.2	Shall perform a vacuum chamber test to verify hardware operation	Section 7.2	Verified by test
PR-4.3	Shall compare laboratory and vacuum chamber test results	Section 7.4	Verified by test
SR-4.1.1	Architecture shall define a laboratory test configuration that tests all the subsystems	Section 7.1	Verified
SR-4.2.1	Architecture shall define a vacuum chamber test configuration that can operate under low-pressure conditions	Section 7.2.1	Verified
SR-4.3.1	Test setup shall provide a means to record and store images	Section 7.1, 7.2	Verified by test
SS-4.1.1.1	Shall include the hardware required to operate the imaging subsystem	Section 7.1	Verified by test
SS-4.1.1.2	Shall provide a fixed test target	Section 7.1, 7.2.1	Verified by test
SS-4.1.1.3	Shall allow adjustment of camera settings during tests	Section 7.1	Verified
SS-4.2.1.1	Shall include a power feedthrough so the subsystem can receive power inside the vacuum chamber	Section 7.2.1	Verified by test
SS-4.2.1.2	Shall capture and store video during the vacuum chamber test, with individual frames extractable for analysis	Section 7.2.2	Verified by test
SS-4.3.1.1	Shall save captured images with identifiable filenames	Section 7.1, 7.2	Verified by test
SS-4.3.1.2	Shall document test configuration for each test run	Section 7.5	Verified
SS-4.3.1.3	Shall compare laboratory and vacuum chamber image results	Section 7.4	Verified by test

4.4 Concept of Operations

The concept of operations describes the sequence of events the imaging payload would follow during a mission. In the planned operational scenario, the CubeSat is deployed from the International Space Station into low Earth orbit at approximately 400 km altitude. After deployment, the spacecraft stabilizes and enters its nominal operating mode.

During designated observation windows, the spacecraft orients toward the Moon using its attitude determination and control system. The Jetson Orin Nano then powers on the IMX219 camera module and initiates image capture. The camera records a short video. Individual frames are extracted from the recorded video for analysis. For navigation use, the frame containing the lunar limb is selected.

After capture, the Jetson stores the image data. In a future implementation, an onboard algorithm could determine whether the Moon is present in the frame and save the image for

priority storage. Images that do not meet quality thresholds would be discarded to conserve storage. For the current prototype, all captured images are retained.

During a ground station pass, the stored images are transmitted to the ground through the spacecraft communications subsystem. For the ground prototype, images are retrieved through a USB connection to a host computer. The images are then evaluated for clarity, exposure, and whether the crescent Moon is identifiable. This data supports future development of autonomous navigation algorithms. On-orbit operations are outside the scope of this project. Instead, the ConOps is validated through laboratory and vacuum chamber testing that simulates the key steps of image capture, storage, and retrieval. Figure 4.5 shows the operational flow.

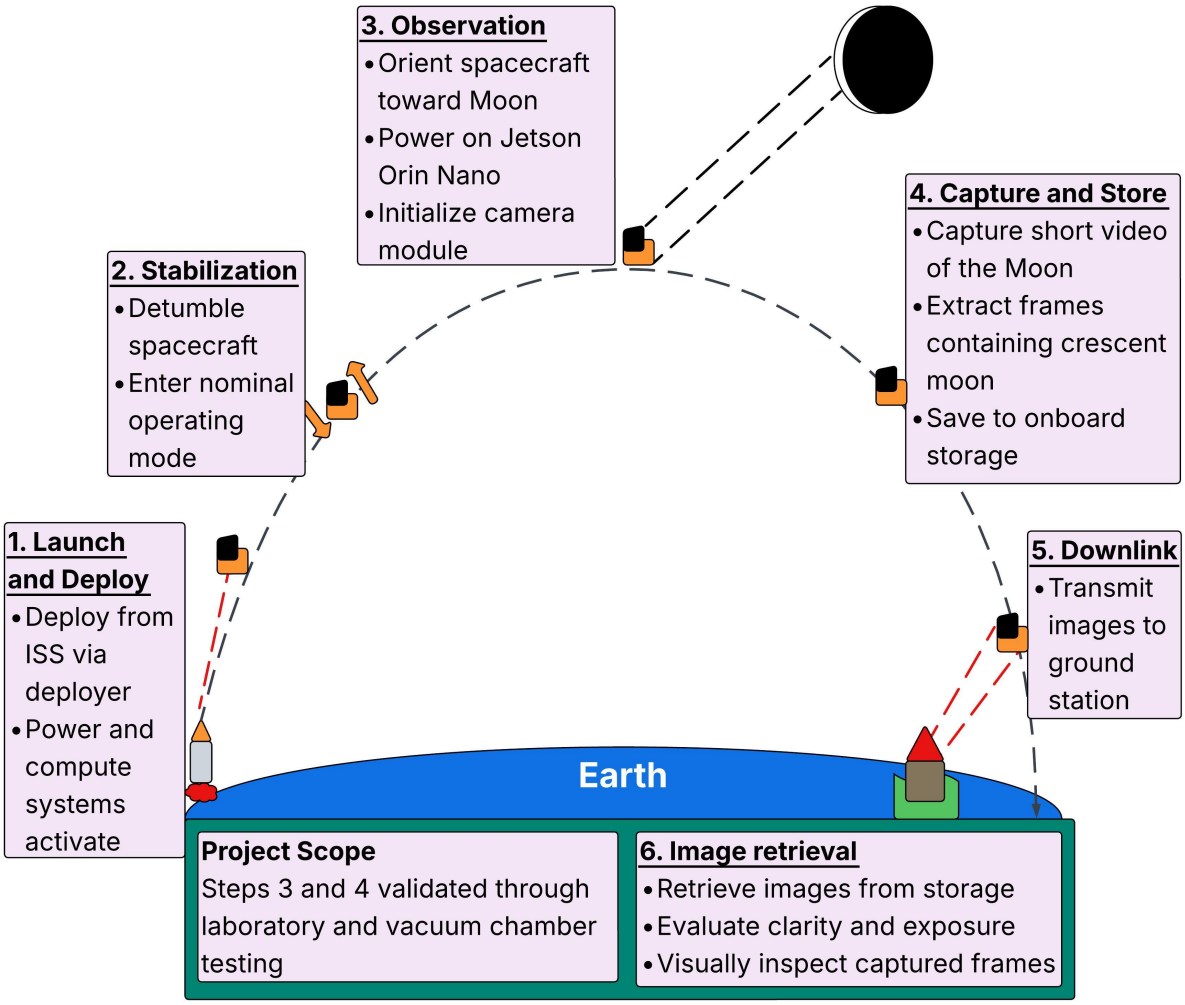


Figure 4.5 – Concept of operations for the visual navigation payload.

5 PRELIMINARY HARDWARE RESEARCH AND SELECTION

5.1 Overview of Required Components

The prototype requires the major components needed to support image capture, local storage, and testing. The principal systems needed for this project are shown in Figure 5.1 and include the compute board, camera, storage, power elements, and supporting interfaces required for prototype operation. Because the project is being developed under a limited budget and timeline, the selection process prioritizes compatibility, practicality, and testability. The computer board was selected for its computing performance, camera interface, proven reliability in space conditions, and onboard storage capability. Paired with the selected camera and onboard storage, the system provides a practical foundation for prototype integration and environmental validation.

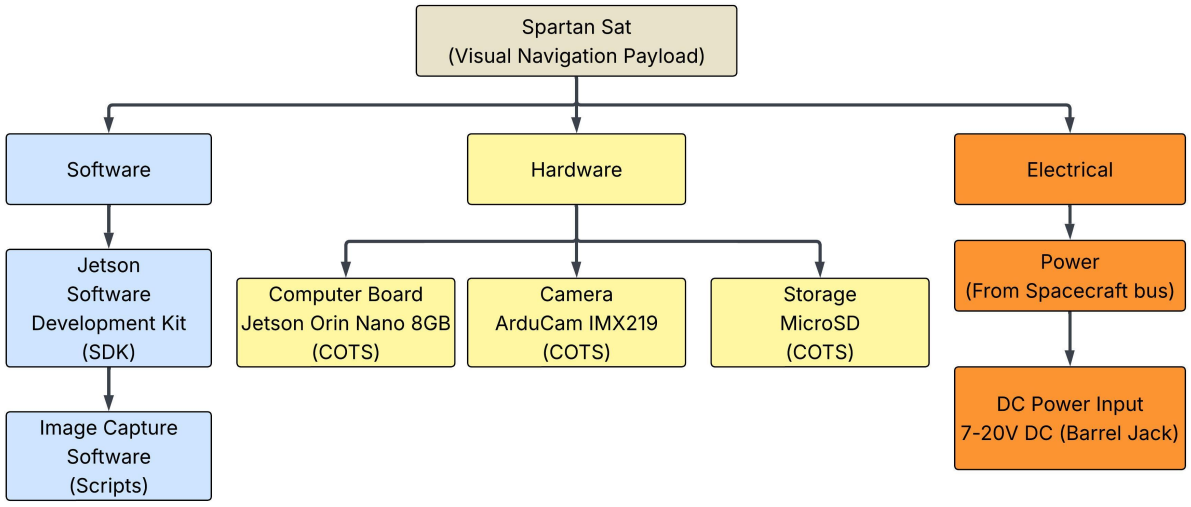


Figure 5.1 – System decomposition of the small satellite hardware.

5.2 Legacy Jetson TX2 Background and Why It Is No Longer Suitable

The NVIDIA Jetson TX2 in Figure 5.2 was originally selected because it offered strong compute capability, low weight, and low power consumption for its small size [50]. For example, it has a spaceflight history through TechEdSat-8, where it recorded and compressed video onboard [1]. However, the Jetson TX2 is no longer usable for this project, primarily due to cost, availability, and interface changes. NVIDIA has shifted developer support toward newer Jetson families. If the project continued to build around it, it would increase the timeline and further complicate the project, increasing design decisions that could further delay the final prototype. In addition, new Jetson board models shown in Figure 5.3 often require different carrier boards, updated interfaces, and more complex integration work, furthering the complexity for a low budget student prototype [51]. For these reasons, the TX2

was dropped and the trade study moved on to other compute board options that better fit the project's objectives.

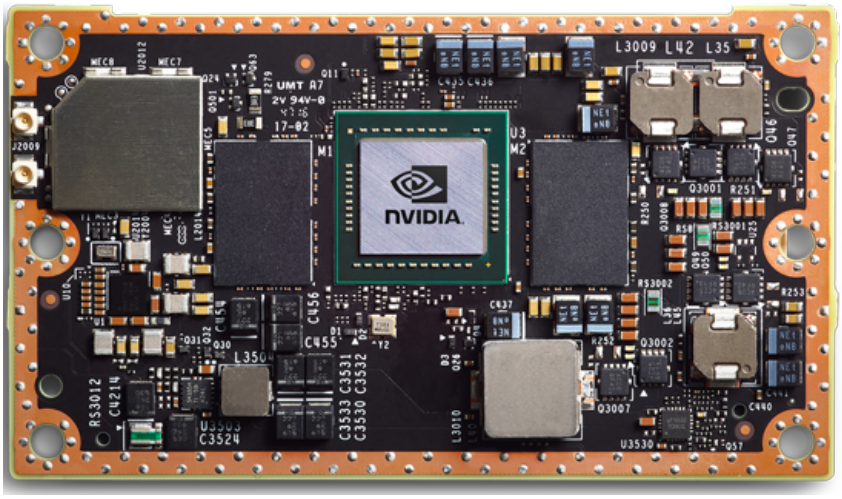


Figure 5.2 – NVIDIA Jetson TX2 (old model).

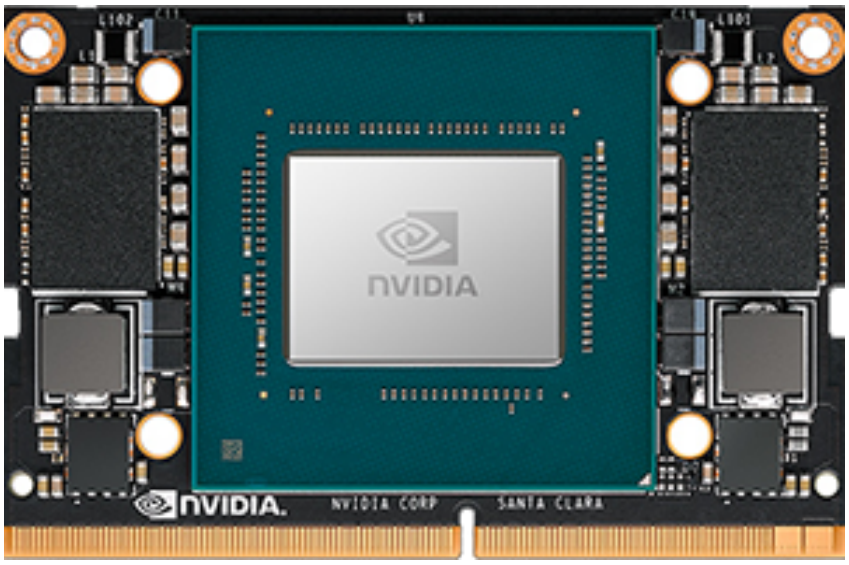


Figure 5.3 – NVIDIA Jetson Xavier NX (new model).

5.3 Candidate Compute Platforms and Selection Approach

Table 5.1 presents a comparison of NVIDIA modules released since 2017, beginning with the Jetson TX2, which was used in the TechEdSat-8. The trade study was made to identify the different computing platforms that could meet the mission objectives while keeping it on a low weight and cost. The Jetson TX2 offers 1.3 TFLOPS (Trillion Floating Point Operations Per

Second), weighs only 85 grams, and costs $399, making it a balanced option for space applications. However, the TX2 has been updated with new interfaces that are not easy to attach to the camera and other subsystems. Since NVIDIA has shifted developer support to newer Jetson families, it would further increase the complexity for new designs. Continued reliance on the TX2 would increase constraints. While newer Jetson models offer significant improvements in computing performance, they also have trade-offs. For example, the Jetson AGX Orin delivers up to 275 TOPS (Trillion Operations Per Second), a large leap in performance. However, it weighs 825 grams, consumes 15–60W of power, and costs $1,999, which limits its feasibility for space use because of its weight and power consumption. The Jetson Orin Nano was selected with more updated technology. It provides 67 TOPS, weighs only 80 grams, operates between 7–15W, and is priced at $250. The Orin Nano needs a compatible carrier board and is more complex to integrate than a microcontroller-based option. But it provides much more compute headroom, enough for image capture, storage, compression, and future AI navigation tasks. For these reasons, the Jetson Orin Nano (8 GB) was selected as the computer board. The NASA Small Spacecraft Technology State of the Art report also lists the Jetson family among computing platforms being used on small satellites [52]. Although the Arduino Portenta H7 was considered during the trade study because of its compact size, lower power consumption, and ease of integration, it was not selected as the primary compute platform for this project. The Portenta is better suited as a lower-power microcontroller-based alternative, but it does not provide the onboard computing capability required for image capture, local storage, compression, and future AI-based lunar navigation tasks. This is why the Orin Nano was chosen over the Portenta H7 despite the higher cost and integration overhead.

Table 5.1 – Computer hardware comparison (2017-2023).

Name	Released	Memory	AI Perf.	Power	Cost ($)	weight
Jetson Orin NX	2023	8 GB or 16 GB LPDDR5	70 / 100 TOPS	10-25 W	$1,400	80 g
NVIDIA Jetson Orin Nano (8 GB)	2023	8 GB LPDDR5	67 TOPS	7-15 W	$250	80 g
Jetson AGX Orin	2022	64 GB 256-bit LPDDR5	275 TOPS	15-60 W	$1,999	825 g
Jetson TX2 NX	2021	4 GB LPDDR4	1.33 TFLOPS	7.5W	$399	85 g
Arduino Portenta H7	2020	8 MB SDRAM + 16 MB Flash	No onboard AI accelerator	0.6-1.5 W	$99	34 g
NVIDIA Jetson Xavier NX	2019	8 GB 128-bit LPDDR4x	21 TOPS	10-15 W	$399	140 g
NVIDIA Jetson AGX Xavier	2018	32 GB 256-bit LPDDR4x	32 TOPS	10-30 W	$1,099	280 g
Jetson TX2	2017	8 GB 128-bit LPDDR4	1.3 TFLOPS	7.5-15 W	$399	85 g

5.4 Camera and Imaging Sensors

To satisfy the mission's imaging requirements, the selected camera must reliably capture clear videos of the Moon, with an emphasis on detecting the crescent phase for navigation validation purposes. It must offer a sufficient field of view to ensure the Moon remains within the camera's range and provide adequate resolution to support potential future lunar navigation systems. Additionally, the camera must integrate with the Jetson Orin Nano (8 GB) to support image acquisition, local storage, and reliable prototype operation during testing. Using these criteria, multiple cameras were compared and evaluated in Table 5.2.

Table 5.2 – Camera hardware comparison.

Name	Cost ($)	Flight Heritage	Size	Weight	Power Use	Field of View (FOV)	Resolution	Sensor Type
LI-OV580-STEREO [53]	$599	Yes	40.0 (L) x 26.0 (W) mm	31 g (w/ lens)	295 mA @ 5 VDC	113.2° diagonal, 98.0° horizontal, 58.0° vertical	4416 x 1242	CMOS, color
SkyFox Labs piCAM	$560	Yes	33.0 (W) x 33.0 (L) x 19.0 (H) mm	40 g	95 mA @ 3.3V (315 mW)	60° diagonal	640 × 480 (VGA)	CMOS, color
Raspberry Pi Camera v2	$25	Yes	25 × 24 × 9 mm	3 g	250 – 300 mW	62.2° horizontal, 48.8° vertical	3280 × 2464	Sony IMX219
PTC08 V3.2 (Sensor MT9V011)	$23	No	32 mm x 32 mm	25 g	75 mA @ 5V (375 mW)	60°	640 × 480 (VGA)	CMOS

Cameras that have previously flown in space were selected and their performance was evaluated based on SWaP (Size, Weight, and Power). SWaP considerations are critical in camera selection, as power consumption impacts the size and weight of the battery required for the satellite. Higher power demands require larger batteries and additional supporting hardware, which increases the satellite's mass and volume. By minimizing power consumption the satellite design can remain within strict CubeSat limitations while maintaining reliable performance. Other criteria to assess were price, field of view, resolution, and sensor type. Priority was placed on low weight and power consumption while ensuring the camera could meet the mission's imaging and navigation requirements. Based on the trade study, the Raspberry Pi Camera v2 stood out due to its low cost of $25, low weight of 3 g, and its Raspberry Pi hardware has been used on the International Space Station through the Astro Pi program [41]. The Raspberry Pi Camera v2 uses the Sony IMX219 sensor, which captures images at 3280 × 2464 pixels with a field of view of 62.2°(horizontal) and 48.8°(vertical). These specifications met the imaging and resolution requirements for the project.

However, for the actual prototype, an Arducam 8MP IMX219 camera module was used instead of the Raspberry Pi Camera v2 [54]. The Arducam uses the same sensor, resolution, and CSI-2 interface as the Raspberry Pi Camera v2. The reason for choosing the Arducam over the Raspberry Pi Camera v2 was compatibility. The Arducam is designed specifically for the NVIDIA Jetson platform and connects directly to the Jetson carrier board CSI connector without requiring an adapter cable. The Raspberry Pi Camera v2 uses a 15-pin connector, while the Jetson Orin Nano Developer Kit carrier board has a 22-pin connector. Using the Arducam avoids the need for a 15-to-22 pin conversion cable, which simplifies integration and reduces potential points of failure.

The Arducam has a programmable autofocus lens. The image focus requirement defined in SR-2.3.1 is met by setting the lens to focus at the test target distance during ground testing. Both cameras use the same sensor and produce the same image quality. Future iterations of the system may integrate the SkyFox Labs piCAM, which is designed for space environments and has a space flight record in CubeSat missions. The selection of the IMX219 camera module satisfies requirements SS-1.2.1.3, SR-2.3.1, and SS-2.3.1.1.

5.5 Mass and Volume Budget

A mass and volume budget was put together to check that the imaging payload fits within the limits of a CubeSat. The CubeSat standard defines one CubeSat unit (1U) as a 100 mm $\times$ 100 mm $\times$ 100 mm cube with a maximum allowable mass of 1.33 kg per unit [55].

5.5.1 Volume Analysis

The volume occupied by each component was calculated from the manufacturer datasheets. The Jetson Orin Nano Developer Kit measures 100 mm $\times$ 79 mm $\times$ 21 mm [56]:

$$V_{\text{Jetson}} = 100 \times 79 \times 21 = 165{,}900 \text{ mm}^3 = 0.166 \text{ L} \tag{5.1}$$

The Arducam IMX219 camera module measures 25 mm $\times$ 24 mm $\times$ 9 mm [54]:

$$V_{\text{Camera}} = 25 \times 24 \times 9 = 5{,}400 \text{ mm}^3 = 0.0054 \text{ L} \tag{5.2}$$

The combined hardware volume from Eqs. (5.1) and (5.2) is the sum of the two:

$$V_{\text{Total}} = V_{\text{Jetson}} + V_{\text{Camera}} = 0.171 \text{ L} \tag{5.3}$$

After adding margin for cables, mounting hardware, and integration, the imaging payload occupies about 0.25 U of the host CubeSat. This satisfies requirement SS-1.1.1.1. The volume fit confirms the payload would fit a CubeSat slot, but the prototype was not mounted in a flight structure, so the mechanical interface is only partially verified.

5.5.2 Mass Budget

Because the imaging payload takes up 0.25 U, the maximum allowable mass for the payload is given by Eq. (5.4):

$$m_{\text{max}} = 0.25 \text{ U} \times 1.33 \text{ kg/U} = 0.33 \text{ kg} = 333 \text{ g} \tag{5.4}$$

The component masses come from manufacturer datasheets and are listed in Table 5.3. The heaviest part of the prototype is the Jetson Orin Nano Developer Kit. This includes the 8 GB module, the reference carrier board, and the heatsink with fan. Together, the developer kit weighs 176 g [57]. The IMX219 camera module adds about 3 g. The CSI-2 ribbon cable, mounting hardware, and power cable bring the total to about 204 g. This is below the maximum from Eq. (5.4) and satisfies requirement SS-1.1.2.1. For future work the developer kit carrier board and heatsink would be replaced with a smaller and lighter carrier board. This would bring the mass down. But for ground testing, the developer kit is used because it is the accessible option for this project.

Table 5.3 – Mass budget for the imaging payload (prototype configuration).

Component	**Mass (g)**
Jetson Orin Nano Developer Kit (module + carrier + thermal)	176
IMX219 camera module (Arducam B0181)	3
CSI-2 ribbon cable (22-pin FFC)	5
Mounting hardware (standoffs, screws)	15
Power cable and connector	5
Total (prototype)	**204**
Maximum allowable (0.25 U)	**333**

5.6 Power Budget

A power budget was put together from manufacturer specs to check that the imaging payload draws what is available to it. The Jetson Orin Nano 8 GB module supports configurable power modes ranging from 7 W to 15 W [58]. The IMX219 camera module draws 0.2 W to 0.3 W during active capture [59]. Table 5.4 summarizes the power draw for each operating mode.

Table 5.4 – Power budget for the imaging payload.

Component	**Mode**	**Power (W)**
Jetson Orin Nano 8 GB	7 W mode (low power) [58]	7.0
Jetson Orin Nano 8 GB	15 W mode (high performance) [58]	15.0
Jetson Orin Nano 8 GB	Image capture (estimated)	8.0 – 12.0
IMX219 camera module	Active capture (typical) [59]	0.2
IMX219 camera module	Active capture (maximum) [59]	0.3
System total	**Idle (7 W mode)**	**∼7.2**
System total	**Image capture (typical)**	**∼10.2**
System total	**Peak (15 W mode)**	**∼15.3**

The Jetson Orin Nano uses the most power out of all the components. The camera module adds less than 0.5 W in all cases, so it does not have a big impact in the total system draw. The 7 W and 15 W values are configurable mode caps set through the NVIDIA power management software. The actual power draw during image capture falls between these two modes depending on what software is running and how hard the processor is working. The values listed in Table 5.4 are based on manufacturer specifications. Further testing is required to validate the actual power draw during operation. Measuring the real system-level power draw in each operating mode is identified as future work for teams continuing this project. This satisfies requirement SS-1.1.3.1.

6 CONCEPTUAL SYSTEM INTEGRATION PLAN

6.1 Integration Strategy and Workflow

The imaging payload prototype is made up of two main hardware components. The first is an NVIDIA Jetson Orin Nano 8 GB Developer Kit. This is the compute board that handles image capture, processing, and storage [57]. The Developer Kit includes three parts in one package. The first is the Jetson Orin Nano 8 GB module, which contains the processor and memory. The second is the reference carrier board, which provides physical connectors such as display ports, camera connector, and power. The third is the heatsink with fan, which keeps the module from overheating during operation. The second component is an Arducam 8MP IMX219 camera module, model B0181 [54]. This is the imaging sensor for the payload. The camera connects to the Jetson through a 22-pin MIPI CSI-2 ribbon cable. The cable carries both data and power to the camera.

Both the Jetson Orin Nano 8 GB and the Arducam are commercial off-the-shelf (COTS) hardware. The reason for using COTS hardware was cost, availability, and the need for a working prototype that can be built and tested within the project timeline.

The system is defined as the NVIDIA Jetson Orin Nano 8 GB Developer Kit, which includes the module, carrier board, and thermal solution. The camera is defined as the Arducam IMX219 camera module.

The integration effort in this project focuses on component placement, secure mounting, cable routing, and verification that the camera and compute board operate together reliably. Once assembled, the system is tested in laboratory and vacuum chamber conditions to evaluate image capture, storage, and overall hardware performance. The integration workflow is broken into five steps, shown in Figure 6.1.

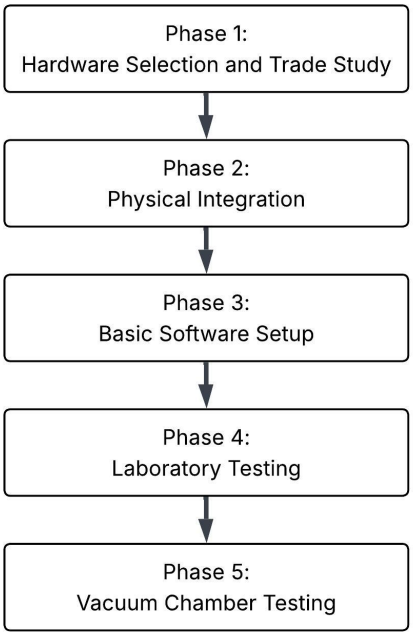


Figure 6.1 – Integration of the hardware and phases.

Figure 6.2 shows the back of the Arducam IMX219 PCB where the CSI-2 ribbon cable connector is. Figure 6.3 shows the camera with the ribbon cable plugged in. Figure 6.4 shows the full assembly with the Jetson, camera, CSI-2 cable, USB, and power connected. Figure 6.5 shows the lab setup used for testing with the display, keyboard, mouse, and power supply.

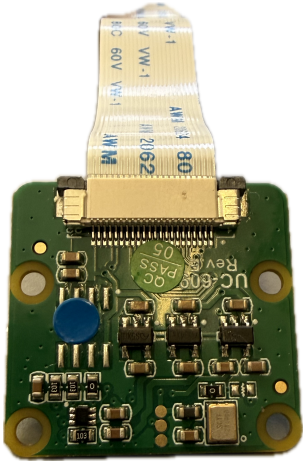


Figure 6.2 – Arducam IMX219 camera module (B0181) showing the PCB back side with CSI-2 ribbon cable connector.

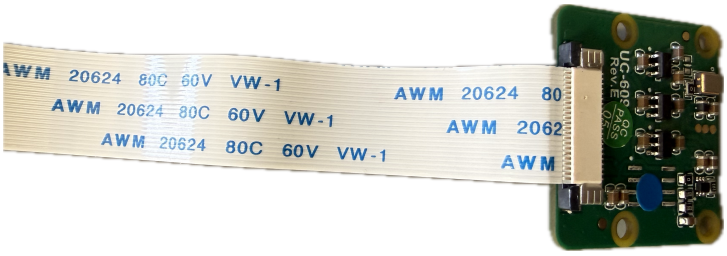


Figure 6.3 – Arducam camera module with the 22-pin CSI-2 ribbon cable attached.

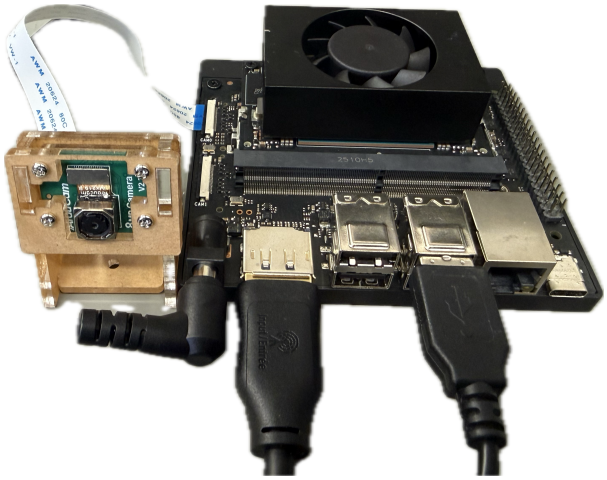


Figure 6.4 – Assembled prototype: Jetson Orin Nano Developer Kit with Arducam IMX219, CSI-2 ribbon cable, and USB/power connections.

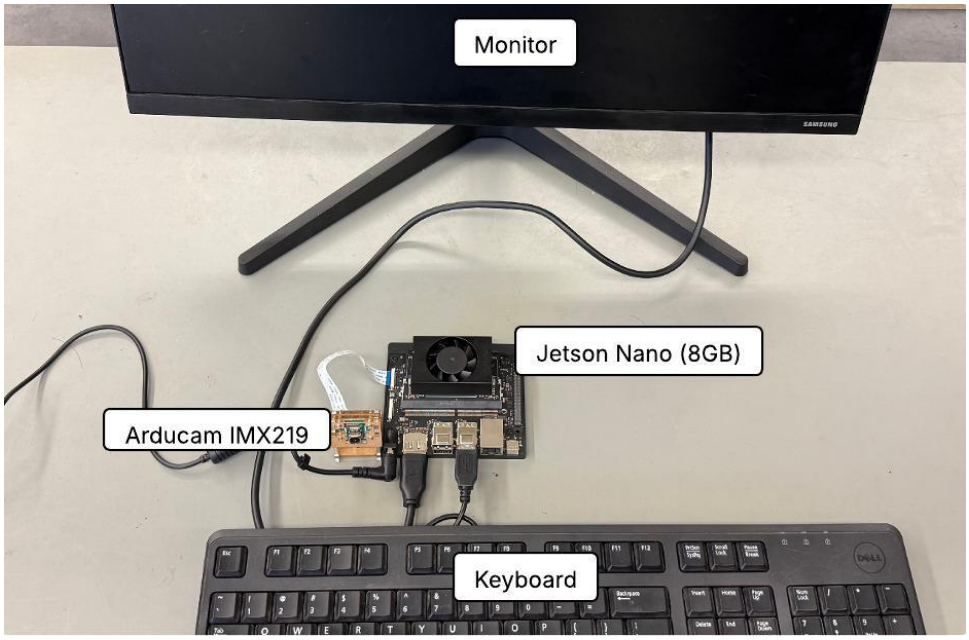


Figure 6.5 – Laboratory test configuration showing the Jetson Orin Nano Developer Kit, display, keyboard, mouse, and IMX219 camera.

6.2 System Communication and Interface Requirements

Reliable data transfer between the camera and the Jetson Orin Nano (8 GB) is needed for the imaging system to work. This is achieved by selecting the Camera Serial Interface (CSI) as the primary communication link between the camera and the Jetson Orin Nano (8 GB). CSI is a standard interface widely used in embedded systems and it is specifically optimized for camera modules, providing high-speed data transfer with low power consumption. Another important advantage of using CSI is that it establishes a direct connection to the processor's memory, reduces latency, and enables faster data acquisition. This direct data path makes CSI the best fit for capturing, storing, and sending image data.

Its low power draw also suits a CubeSat's tight power and volume limits, allowing a smaller battery. Together, the direct data path and low power use make CSI the right interface for this imaging system.

6.3 System Block Diagram

A system block diagram was created to show the internal connections between the major hardware components of the imaging payload. Figure 6.6 shows the physical interfaces, data paths, and power connections.

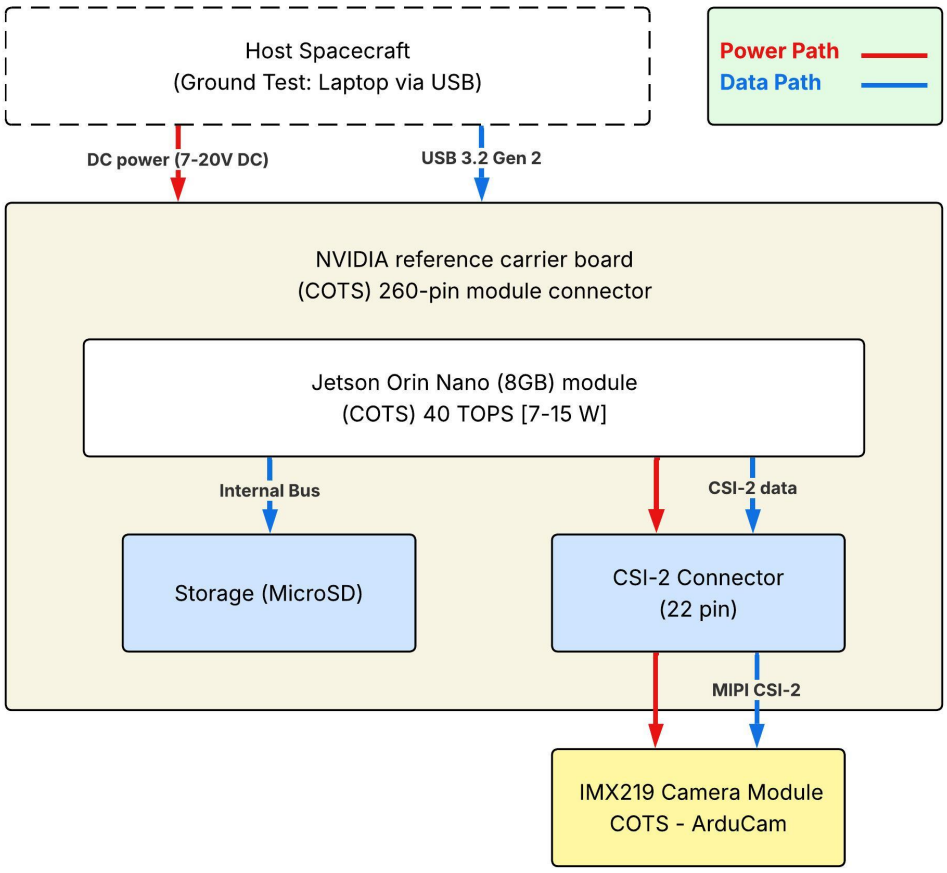


Figure 6.6 – System block diagram of the imaging payload showing data and power interfaces.

The IMX219 camera module connects to the Jetson Orin Nano through a CSI-2 interface using a 22-pin flat flexible cable. This interface supports a combined data transfer rate of up to 1.8 Gbps, which transfers full-resolution 8-megapixel images. The camera receives power directly from the Jetson board through the CSI connector.

The Jetson Orin Nano module is mounted on the NVIDIA reference carrier board via a 260-pin connector. The carrier board provides the CSI camera connector, USB 3.2 ports for data retrieval, DisplayPort for display output, and a DC barrel jack for power input [56]. Power is supplied through a DC power port that accepts 7–20V DC input, with the included supply providing 19V.

Captured images are stored on the Jetson's onboard storage (microSD card). Images are retrieved through a USB connection to a host computer during ground testing. All components in the imaging payload are commercial off-the-shelf (COTS) hardware. The physical integration of the camera and Jetson board is shown in Figures 6.3 and 6.4. This satisfies requirements SS-3.1.1.2 and SS-3.1.1.3.

6.4 Interface Specifications

Table 6.1 lists the interface specifications for each connection in the imaging payload. These values come from the NVIDIA Jetson Orin Nano Developer Kit carrier board specification and the camera datasheet [56].

Table 6.1 – Interface specifications for the imaging payload.

Interface	**Connector**	**Signal type**	**Specifications**
Camera to Jetson	22-pin FPC	MIPI CSI-2, 2-lane	Up to 912 Mbps per lane
Jetson module to carrier	260-pin SO-DIMM	Power + data	PCIe, USB, I2C
Data retrieval (test)	USB 3.2 Gen2 Type-A	Serial data	Up to 10 Gbps
Display output (test)	DisplayPort 1.2	Video	Up to 4K at 30 Hz
Power input	DC barrel jack	DC power	7–20V DC (19V supply included)
Storage	microSD slot	Data	UHS-I, up to 104 MB/s

The most important interface is the CSI-2 link between the camera and the Jetson. Each lane supports up to 912 Mbps, and the two-lane configuration provides up to 1.8 Gbps total. The Arducam B0181 connects directly to the 22-pin connector on the developer kit carrier board without requiring an adapter. Power is supplied through the DC barrel jack, which accepts an input range of 7–20V DC. The included power supply provides 19V. This satisfies requirement SS-3.2.1.1.

6.5 N2 Interface Diagram

Figure 6.7 shows the N2 diagram for the imaging payload. The N2 is a standard systems engineering tool that maps how each subsystem works together.

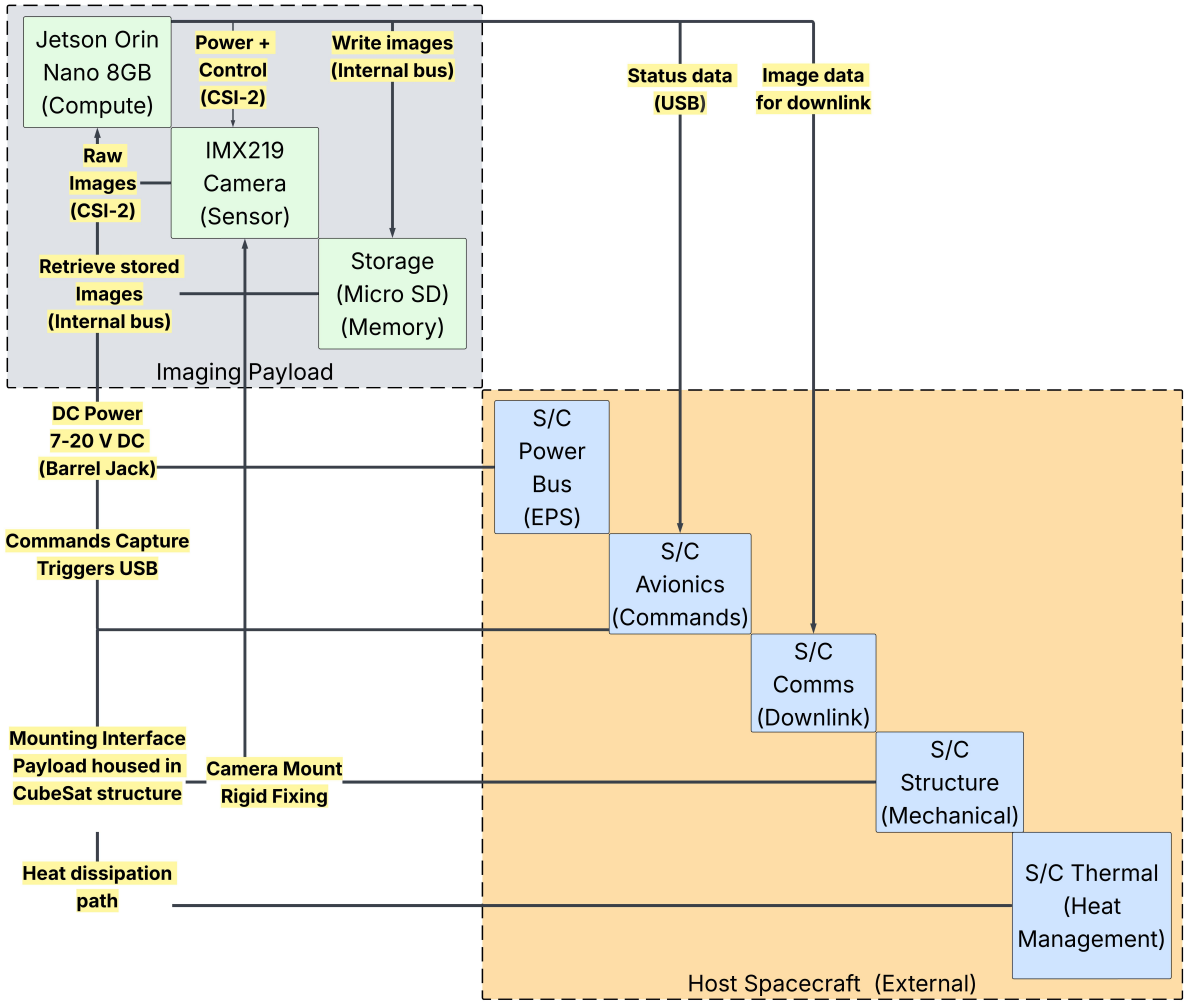


Figure 6.7 – N2 interface diagram for the imaging payload subsystem.

The N2 diagram shows that the Jetson Orin Nano serves as the central node in the system. It receives raw image data from the camera and writes captured images to the microSD storage. On the spacecraft side, the Jetson receives DC power and capture commands from the avionics. The Jetson sends status data to the avionics and image data to the communications subsystem for downlink. The camera has a single interface to the compute board. All data passes through the Jetson. The spacecraft subsystem interfaces are defined for future integration but are outside the scope of this project. This satisfies requirement SR-3.2.1.

7 TESTING AND VALIDATION

Two tests were performed to validate the imaging subsystem. The first was an indoor laboratory test that confirmed the subsystem could operate in a controlled environment. The second was a vacuum chamber test that tested the same hardware under reduced pressure. Both tests used the same imaging payload, the same five moon images as the target [60], and the same software pipeline. Using the same setup in both tests makes the results directly comparable. The complete test plans are included in Appendix A (TP-SPARTAN-001-INDOOR) and Appendix B (TP-SPARTAN-002-VACUUM).

7.1 Indoor Laboratory Test

The indoor test used a monitor as the target inside a darkened laboratory. The monitor was positioned 0.508 m in front of the camera and displayed a five-image moon sequence full screen. The room lights were turned off so that the monitor remained the only illumination source. The Jetson Orin Nano captured video at 1280×720 resolution and approximately 40 fps using default camera settings. A single continuous video was recorded while the five moon phase images were displayed in sequence. The file was then processed through the software pipeline. The Jetson operated without crashes or camera disconnects, and the pipeline identified a recognizable crescent in the best frame extracted for each moon phase.

7.2 Vacuum Chamber Test

The vacuum chamber test ran the same hardware under reduced pressure. The goal was to confirm that the imaging subsystem still operates under reduced convective cooling and lower air pressure. The test was conducted in an Abbess Instruments vacuum chamber.

7.2.1 Test Configuration

The Jetson was mounted on a Kapton-tape-backed plate at the center of the chamber floor with the IMX219 camera oriented upward. Figure 7.1 shows the integrated payload installed inside the chamber. Power was supplied externally by a bench DC supply set to 19 V with a 3 A current limit, routed through the chamber feedthrough to a barrel-jack adapter cable inside the chamber. A host laptop located outside the chamber controlled the Jetson over SSH. The SSH connection was established before the chamber was sealed so that capture commands and file checks could be performed without breaking vacuum.

The test target was an iPad placed on top of the closed chamber lid, with the screen facing downward, approximately 0.5 m above the camera. The iPad displayed the same five moon images used in the indoor test, advanced as a slideshow during the capture window. Two 100%-rated blackout curtains were placed over the chamber to block ambient light through the transparent walls, and the laboratory lights were turned off. Figure 7.2 shows the full configuration.

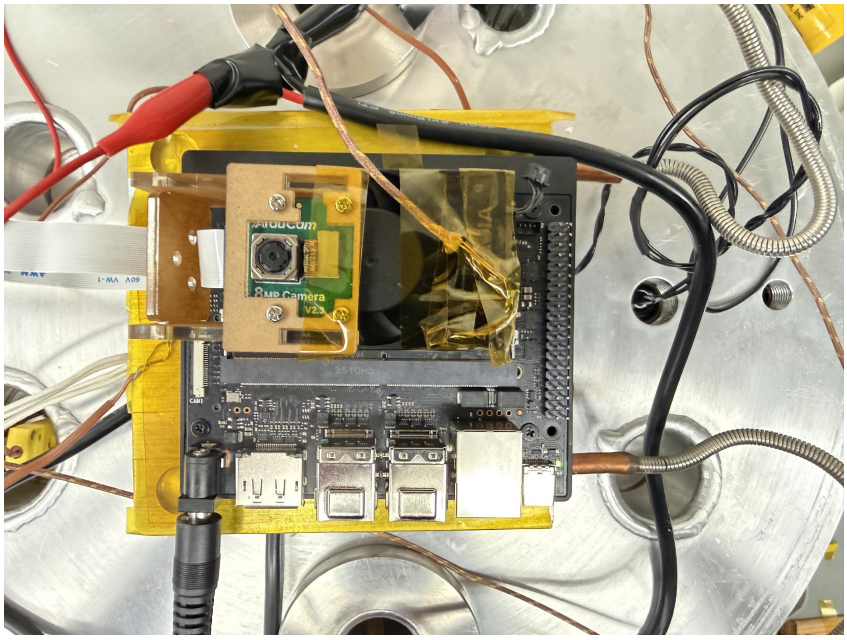


Figure 7.1 – Imaging payload mounted inside the vacuum chamber.



Figure 7.2 – Vacuum chamber test setup with the blackout curtains partially pulled back.

7.2.2 Procedure and Results

The chamber was pumped down to a stable pressure of 8.1 Torr (1.08 kPa) over approximately ten minutes. Once the pressure stabilized, video capture was started remotely, and the iPad slideshow was advanced through the five moon images during a one-minute capture window. The capture produced a 40-second video at 1280×720 resolution, totaling approximately 50 MB on the microSD. The chamber was then vented to ambient pressure, and the video file was retrieved from the Jetson over USB.

The video was processed through the same pipeline used for the indoor data, which selected the best crescent frame for each Moon ID in the slideshow. The Jetson booted through the feedthrough power path and ran continuously through the pump-down, hold, and vent cycle without losing power, dropping the camera link, or corrupting any files.

7.3 Crescent Detection Pipeline

Both tests used the same software pipeline to process the captured video. The pipeline extracts frames from the captured stream, runs each frame through a crescent detection

algorithm, and selects the best result for each Moon ID. Figures 7.3 and 7.4 show the pipeline output for the indoor laboratory test and the vacuum chamber test, respectively.

In each figure, each row corresponds to one Moon ID. The left column shows the captured grayscale frame, and the right column shows the same frame with the algorithm output overlaid. The green outline traces the detected lit edge of the moon, the yellow circle represents the inferred full-moon size based on the visible crescent arc, and the red box marks the region of interest used by the detection algorithm. The position of the red ROI shifts depending on which side of the moon is illuminated, demonstrating that the pipeline tracks the orientation of each crescent rather than assuming a fixed location. These results demonstrate that the imaging payload produces video the pipeline can process.

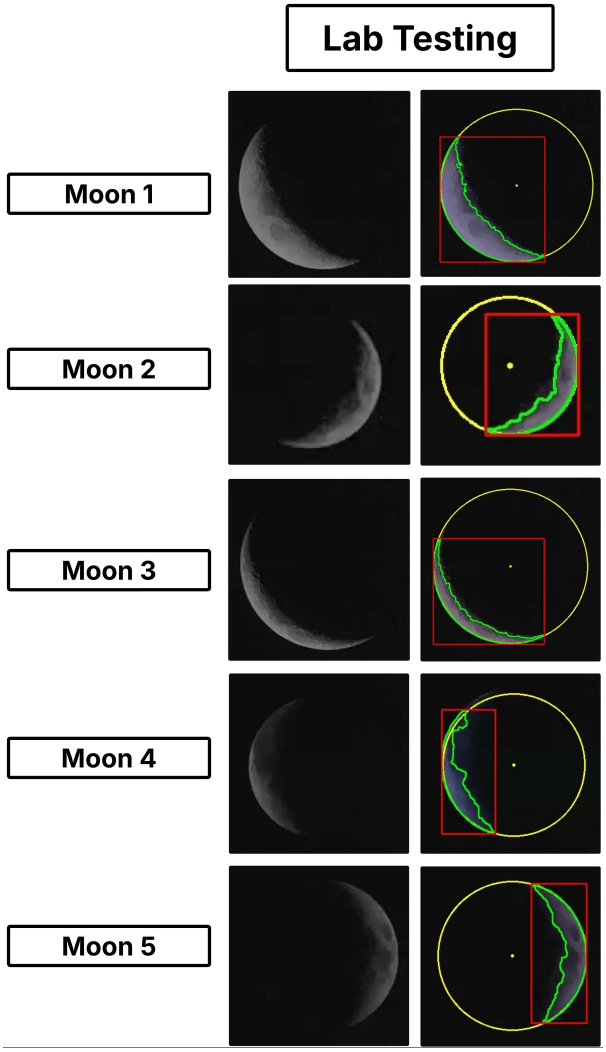


Figure 7.3 – Indoor laboratory crescent detection results for Moon 1 through Moon 5. Left column: captured grayscale frame. Right column: same frame with algorithm output overlaid.

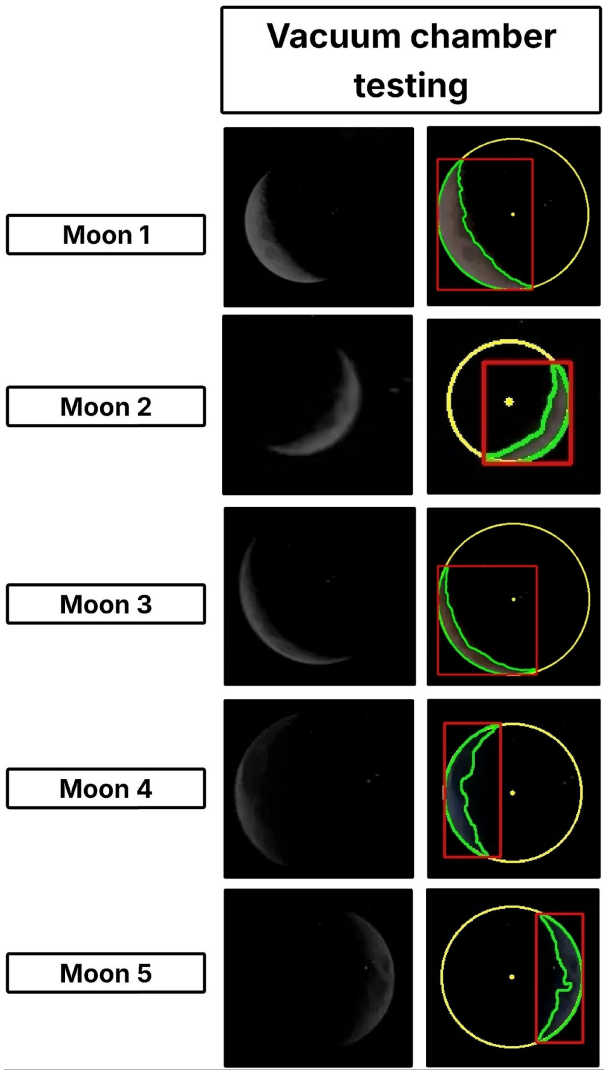


Figure 7.4 – Vacuum chamber crescent detection results for Moon 1 through Moon 5 at 8.1 Torr. Left column: captured grayscale frame. Right column: same frame with algorithm output overlaid.

7.4 Indoor and Vacuum Test Results

Figure 7.5 shows the detection results from both tests in a side-by-side layout. The pipeline identified the lit edge of the moon for all five Moon IDs in both environments. Detection was strongest on Moon 1, Moon 2, and Moon 3, where the lit edge was bright and well-defined. Moon 4 and Moon 5 are dimmer near-new images with less illuminated arc, but the algorithm still detected enough of the lit edge to produce a recognizable result in both columns. The captured imagery in the vacuum column is slightly dimmer than in the indoor column. Vacuum at this pressure does not affect light reaching the camera, so the brightness difference comes from the test setup, not the vacuum itself.

Two specific differences appear between the indoor and vacuum frames in Figure 7.5. In Moon 2, the red region of interest is larger in the vacuum frame than in the indoor frame. In Moon 4, the green crescent edge traces a different part of the lit region in the vacuum frame. The same algorithm was used on both videos, so these differences come from the captured images and not from the processing. With only one test run, the cause of the image differences cannot be determined. Several factors could explain them, including reflection through the chamber viewport or differences in target setup. The single run results show that the imaging payload works in both environments, but they are not enough to compare image quality between the indoor and vacuum cases. A statistical comparison would require running the test multiple times under the same conditions.

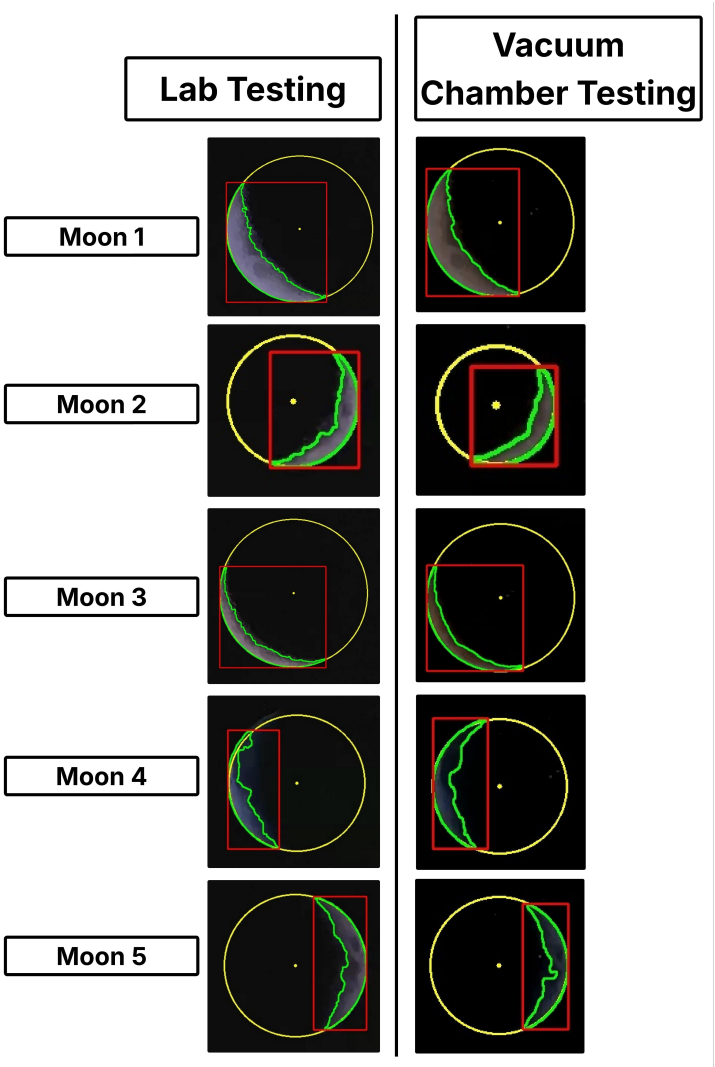


Figure 7.5 – Crescent detection results for Moon 1 through Moon 5 in the indoor laboratory test (left) and the vacuum chamber test (right).

Operating under reduced pressure did not introduce any new failure modes. The system booted, captured, stored, and returned video files in both tests, and the pipeline produced consistent results on both data sets.

These results connect back to Section 2.4 and Section 2.5. The Lunar Flashlight Optical Navigation Experiment (LONEStar) demonstrated optical navigation by imaging the Moon and other celestial bodies with an onboard camera [38], and Christian's tutorial on horizon-based navigation explains why an image of the moon's edge is a useful navigation input [37]. This project does not estimate position from the captured images. It does show that the imaging hardware needed for that kind of navigation can produce usable crescent imagery under both laboratory and reduced pressure conditions.

7.5 Performance Summary and Requirements

The criteria established in TP-SPARTAN-001-INDOOR Section 7 and TP-SPARTAN-002-VACUUM Section 7 were satisfied in both tests, including the vacuum-only criterion of sustained operation while the chamber was at reduced pressure. The results in this chapter satisfy the PR-2, PR-4, and SS-4 level requirements traced in Section 4.3.

Table 7.1 – Summary of test conditions and outcomes for both tests.

Parameter	**Indoor Lab**	**Vacuum Chamber**
Date	April 15, 2026	May 1, 2026
Location	Engr 125	AE 236
Target	Monitor at 0.508 m	iPad at 0.5 m above camera
Pressure	Ambient ($\sim$760 Torr)	8.1 Torr (1.08 kPa)
Resolution	1280$\times$720	1280$\times$720
Capture duration	$\sim$4 s	40 s
Total video size	858.8 kB	$\sim$50 MB
Moon IDs detected	5 of 5	5 of 5
Result	Pass	Pass

7.6 Environmental Considerations

The testing in this chapter was performed on the ground, but the hardware was selected with flight conditions in mind. In low Earth orbit, a satellite cycles between extreme heat in sunlight and extreme cold in eclipse. Both the Jetson Orin Nano and the IMX219 sensor are commercial off-the-shelf parts with operating temperature ranges specified for terrestrial use, and selecting COTS hardware for a flight payload requires confirming those ranges against the expected on-orbit thermal environment before deployment. The rough-vacuum test in this chapter shows that the hardware keeps working at reduced pressure but does not test thermal cycling, radiation, or orbital-level vacuum. These qualifications would still be required before any flight deployment, and they are identified as future work in Section 8.1.

8 CONCLUSION

This project was made to test a low-cost imaging payload that spacecraft could use for lunar navigation. It would use a camera to recognize the crescent Moon and treat it as a position reference, instead of relying on expensive sensors or constant ground tracking. The project took that idea from requirements to a working prototype tested on the ground.

The hardware was chosen through SWaP trade studies that weighed compute power, size, weight, power, and cost. The NVIDIA Jetson Orin Nano (8 GB) was selected as the compute board because it had enough processing room for image capture while staying within a small mass and power budget. The Arducam IMX219 was selected as the camera because it uses the same sensor as the Raspberry Pi Camera and connects directly to the Jetson carrier board without an adapter. Both parts are commercial off-the-shelf, which keeps costs low and makes them easy to find.

The payload was then defined through a full set of requirements traced from the mission objectives down to the subsystem level. Mass, volume, and power budgets confirmed that the payload fits inside a CubeSat. A concept of operations, a system block diagram, and an interface plan described how the camera, compute board, storage, and power work together. The prototype was then built from these parts and tested.

The prototype stayed within the mass and volume limits of a CubeSat payload. It took up about 0.25 U and weighed 204 g, well under the 333 g allowed for that volume. The Jetson and camera were tested in a darkened laboratory and inside a vacuum chamber at 8.1 Torr. In both environments, the pipeline found the lit edge of the Moon in all five test images. During the vacuum test, the system turned on, captured, stored, and returned video without losing power, dropping the camera link, or corrupting a file. These results show that a low-cost imaging payload built from off-the-shelf parts can capture usable crescent imagery and keep working under reduced pressure.

8.1 Future Work

Several tasks still need work before the imaging payload is ready for a flight unit. Future teams should measure the power draw in each operating mode. Those numbers feed into battery sizing and determine whether solar cell recharging can sustain continuous imaging operations.

A flight-ready carrier board should replace the Jetson Orin Nano Developer Kit. The developer kit board carries mass and bulk that a flight unit cannot afford. Moving to a smaller carrier should bring the payload below the 204 g prototype configuration documented in Section 5.5.2.

Outdoor night sky testing is the next step after indoor and vacuum chamber tests. Imaging the crescent Moon under night-sky conditions would close the gap between lab testing and the actual mission target. Outdoor testing was planned for this project but could not be done because of limited time and poor weather during the crescent moon windows. A separate test plan should cover observation sites such as Lick Observatory, portable power for the Jetson, and a mount that can point the camera at the Moon.

The tests in Chapter 7 were each only run once. Because of that, it is hard to say if the differences in Section 7.4 came from the vacuum or from something else in the setup. A Design of Experiments (DOE) setup would also help show how much of the difference comes from the pressure versus the chamber glass, the target distance, or the exposure between runs.

Finally, the vacuum chamber test in Chapter 7 ran at 8.1 Torr without temperature control. In orbit, the payload would experience temperature changes between sunlight and eclipse, and the pressure would drop even lower than the vacuum chamber could reach. A thermal vacuum test would check that the hardware still works under those conditions.

8.2 Contribution and Impact

This project shows how a working CubeSat imaging system for lunar navigation can be built from off-the-shelf parts on a student budget. The Jetson Orin Nano and Arducam IMX219 combination is documented (trade studies, integration, and test results) so future teams can pick it up and build on it instead of starting from scratch.

The contribution is more than a parts list. The requirements, the traceability tables, and the two test plans in Appendices A and B give another student team a path to follow, from a mission objective down to a tested prototype. Writing the work down this way is meant to make the next project faster than this one.

The bigger goal is to make camera-based navigation more accessible. Star trackers do attitude well but cost approximately $30,000 [40]. A $275 camera setup that can track the Moon as a position reference opens the door for smaller teams and missions where star trackers are too expensive. More CubeSats are heading toward the Moon every year, and most still depend on ground tracking or costly sensors for navigation. A camera that uses the Moon itself as a reference is one way to make that navigation cheaper and more self-reliant.

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Appendix A
INDOOR LABORATORY TEST PLAN AND RESULTS

Document ID: TP-SPARTAN-001-INDOOR *Revision:* 2.0
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A.1 Purpose

This test plan defines the procedures for validating the SpartanSat imaging subsystem hardware through a controlled indoor laboratory test using a dark room setup with an artificial crescent moon target. The imaging subsystem consists of the Jetson Orin Nano (8 GB) developer kit and the ArduCam B0181 IMX219 camera module connected through a CSI-2 interface.

This indoor test plan is the first of two planned test campaigns for the imaging subsystem. Vacuum chamber testing is identified as the next step to validate hardware operation under low-pressure conditions. The indoor test validates the core capability: the ability to capture, store, and retrieve a clear image of a crescent target in a controlled environment.

The primary objectives of this test plan are:

- Verify that the Jetson Orin Nano can command the IMX219 camera to capture and store images (PR-2.1, PR-2.2).
- Validate image quality (focus, exposure, target visibility) under controlled indoor conditions (PR-4.1).
- Capture at least one recognizable image of an artificial crescent target in a dark room setup (PR-2.3).
- Document test configurations and results with identifiable filenames for traceability (SS-4.3.1.1, SS-4.3.1.2).

This test plan supports Project Objective 4 (PO-4): Validate the ground test unit imaging subsystem hardware through laboratory and vacuum chamber testing.

A.2 Applicable Requirements

The following requirements from the SpartanSat system definition are verified by the tests in this plan. Vacuum chamber requirements (SS-4.2.1.1, SS-4.2.1.2, SS-4.3.1.3) are addressed in Appendix B.

Table A.1 – Requirements verified by the indoor laboratory test plan.

Req ID	Requirement	Verified By
PR-2.1	Jetson shall be able to control the camera to capture an image on request	All tests
PR-2.2	Jetson shall store at least one image	All tests
PR-2.3	Image shall be in focus	All tests
PR-4.1	Shall perform controlled laboratory tests to verify basic image capture	All tests
SR-4.1.1	Architecture shall define a laboratory test configuration that tests all the subsystems	Test setup
SR-4.3.1	Test setup shall provide a means to record and store images	All tests
SS-4.1.1.1	Shall include the hardware required to operate the imaging subsystem	All tests
SS-4.1.1.2	Shall provide a fixed test target	Indoor target setup
SS-4.1.1.3	Shall allow adjustment of camera settings during tests	All tests
SS-4.3.1.1	Shall save captured images with identifiable filenames	All tests
SS-4.3.1.2	Shall document test configuration for each test run	Data sheet

A.3 Equipment and Materials

A.3.1 Hardware

- Jetson Orin Nano Developer Kit (8 GB) with microSD card and 19 V power supply.
- ArduCam B0181 IMX219 camera module with 22-pin CSI-2 ribbon cable.
- USB cable (Type-A to host laptop for image retrieval).
- HDMI/DisplayPort cable and monitor (for setup and live preview).
- Keyboard and mouse (for Jetson interaction during setup).
- Laptop (host computer for image retrieval and backup).

A.3.2 Test Fixtures and Targets

- Camera mini stand (included with the ArduCam module).
- Second monitor or screen to display the crescent moon image as the test target.
- Crescent moon image file (still or short video) shown full-screen on the monitor.
- Laptop or computer to drive the second monitor and display the moon image.
- Dark room with no ambient light (AE department conference room or equivalent).

A.3.3 Software

- JetPack OS (pre-installed on Jetson microSD).
- Image and video capture: `nvgstcapture-1.0` (built into the Jetson).
- File transfer: standard USB mount or `scp` from the Jetson to the host laptop.
- Software pipeline (run after capture): frame extraction $\rightarrow$ crescent detection $\rightarrow$ ROI cropping $\rightarrow$ noise removal $\rightarrow$ low-light enhancement (if needed).

A.4 Test Plan

Testing is organized into two phases. Phase 1 is the indoor capture test in the dark room. Phase 2 is data analysis. Each phase must be completed before the next.

A.4.1 Phase 1 — Indoor Laboratory Test

Objective.
Verify that the imaging subsystem can capture, store, and retrieve a clear image of an artificial crescent target in a dark room. This validates basic hardware functionality and provides real test footage for the software pipeline to process.

Location.
AE department conference room (lights off, pitch black) or equivalent dark lab space.

Target.
Crescent moon image displayed full-screen on a second monitor positioned in front of the camera. The monitor brightness can be adjusted to simulate different lighting conditions.

Hold constant.
Hardware configuration (Jetson + IMX219 + CSI-2), distance from camera to monitor, room darkness, monitor brightness, exposure setting, focus mode.

Capture method.
Point the camera at the monitor and record a short video using the default camera settings. The capture only needs to be long enough for the software pipeline to extract multiple frames containing the crescent; a few seconds is sufficient. No exposure, focus, or brightness adjustments are made during the run. The five moon phase images are advanced in sequence during one continuous capture, giving the pipeline frames for each phase.

What to look for.
Target is visible and identifiable as a crescent shape. Image is not completely dark or completely blown out. File is saved on the microSD and can be retrieved over USB.

A.4.2 Phase 2 — Data Analysis

Objective. Review the captured videos and the best extracted frames from the software pipeline. Evaluate frame quality against the pass/fail criteria in Section A.7. Document findings for the final report. This phase is desk work only; no additional hardware testing is required.

A.5 Test Matrix

The following matrix defines each planned test run. Additional runs can be added based on results. All tests are conducted in the dark room.

Table A.2 – Indoor laboratory test matrix.

Test #	Date	Setting	Notes
1	04/15/2026	Crescent moon image full-screen on monitor, default settings	First run

Note: The five moon phase images are shown in sequence during a single continuous capture, giving the software pipeline frames for each phase to extract and run crescent detection on.

A.6 Procedure Per Test Run

A.6.1 Setup

- Record ambient conditions: time of day and lighting conditions.
- Verify hardware connections: IMX219 camera seated in CSI-2 connector, microSD card inserted, 19 V power supply connected.
- Set up the second monitor in front of the camera and display the crescent moon image full-screen.
- Place the camera on its mini stand and point it at the monitor screen.
- Confirm the crescent image is centered in the camera frame using the live preview on the Jetson's monitor.
- Turn off the room lights and confirm the room is fully dark.

A.6.2 Video Capture

- Power on the Jetson Orin Nano. Wait for full boot (about 30–60 seconds).
- Verify the camera is detected by the system (check `/dev/video0` or run the detection command).
- Trigger video capture using `nvgstcapture-1.0`. Record a short clip (a few seconds) using default camera settings. The clip only needs to be long enough for the pipeline to extract multiple frames containing the crescent.
- The video runs at approximately 40 fps. The software pipeline extracts every third frame ($\sim$40 frames per 3 seconds), runs crescent detection on each frame, and selects the best frame for analysis.
- Verify the video file was saved to the microSD. Check that the file size is non-zero and that the clip contains enough frames for the software pipeline.
- Repeat for each test run. No camera or monitor settings are changed between runs.

A.6.3 File Naming Convention

All captured video files shall follow this naming format:

`SS_T[test#]_LAB_MOON_[YYYYMMDD]_[HHMM].mp4`

Example: `SS_T01_LAB_MOON_20260507_2115.mp4`. This satisfies requirement SS-4.3.1.1 (identifiable filenames).

A.6.4 Document and Retrieve

- Fill out the data collection sheet (Section A.8) immediately after each test run.
- Connect the Jetson to the host laptop via USB. Transfer all video files.
- Back up files to a second location (Google Drive, external drive).
- Hand off all video files to the software team for processing. The pipeline extracts frames and selects the best crescent moon frame from each video.
- Power down the Jetson cleanly.

A.7 Pass / Fail Criteria

Each test run is evaluated against the following criteria:

Table A.3 – Pass/fail criteria for the indoor laboratory test.

Criterion	Pass	Fail
Video capture	Camera captures and saves a non-zero video file with sufficient duration for the pipeline	No file created, or file is corrupt / zero bytes
Video storage	File is retrievable from microSD via USB after the test	File cannot be found or transferred
Frame extraction	Frames can be pulled from the video by the software pipeline	Video is corrupted or frames cannot be extracted
Best frame visibility	At least one extracted frame shows the crescent target recognizable to a human observer	No frame is clear enough; image is fully dark, blown out, or target not identifiable
Focus	Crescent edges are sharp in the best extracted frame	All extracted frames are blurry; shape cannot be determined
System stability	Jetson runs without crashes during the full test	System freezes, reboots, or loses camera connection

Overall test success. The imaging subsystem passes if it captures and stores at least one video where the software pipeline can extract a recognizable crescent frame. This satisfies the minimum success criteria defined for the imaging subsystem.

A.8 Data Collection Sheet

Complete the data sheet for the single test run.

Table A.4 – Indoor laboratory test data collection sheet.

Field	Test 1
Test ID	1
Date / Time	04/15/2026, 6:09 PM
Location	ENGR 125
Target description	Crescent moon image displayed full-screen on second monitor
Camera-to-monitor distance	20 in (0.508 m)
Video duration	4 s
Video filename	`video4.mp4`
Video file size	858.8 kB
Video resolution	1280×720
Best extracted frame filename	—
Room fully dark? (Y/N)	Y
Image quality (subjective)	Moderate reduction in image quality compared to original; crescent still visible, could use more pixels
Crescent recognizable in best frame? (Y/N)	Y
System errors / notes	Hardware resolution limitations hindered crescent detection in the first quarter
Pass / Fail	Pass

A.9 Analysis Method

A.9.1 Visual Inspection

For each test run, the best extracted frame from the software pipeline is evaluated by visual inspection for the following:

- Is the crescent target recognizable to a human observer?
- Is the frame in focus? Are the edges of the crescent sharp or blurry?
- Is the exposure appropriate (not fully dark, not fully white/blown out)?
- Is the frame resolution at least 1280×720 (720p) as required by the mission performance requirements?

A.9.2 Software Pipeline

Every test run produces a video file. Each video is processed by the software pipeline. The pipeline extracts frames (every third frame from a 40 fps video, giving roughly 40 frames per 3 seconds), runs a crescent detection algorithm on each frame, and sorts each frame into one of three folders: crescent, non-crescent, or unknown.

From the frames flagged as crescent, the pipeline selects the best frame based on focus, exposure, and confidence score from the detection algorithm. The best frame is then cropped to the region of interest, processed for noise removal, and (if needed) enhanced with a low-light algorithm.

For the indoor test, the goal is to confirm that the captured video produces a usable best frame. This is not a test of the algorithm itself, but a check that the imaging hardware delivers video the pipeline can work with.

A.9.3 Test Results

During testing, five moon phase images, labeled Moon 1 through Moon 5, were displayed sequentially on the test monitor while the camera recorded a single continuous video. The software pipeline processed the video and identified the best crescent frame for each phase. Figure A.1 shows the five moon phase images used as test inputs. Figure A.2 shows the lab detection results for each phase. Table A.5 maps each Moon ID to its extracted video frame number for traceability.

The pipeline converts each frame to grayscale before running edge detection, producing the gray appearance in the left column. The detection algorithm successfully identified the crescent shape in all five moon phases. In each output frame, the green outline traces the lit edge of the moon, the yellow circle represents the inferred full-moon size based on the visible crescent, and the red box marks the region of interest used by the algorithm. Detection performance was strongest on Moon 1, Moon 2, and Moon 3, where the lit edge was bright and well-defined. For Moon 4 and Moon 5, the phases had lower illumination, but the algorithm still picked up enough of the lit edge to produce a recognizable detection. The position of the red region of interest shifts from one frame to the next depending on which side of the moon is illuminated, showing that the pipeline tracks the orientation of each crescent rather than assuming a fixed position. Overall, these results confirm that the imaging payload can capture and recognize crescent shapes across a range of moon phases under controlled indoor laboratory conditions.



Figure A.1 – Five moon phase images displayed on the test monitor during indoor laboratory testing, labeled Moon 1 through Moon 5.

Table A.5 – Phase traceability: mapping of Moon ID to extracted video frame number from the lab test.

Moon ID	Lab Frame
Moon 1	00057
Moon 2	00069
Moon 3	00081
Moon 4	00138
Moon 5	00162

A.9.4 Reporting

Results from all test runs are documented in the data collection sheet (Table A.4) and summarized in the final project report. The best frame from any of the runs is included as a figure in the report.

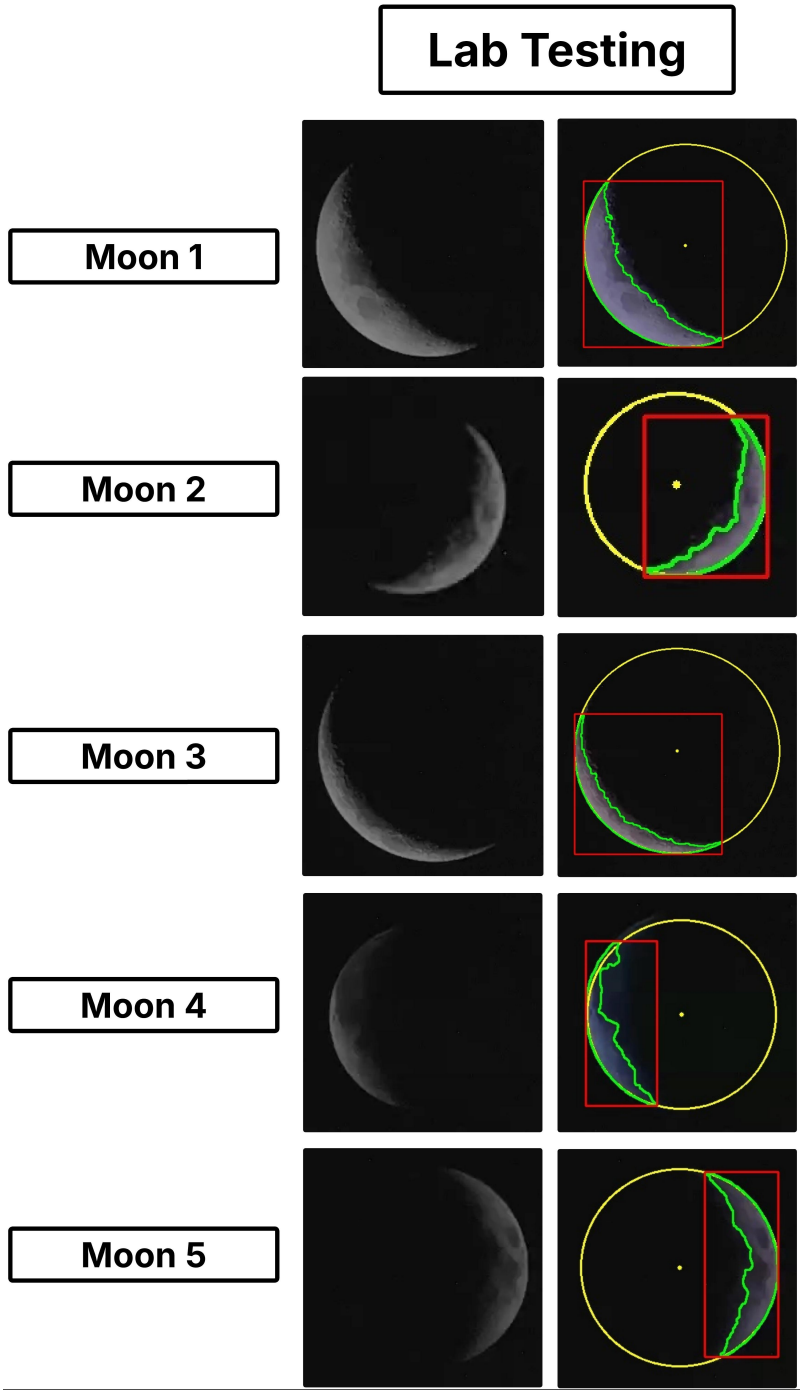


Figure A.2 – Lab detection results for Moon 1 through Moon 5. Left column: grayscale camera frame. Right column: algorithm output (green = detected lit edge, yellow = inferred full-moon, red = ROI).

A.10 Roles and Responsibilities

Table A.6 – Roles and responsibilities for the indoor laboratory test.

Person	Role	Responsibilities
Jose (Jaime)	Systems / Hardware Lead	Test plan author, hardware setup, test execution, image retrieval, data collection, final report
Gloria	Software Lead	Capture command (`nvgstcapture-1.0`), frame extraction, crescent detection algorithm, software troubleshooting
Ali	Adviser	Review test plan, review results, provide guidance on scope and schedule
Team members	Support	Assist with setup, target placement, and operating the camera during testing

A.11 Future Work and Notes

Vacuum chamber testing (next step).
Vacuum chamber testing is the immediate next step for the imaging subsystem. A separate test plan (Appendix B) covers hardware operation under low-pressure conditions using the Abbess Instruments chamber in the AE lab. That testing addresses the SS-4.2.1.x vacuum chamber requirements (power feedthrough, video capture and storage under vacuum, and comparison of laboratory and vacuum chamber image results).

Crescent detection algorithm.
The detection algorithm and ML model are under active development. The videos from this test plan will be the first real input to the pipeline. Once the ML training data is built up, future teams should run more video sets through the pipeline to keep training the model.

Better camera / lens.
The IMX219 has a fixed focal length and a 62.2° horizontal field of view. Future iterations should evaluate the SkyFox Labs piCAM or pair the current camera with a telephoto lens or telescope adapter for improved imaging performance.

Power measurement.
Measuring actual power draw during image capture and video recording is identified as future work. This would refine the power budget values currently based on manufacturer specifications.

Thermal analysis.
Heat generated by the Jetson Orin Nano during image capture should be measured and used to benchmark thermal performance of the board. This can serve as a baseline for future thermal vacuum testing.

Appendix B
VACUUM CHAMBER TEST PLAN AND RESULTS

Document ID: TP-SPARTAN-002-VACUUM
Project: SpartanSat — CubeSat Imaging System for Lunar Navigation
Author: Jose Jaime Esquivel Patricio
Adviser: Prof. Ali Guarneros-Luna
Software Lead: Gloria (Software / Algorithm)
Date: April 28, 2026

B.1 Purpose

This vacuum chamber test plan is the second of two planned test campaigns for the SpartanSat imaging subsystem. It follows the indoor test plan (Appendix A) and validates that the imaging payload can operate under low-pressure conditions representative of the space environment.

This test plan supports Project Objective 4 (PO-4): Validate the ground test unit imaging subsystem hardware through laboratory and vacuum chamber testing.

The primary objectives of this test plan are:

- Verify that the imaging payload can be powered through a vacuum chamber feedthrough using an external 19 V / 3 A DC supply (SS-4.2.1.1).
- Verify that the Jetson Orin Nano can command the IMX219 camera to capture and store video while the chamber is held at low pressure (SS-4.2.1.2, PR-2.1, PR-2.2).
- Capture at least one recognizable image of a crescent moon target displayed above the chamber (PR-2.3).
- Compare laboratory and vacuum chamber results to evaluate how the operating environment affects image quality (SS-4.3.1.3, PR-4.3).

B.2 Applicable Requirements

The following requirements from the SpartanSat system definition are verified by the tests in this plan. Requirements verified by the indoor test plan (Appendix A) are not repeated here.

Table B.1 – Requirements verified by the vacuum chamber test plan.

Req ID	Requirement	Verification
PR-2.1	Jetson shall be able to control the camera to capture an image on request	All tests
PR-2.2	Jetson shall store at least one image	All tests
PR-2.3	Image shall be in focus	All tests
PR-4.2	Shall perform a vacuum chamber test to verify hardware operation	All tests
PR-4.3	Shall compare laboratory and vacuum chamber test results	Analysis (§B.9.3)
SR-4.2.1	Architecture shall define a vacuum chamber test configuration that can operate under low-pressure conditions	Test setup
SR-4.3.1	Test setup shall provide a means to record and store images	All tests
SS-4.2.1.1	Shall include a power feedthrough so the subsystem can receive power inside the vacuum chamber	Test setup
SS-4.2.1.2	Shall capture and store video during the vacuum chamber test, with individual frames extractable for analysis	All tests
SS-4.3.1.3	Shall compare laboratory and vacuum chamber image results	Analysis (§B.9.3)

B.3 Equipment and Materials

B.3.1 Hardware

- NVIDIA Jetson Orin Nano 8 GB Developer Kit.
- Arducam IMX219 camera module (B0181).
- 22-pin CSI-2 ribbon cable (camera to Jetson).
- DC barrel jack adapter cable (matching the Jetson Orin Nano Developer Kit input) — used inside the chamber to convert feedthrough wires to the Jetson power connector.
- Bench DC power supply, set to 19 V with a 3 A current limit.
- Abbess Instruments vacuum chamber (existing AE lab chamber).
- Vacuum chamber electrical feedthrough (two conductors: ground and positive).
- Mounting stand inside the chamber to position the Jetson and camera with the lens pointed upward.
- iPad (used as the test target, placed on top of the chamber lid displaying moon images).

B.3.2 Environment Control

- Two 100%-rated blackout curtains placed over the chamber to block ambient light through the transparent walls.
- AE lab vacuum chamber area, with room lights off during capture.

B.3.3 Software

- `nvgstcapture-1.0` for video capture on the Jetson.
- Software pipeline (run after capture): frame extraction $\rightarrow$ crescent detection $\rightarrow$ ROI cropping $\rightarrow$ noise removal $\rightarrow$ low-light enhancement (if needed).
- Slideshow application on the iPad to display the 5 moon phase images sequentially.

B.4 Test Plan

Testing is organized into two phases. Phase 1 is the vacuum chamber capture run. Phase 2 is data analysis, including the indoor-versus-vacuum comparison. Each phase must be completed before the next.

B.4.1 Phase 1 — Vacuum Chamber Capture

Objective.
Verify that the imaging subsystem can capture, store, and retrieve a clear image of a crescent target displayed above the vacuum chamber while the chamber is held at low pressure. This validates hardware operation under vacuum and provides real test footage for the software pipeline to process.

Location.
AE lab vacuum chamber area, with blackout curtains placed over the transparent chamber walls to eliminate ambient light.

Test target.
An iPad is placed on top of the vacuum chamber lid, screen facing down, approximately 0.5 m above the camera, displaying the same five moon phase images used in the indoor test plan

(Appendix A). The images are advanced sequentially as a slideshow during the capture window.

Capture method.
The Jetson Orin Nano is placed at the center of the chamber on a mounting stand with the IMX219 camera pointed upward toward the iPad. Power is supplied externally by a bench DC supply (19 V, 3 A limit) connected through the chamber feedthrough to a barrel-jack adapter cable inside, which plugs into the Jetson. The Jetson is controlled remotely from a laptop over SSH (configured before the run while the chamber was open) so capture commands can be sent without opening the chamber. The chamber is pumped down to the target pressure, held for the capture window ($\sim$1 min), and then vented. Capture runs while the chamber is held at low pressure.

B.4.2 Phase 2 — Data Analysis and Indoor-vs-Vacuum Comparison

Objective. Review the captured videos and the best extracted frames from the software pipeline. Evaluate frame quality against the pass/fail criteria in Section B.7. Compare the best vacuum-chamber frames against the best indoor frames from Appendix A (see Section B.9.3). Document findings for the final report.

B.5 Test Matrix

The test uses the DC supply setting, chamber pressure target, and the five-image moon slideshow on the iPad described in the equipment and procedure sections.

Table B.2 – Vacuum chamber test matrix.

Test #	Date	Setting	Notes
1	05/01/2026	Slideshow of 5 moon images, vacuum hold	First vacuum run

B.6 Procedure Per Test Run

B.6.1 Setup

- Confirm the vacuum chamber is at ambient pressure and the chamber lid is open.
- Place the Jetson Orin Nano on the mounting stand at the center of the chamber, with the IMX219 camera pointed upward toward where the iPad will sit.
- Connect the 22-pin CSI-2 ribbon cable between the IMX219 camera and the Jetson carrier board.
- Route the chamber feedthrough cables: outside the chamber, connect the two feedthrough conductors (ground and positive) to the bench DC power supply. Inside the chamber, connect the matching conductors to the barrel-jack adapter cable.
- Plug the barrel-jack adapter into the Jetson DC input.
- Confirm the bench DC supply is set to 19 V with a 3 A current limit. Do not power on yet.
- Power on the Jetson by enabling the DC supply output. Confirm the Jetson boots and the camera is detected before sealing the chamber.

- Position the iPad on top of the chamber lid, screen facing down toward the camera, displaying the first moon phase image of the slideshow.
- Place the two 100%-rated blackout curtains over the chamber to block ambient light through the transparent walls. Verify there are no light leaks.
- Record ambient conditions: time of day and room lighting state (room lights off, curtains active).
- Close and seal the chamber lid.

B.6.2 Vacuum Pump-Down and Video Capture

- Power on the vacuum chamber pump.
- Power on the chamber pressure reader.
- Press START on the vacuum chamber controls to begin pump-down.
- Wait approximately 10 minutes for the chamber to reach the target pressure. Record the final stable pressure on the chamber reader.
- Once the chamber pressure is stable, begin video capture on the Jetson using `nvgstcapture-1.0`.
- Advance the iPad slideshow through the five moon phase images during the capture window.
- Capture for approximately 1 minute, or until the full slideshow has been shown at least once.
- Stop video capture on the Jetson.
- Press STOP on the chamber controls to begin venting (depressurization).
- Wait for the chamber to return to ambient pressure before opening the lid.

B.6.3 File Identification

Each captured video file is named with the convention:

`SS_T[test#]_VAC_MOON_[YYYYMMDD]_[HHMM].mp4`

For example: `SS_T01_VAC_MOON_20260518_1430.mp4`. This satisfies requirement SS-4.3.1.1.

B.6.4 Document and Retrieve

- After the chamber is vented and the lid is open, remove the Jetson from the chamber.
- Connect the Jetson to the host computer via USB and transfer the captured video files.
- Hand off all video files to the software team for processing. The pipeline extracts frames and selects the best crescent moon frame from each video.
- Document any anomalies observed during the test in the data collection sheet.

B.7 Pass / Fail Criteria

The imaging subsystem passes vacuum chamber testing if all of the following are met:

- Jetson successfully boots through the chamber feedthrough power path and remains operational through the full pump-down $\rightarrow$ hold $\rightarrow$ vent cycle.
- Video files are successfully captured and stored on the Jetson under vacuum.

- Video files can be retrieved from the Jetson after depressurization.
- Frames can be pulled from the video by the software pipeline.
- At least one frame contains a recognizable crescent shape that can be identified by the detection algorithm.

The test fails if any of the following occur:

- Jetson loses power during the vacuum cycle.
- Camera fails to capture video under vacuum.
- Stored video files are corrupted or unreadable after depressurization.
- No frames are extracted or identified as crescent moons by the software pipeline.

Passing this test satisfies the minimum success criteria for vacuum operation and demonstrates closure of requirements SS-4.2.1.1 and SS-4.2.1.2.

B.8 Data Collection Sheet

Complete one column per test run.

Table B.3 – Vacuum chamber test data collection sheet.

Field	Value
Test ID	SS_T01
Date / Time	05/01/2026, 2:30 PM
Location	AE 236 Space System Lab
Target description	Crescent moon image displayed on iPad
Camera-to-iPad distance	0.5 m
Video duration	40 s
Video filename	`video2`
Video file size	50 MB
Video resolution	1280×720
Best extracted frame filename	`SS_T01_BEST_FRAME_0042.jpg` (frame 58 of 1200)
Target pressure	8.1 Torr (1.080 kPa)
Pump-down duration	∼10 min
Blackout curtains active? (Y/N)	Y
Image quality (subjective)	Crescent shape clearly visible in best frame, sharp edges, monitor pixels not visible at this distance
Crescent recognizable in best frame? (Y/N)	Y
System errors / notes	—
Pass / Fail	PASS

B.9 Analysis Method

B.9.1 Visual Inspection

For each test run, the best extracted frame from the software pipeline is evaluated by visual inspection for the following:

- Is the crescent shape clearly identifiable?
- Is the frame in focus?
- Is the exposure appropriate to see the crescent against the dark background?

- Are there any artifacts (compression, noise, glare, condensation, light leaks) introduced by the vacuum environment or the chamber walls?

B.9.2 Software Pipeline

Every test run produces video footage. Each video is processed by the same software pipeline used for indoor testing. The pipeline extracts frames (every third frame from a 40 fps video), runs a crescent detection algorithm on each frame, and sorts each frame into one of three folders: crescent, non-crescent, or unknown.

B.9.3 Test Results

During testing, five moon phase images, labeled Moon 1 through Moon 5, were displayed sequentially on the iPad while the camera recorded continuously inside the vacuum chamber. The software pipeline processed the video and identified the best crescent frame for each phase. Figure B.1 shows the five moon phase images used as test inputs. Figure B.2 shows the vacuum chamber detection results for each phase. Table B.4 maps each Moon ID to its extracted video frame number for traceability.



Figure B.1 – Five moon phase images displayed on the iPad during vacuum chamber testing, labeled Moon 1 through Moon 5.

The pipeline converts each frame to grayscale before running edge detection, producing the gray appearance in the left column. The detection algorithm successfully identified the

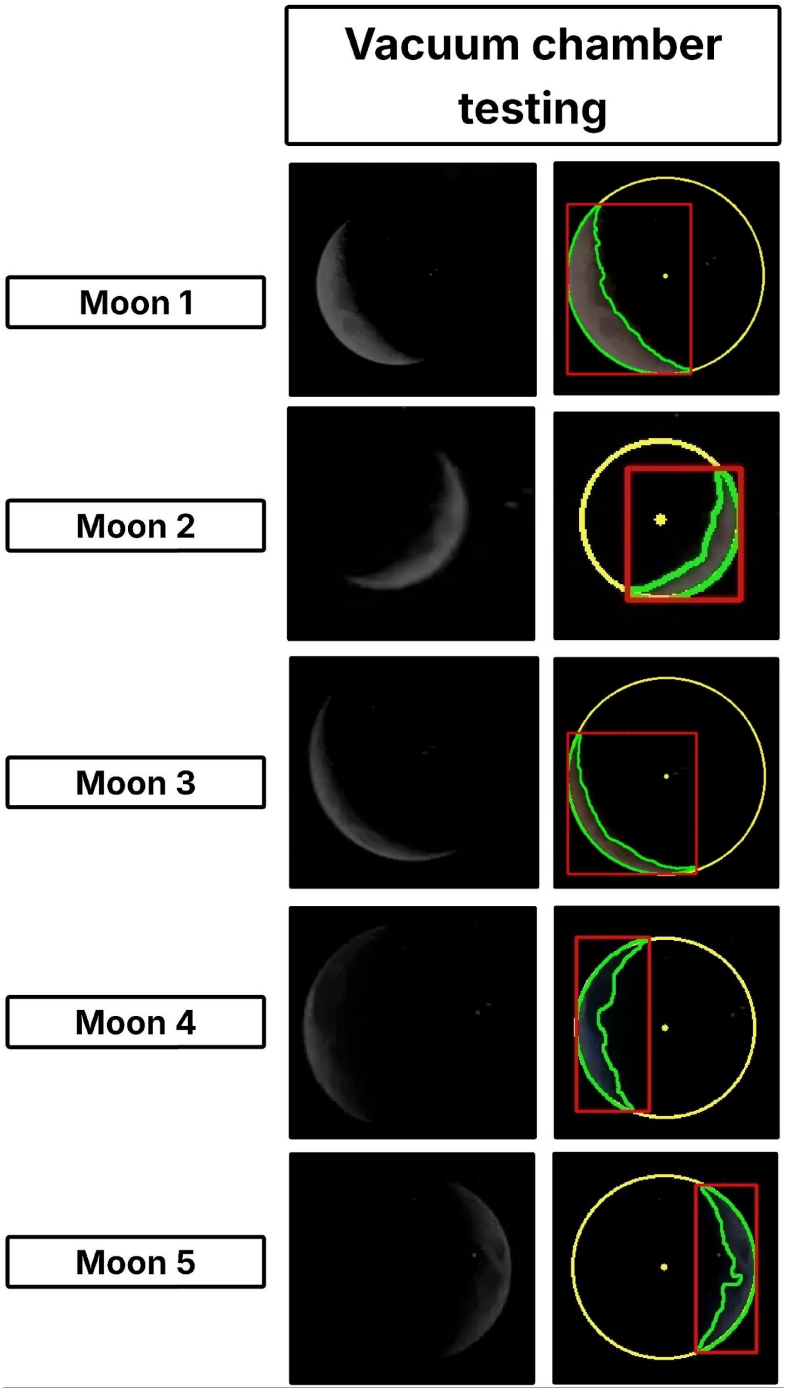


Figure B.2 – Vacuum chamber detection results for Moon 1 through Moon 5. Left column: grayscale camera frame. Right column: algorithm output (green = detected lit edge, yellow = inferred full-moon, red = ROI).

crescent shape in all five moon phases under vacuum. In each output frame, the green outline traces the lit edge of the moon, the yellow circle represents the inferred full-moon size based on the visible crescent, and the red box marks the region of interest used by the algorithm. Detection performance was strongest on Moon 1, Moon 2, and Moon 3, where the lit edge was bright and well-defined. For Moon 4 and Moon 5, the phases had lower illumination, but the algorithm still picked up enough of the lit edge to produce a recognizable detection. These results confirm that the imaging hardware operated correctly under vacuum at a chamber pressure of 1.080 kPa (8.1 Torr) and that the detection pipeline produces consistent results when processing video captured under vacuum conditions.

Table B.4 – Phase traceability: mapping of Moon ID to extracted video frame number from the vacuum chamber test.

Moon ID	Vacuum Frame
Moon 1	00267
Moon 2	00288
Moon 3	00309
Moon 4	00381
Moon 5	00414

B.9.4 Test Setup Photos

Photos of the test setup are included for traceability and to document how the chamber feedthrough power path and camera mounting were configured.

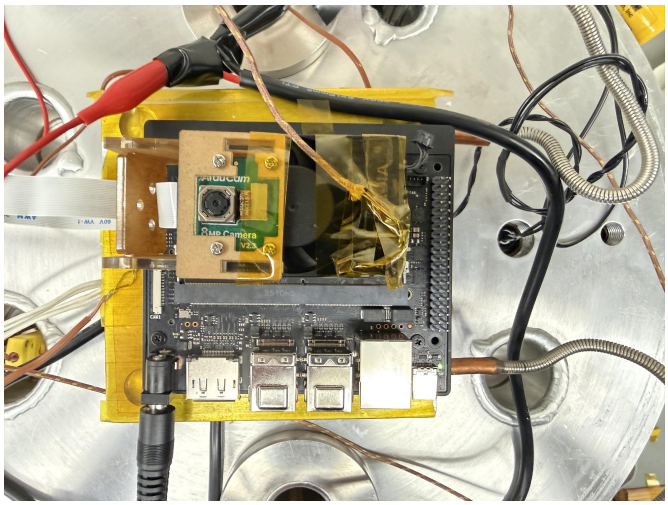


Figure B.3 – Imaging payload mounted inside the vacuum chamber.

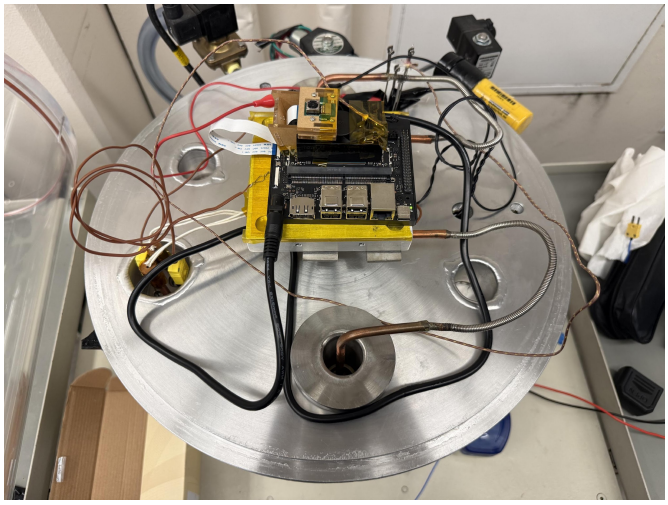


Figure B.4 – Power feedthrough configuration (19 V, 3 A limit, external bench DC supply).



Figure B.5 – Chamber with blackout curtains and iPad target in place.

B.10 Roles and Responsibilities

Table B.5 – Roles and responsibilities for the vacuum chamber test.

Name	Role	Responsibilities
Jose (Jaime)	Project Lead	Test plan author, hardware setup, vacuum chamber operation, video capture, results documentation
Gloria	Software Lead	Capture command (`nvgstcapture-1.0`), frame extraction, crescent detection algorithm, software troubleshooting
Ali	Adviser	Review test plan, review results, provide guidance on scope and schedule

B.11 Future Work and Notes

Thermal-vacuum testing.
This test plan validates operation under vacuum at ambient temperature. Adding controlled temperature cycling (thermal-vacuum testing) would extend the validation to a closer approximation of the space environment. This is identified as future work.

Pressure logging.
Future runs should record a time-stamped pressure trace (start of pump-down, time to reach target pressure, hold pressure, vent start, vent end) rather than the single steady-state reading captured here.

Multiple pressure set points.
This plan tests at a single target pressure. A follow-on campaign could repeat the capture at several pressure set points to characterize how image quality varies with chamber pressure.

Endurance testing.
The current capture window is approximately 1 minute. A longer-duration capture would help characterize the Jetson's behavior under sustained vacuum conditions.