University of Colorado Boulder
Department of Aerospace Engineering Sciences

NanoSAM II - Conceptual Design Document

ASEN 4013 - Senior Design

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I. General Information

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Contents

Nomenclature

ADC	=	Analog to Digital Converter
CTE	=	Coefficient of Thermal Expansion
FOV	=	Field of View
ICD	=	Interface Control Document
LEO	=	Low-Earth Orbit
MTF	=	Modular Transfer Function
NanoSAM	=	Nano-Stratospheric Aerosol Measurement
NASA	=	National Aeronautics and Space Administration
NS1	=	NanoSAM I
SNR	=	Signal to Noise Ratio
SAGE	=	Stratospheric Aerosol and Gas Experiment
SAM	=	Stratospheric Aerosol Measurement
R_λ	=	Responsivity at given wavelength
λ	=	Wavelength
I_p	=	Photodiode Current
V	=	Voltage
P	=	Power

II. Project Description

The goal of the Nano-Stratospheric Aerosol Measurement (NanoSAM) mission is to produce a compact method of measuring aerosol concentration in the stratosphere. These measurements can have impacts on both daily life and long term scientific research. On a daily basis, aerosol concentration affects visibility in the atmosphere, an important aspect to consider for crewed aircraft. High aerosol concentration is also an indication of poor air quality that could affect human health. According to an article by NASA Langley, atmospheric aerosol concentration affects the radiative balance of the Earth by changing how sunlight reflects off of clouds in the atmosphere, which has implications on Earth's climate and environmental change [1]. This same article states that "current observations of the buildup [of aerosols in the atmosphere] are available only for a few locations around the globe and these observations are fragmentary" [1]. Therefore, NanoSAM aims to fill the need of increasing the availability of these measurements by providing a low-cost, low-mass instrument that can be deployed into Low-Earth Orbit (LEO) a constellation.

NanoSAM seeks to use solar occultation to measure the aerosol concentrations, similar to Stratospheric Aerosol Measurement II (SAM-II) experiment from 1978. Solar occultation is "a technique in which the transmission of sunlight through the Earth's atmosphere is measured and ratioed to solar measurements recorded with no atmospheric attenuation" [2]. By designing the NanoSAM CubeSat that can meet or exceed the optical specifications of SAM-II, which already produced scientifically valuable data, then it can be assumed that the NanoSAM CubeSat will also produce scientifically valuable data. This saves the need to perform exhaustive research into the rationale behind the optics performance metrics, something the customer wishes to avoid. The NanoSAM instrument is designed to have a mass of approximately 1.33 kg, which is the the standard mass of a 1U CubeSat according to the NASA CubeSat 101 guide [3]. This is only around 2% of the 76 kg mass of the Stratospheric Aerosols and Gases Experiment III (SAGE-III) system [4] (the latest evolution of the initial SAM system). Packaging this aerosol measurement sensor in such a small enclosure greatly reduces launch costs associated with the instrument, allowing NanoSAM to potentially ride along with existing LEO missions. Deploying NanoSAM instruments as a constellation would lead to a much higher measurement frequency than SAM-II, which is what makes this project of interest to the customer, the Ball Aerospace Corporation.

As the second step down a multi-year design trajectory with the ultimate goal of spaceflight readiness, the NanoSAM II team is designing a 0.5U payload for gathering stratospheric aerosol data. This will require new design work in the areas of structures, electronics, and software, along with iterative improvements to the optical system designed for NanoSAM I in the 2019 academic year. The NanoSAM II payload enclosure will be designed with a volume of 0.5U to maximize compatibility with existing missions, supporting the overall goal of compatibility with a future bus. This bus may be built by a future team, or may be a bus that already exists that a future team integrates the NanoSAM instrument into. The payload enclosure will be designed to withstand the environmental stresses associated with spaceflight, such as temperature, vacuum, and vibration. This will involve significant new design over NanoSAM I, which only had a basic ground-test structure with a 1.5U size requirement and no environmental requirements. The smaller payload volume compared to last year will necessitate an electronics board redesign to fit both the optics bench and electronics board in the 0.5U enclosure. The optics team will undertake a mix of new design and iterative design, as they will design new alignment tooling to support the existing optics system from the NanoSAM I project. The refined optical system will detect wavelengths of light allowing for aerosol measurement while operating in conditions experienced in low-earth orbit (LEO). Flight software will be designed that will handle the logic and timing necessary to gather and store this solar occultation data.

A. Previous Work

The technology to measure aerosol concentration in the stratosphere while in orbit started with the mission SAM-II, which used vertical scanning. Technology from SAM-II was furthered in the development of the Stratospheric Aerosols and Gases Experiment (SAGE) project on Explorer 60 which used a spectrometer to filter for four different wavelengths in order to measure aerosols, ozone, water, and nitrogen dioxide concentrations in the atmosphere [5]. SAGE-I capabilities were improved upon with the SAGE-II project, which used a spectrometer to measure aerosol concentration across seven different wavelengths. This system was able to determine the cause of the depletion of the ozone layer [1] and led to the banning of CFCs (chlorofluorocarbons) allowing the Antarctic ozone to recover. Finally, the current iteration, SAGE-III was developed and is currently being used on the International Space Station. SAGE-III uses the solar occultation method to measure 5 narrow bands of light, three of which employ hyperspectral imaging techniques, and a discrete shortwave infrared (SWIR) measurement [5]. Although a successful project, the SAGE-III instrument is large, expensive, and has a small measurement temporal density, collecting only 30 aerosol measurements per day [6].

In contrast, the purpose of the NanoSAM project is to design and build a small, low cost scientific payload with similar capabilities to SAM-II. The SAM-II instrument measured aerosol concentrations aboard Nimbus-7, which had an altitude of 950 km with an orbital period of 104 minutes [7]. The orbit of Nimbus-7 and SAM-II observed 14 sunrises and 14 sunsets every 24 hours, a total of 28 windows per day when SAM-II took measurements using the solar occultation method with a 15 arcminute/s sweep rate [8]. SAM-II collected light intensity data with a bandwidth of 0.038 µm at a sample rate of 50 Hz [8]. Reducing the size and cost of NanoSAM will allow the sensors to be deployed in a constellation of CubeSats thus increasing the quality and quantity of data collected.

The most recent work on the NanoSAM mission was done by the University of Colorado NanoSAM I senior project team in 2019 and 2020. While the NanoSAM mission is designed to carry out similar kinds of measurements as the instruments mentioned above, it does so with a much simpler optics implementation. By using an OAP mirror, the NanoSAM I team designed a low-cost, low-mass system to measure aerosol concentration in the stratosphere. However, this team stopped short of designing a flight-ready system. Additionally, progress was interrupted by the 2020 pandemic before much of their planned testing could be performed [6]. Among the main subsystems in the project (electronics, hardware, software, and optics), the previous team focused most of their effort on optics design. This means the requirements for this previous project dealt heavily with functionality of the optical system. These requirements included successful solar irradiance data collection, clearing a specific signal to noise ratio threshold, and collecting accurate data with a particular vertical resolution. The NanoSAM I team succeeded in creating and manufacturing optics designs to accomplish the NanoSAM mission. Their accomplishments include designing and constructing a payload optics system to measure solar irradiance in a narrow spectral band (about 1.03 µm) [6] as well as developing an electronics system to collect and output this irradiance data. Some previous project elements do require improvements as mentioned in the 2019-2020 project final report. These systems include modifying the electronics board to be compatible with the chosen analog to digital converter as well as improving the optical system's pinhole alignment. In conjunction with the required new design, testing will be carried out to ensure that the most possible information is gathered about the NanoSAM I system performance. The lessons learned from the previous system can then be used to inform future design choices.

B. Specific Objectives

Specific objectives of the project are the tasks and specifications that the NanoSAM II project seeks to meet for a successful mission. These objectives are broken into three levels of success to support the NanoSAM II project requirements. While the project is incorporating lessons learned and some legacy hardware provided by the NanoSAM I team, this year's specific objectives have their own unique set of design challenges that set them apart from simply iterating on the goals of NanoSAM I. Testing will be carried out on the existing hardware to learn all possible lessons from last year's progress, and the known issues from the NanoSAM I Project Final Report will be kept in mind. However, NanoSAM II places an increased emphasis on the design required for successful optics performance in the spaceflight environment.

All level one objectives represent new capabilities beyond what was accomplished by NanoSAM I in the 2019-2020 academic year. Achieving the Level 1 objectives will allow NanoSAM II to carry out a solar tracking test with the optics and electronics in a 0.5U enclosure, three times smaller than the test structure designed for last year. Level 2 objectives are those that lead to an improved ground performance, coming from iterations in optics and electronics design along with implementing existing industry standards for CubeSat payload housings. Lastly, level 3 objectives relate to testing to verify that the payload is flight capable and meets the objectives set forth by the customer. Level 3 will require the team to prepare the enclosure such that it can be successfully mated with a typical industry bus and also passes environmental testing. Due to the current social and economic environment, it is unknown if the payload will be able to be flown this year. By designing to industry bus ICD standards, this project aims to minimize future teams' work required to make payload systems compatible with a bus.

These three levels of objectives support the uncertainty in the availability of testing equipment and facilities that this year's team will face. Early testing will be done using the previous team's components while the design team focuses on the new design required to meet Level 1 objectives. This early testing will help inform and improve testing procedures for the upgraded system in order to validate the level 2 objectives. Level 3 environmental tests will then be carried out in the case that COVID-19 restrictions can be relaxed in the Spring of 2021, allowing the team to access the facilities necessary to verify the environmental objectives. The values for the thermal and vibrational requirements were referenced from the QB50 System Requirements guidelines for CubeSats [12].

	Level 1 (Solar Tracking Test)	**Level 2** (Improved Ground Performance)	**Level 3** (Flight Capability Testing)
Payload Housing	The payload housing contains the integrated electronics board and optics bench inside a 0.5U enclosure.	The payload housing structural interface is compatible with an industry standard bus.	The payload housing functions within the operating temperature range of -20°C to 50°C and its lowest vibrational natural frequency is greater than 90Hz [12].
Data Capture	Software and electronics acquires, digitizes, packetizes, and downloads raw data from a photodetector to a computer at a rate of at least 50Hz within the mission-specific measurement schedule detailed in the CONOPS	Error checking measures are implemented in the ground software to detect data corruption occurring during transmission	Data is transferred from the payload to an industry standard CubeSat bus communications system, within ICD specifications. [13]
Electronics & Control	The redesigned electronics board successfully controls and powers all on-board operations and has a footprint compatible with the 0.5U payload enclosure.	The redesigned electronics board supports all optical design improvements.	The redesigned electronics board remains within the operating temperature range of -20°C to 50°C and its lowest vibrational natural frequency is greater than 90Hz [12].

Table 1 Specific Objectives

C. CONOPS

NanoSAM is a multi-year project ultimately pursuing the goal of putting a CubeSat into orbit to profile aerosols in the atmosphere using the solar occultation methodology. This overarching concept of operations diagram is shown in Figure 1. This figure is adapted from the NanoSAM I CONOPS, because the design choices made this year are pursuing the same ultimate goal of deploying CubeSats into orbit for which the groundwork was laid in the NanoSAM I project. By choosing a circular orbit at an altitude of 500km, the payload will pass through 30.5 measurement windows every 24 hours. A measurement window is the region in the orbit where the instrument is seeing sunlight that has passed through the stratosphere (and therefore interacted with stratospheric aerosols). Each of these windows were calculated to last 34.4 seconds, occurring 5 minutes and 9 seconds after the baseline measurement would have been taken (step 1 in the diagram). The measurement rate of 50Hz ends up requiring 1720 total irradiance values gathered for each stratospheric measurement window with these times. The spacecraft is over parts of the Earth's surface that are not illuminated by the Sun during the time that the payload is gathering data. This means that this instrument would be a strong candidate for integration with another mission that is carrying out remote sensing on illuminated parts of the Earth's surface. This would free up additional power for NanoSAM during the parts of the orbit where it would be active. It would also increase the robustness of the mission proposal for the remote sensing payload, as it would eliminate the window of spacecraft inactivity on the dark side of the planet.

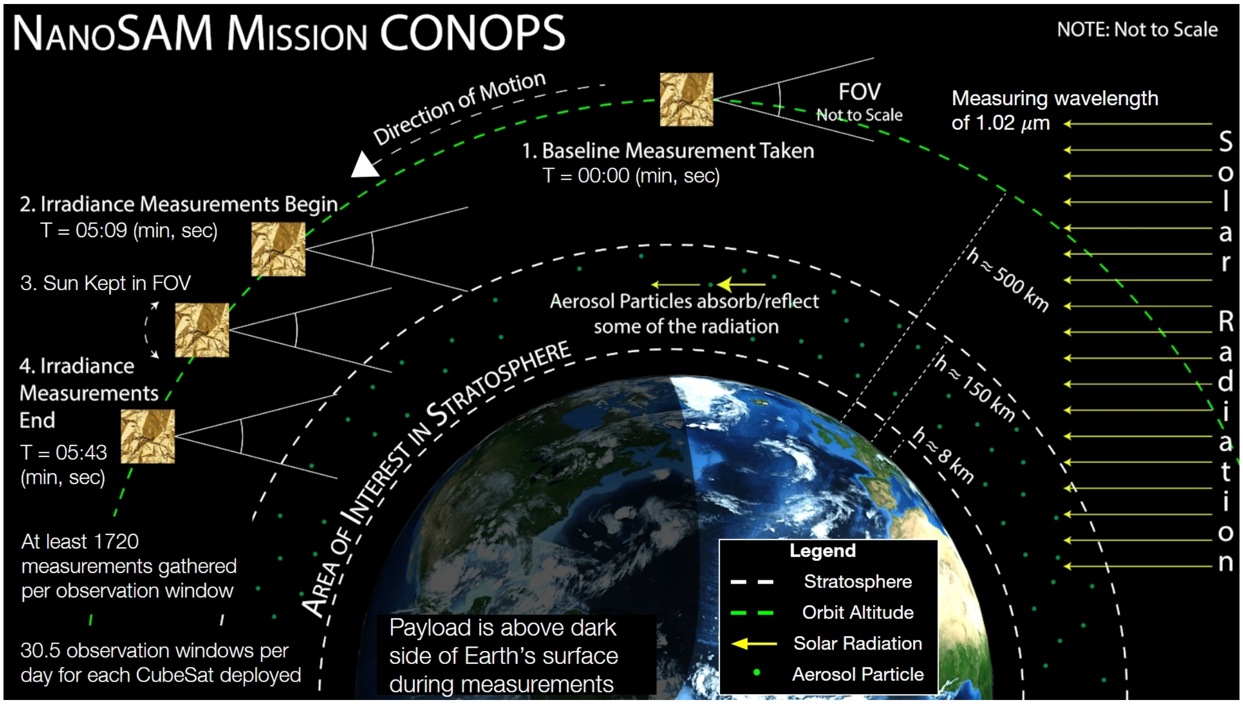

Fig. 1 NanoSAM Orbital Mission CONOPS

D. Organization

To complete this mission, the following role breakdown has been chosen by the team:

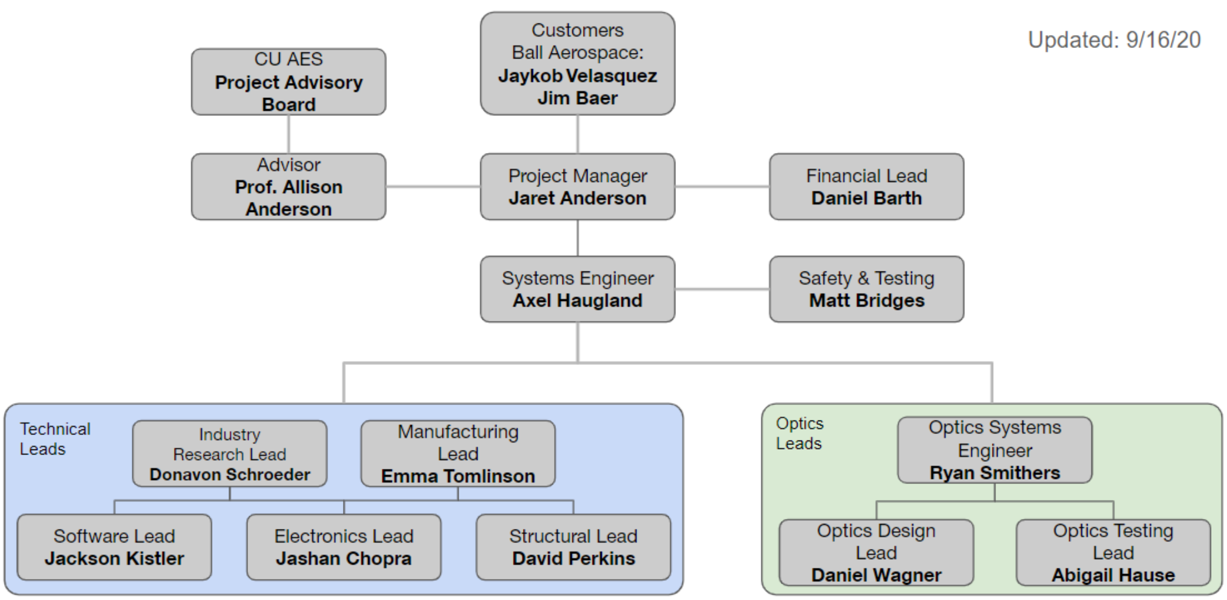

Fig. 2 Team Role Organization Chart

Additionally, the program is organized into multiple years of design. The following figure illustrates what portions of design the team is planning to undertake this year, how that scaffolds on the designs of last year's team, and what work is left for future teams to carry out:

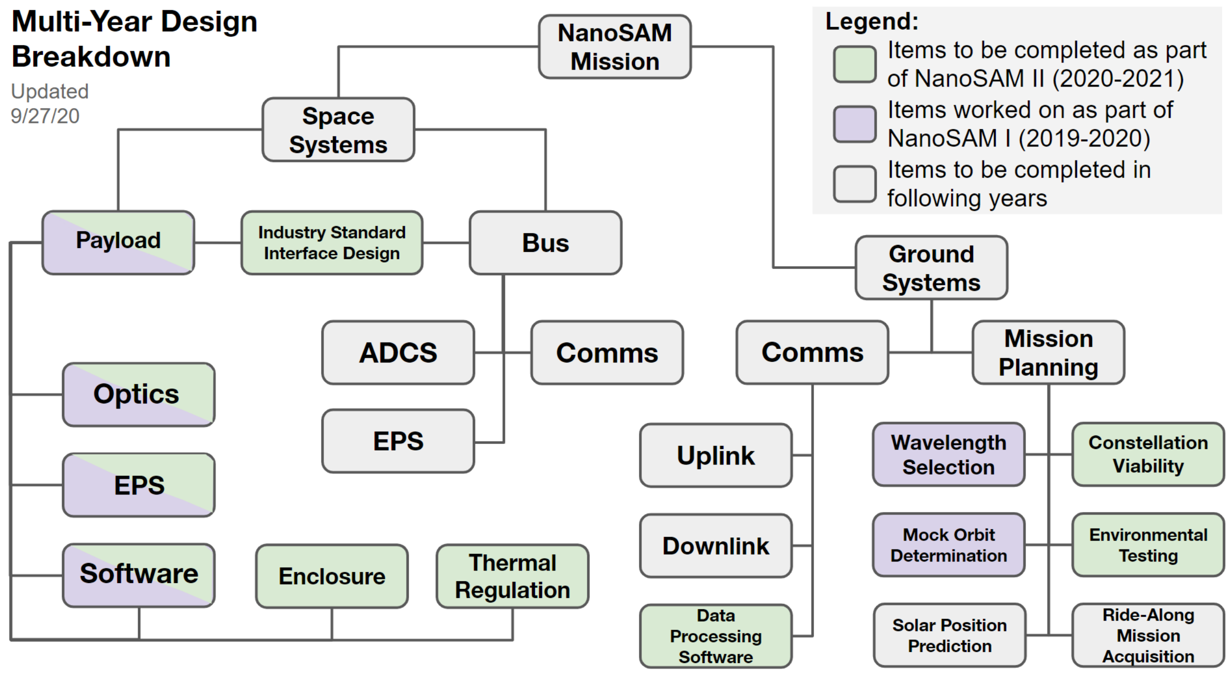

Fig. 3 NanoSAM Multi-Year Design Breakdown

E. Functional Requirements

The following high level functional requirements are derived from the specific objectives laid out in Section II.B. The goal of these functional requirements is to leave no specific objective uncovered.

Number	Name	Requirement Description
1.0	Data Capture	The supporting electronics and software shall digitize, packetize, and store housekeeping data and information collected from the photodiode.
2.0	Communications	The supporting electronics and software shall communicate digitzed data to a ground computer during testing, and to a standard bus ICD system for downlink during on-orbit operations.
3.0	SAM-II Equivalent Optics	NanoSam shall have optical performance capabilities that are equivalent to or surpass that of SAM-II.
4.0	Payload Dimensions	The payload shall have dimensions to allow for integration with an industry standard CubeSat bus in future years
5.0	Flight Testing	All payload components shall maintain their design requirements through space environment testing
6.0	Cost	The project shall limit all spending to a budget of $5,000.

Table 2 High Level Functional Requirements

In order to collect useful measurements from the designed optics system, the electronics and software must work in unison to collect and refine photodiode information, as well as communicate this data in testing and flight operations. Functional requirements 0.1 and 0.2 enforce this need. Functional requirement 0.3 relates to a successful design on the optics system, meeting the SAM-II performance and improving it. The customer wishes to avoid the extremely in-depth analysis required to determine metrics for certifying the data gathered by this mission as scientifically useful, and instead gave the team guidance to just use the optical metrics that the SAM-II mission designed to.

Lastly, functional requirements 0.4 and 0.5 relate to the level three specific objectives of a flight capable payload. For this project, the payload will fit in a 0.5U package, or 10 cm x 10 cm x 5 cm. Keeping the size within the 1.5U package is important not only to meet previous performance, but also to successfully mate with industry standard bus specifications to allow for integration. These functional requirements also lead to the need for flight testing, including thermal range, vacuum testing, and analysis and testing of vibration resonant frequencies. For a successful payload in a CubeSat, the low-earth orbit environment must be accounted for in order to create a robust design.

In the design requirements section below, these requirements are elaborated on further in a hierarchical organization to flesh out their specificity and ensure that the system performance can be verified.

1. Functional Block Diagram

This functional block diagram shows the interactions of various subsystems and components to meet the requirements set forth for the NanoSAM payload. The functional block diagram for this year's NanoSAM mission shares many similarities to the NanoSAM I functional block diagram. The requirements for this year's mission revolve mainly around improving existing designs for the subsystems rather than reworking the ways in which the subsystems fit together. The bus shown in this FBD is not part of the design scope of NanoSAM II, which aims to lay the groundwork for integrating with an existing bus in future years. For the purposes of this year's ground testing, the bus in this FBD will be emulated using a 12V power supply and a laptop, as that ground testing is designed for verifying the instrument performance rather than the performance of an entire CubeSat which contains the NanoSAM payload.

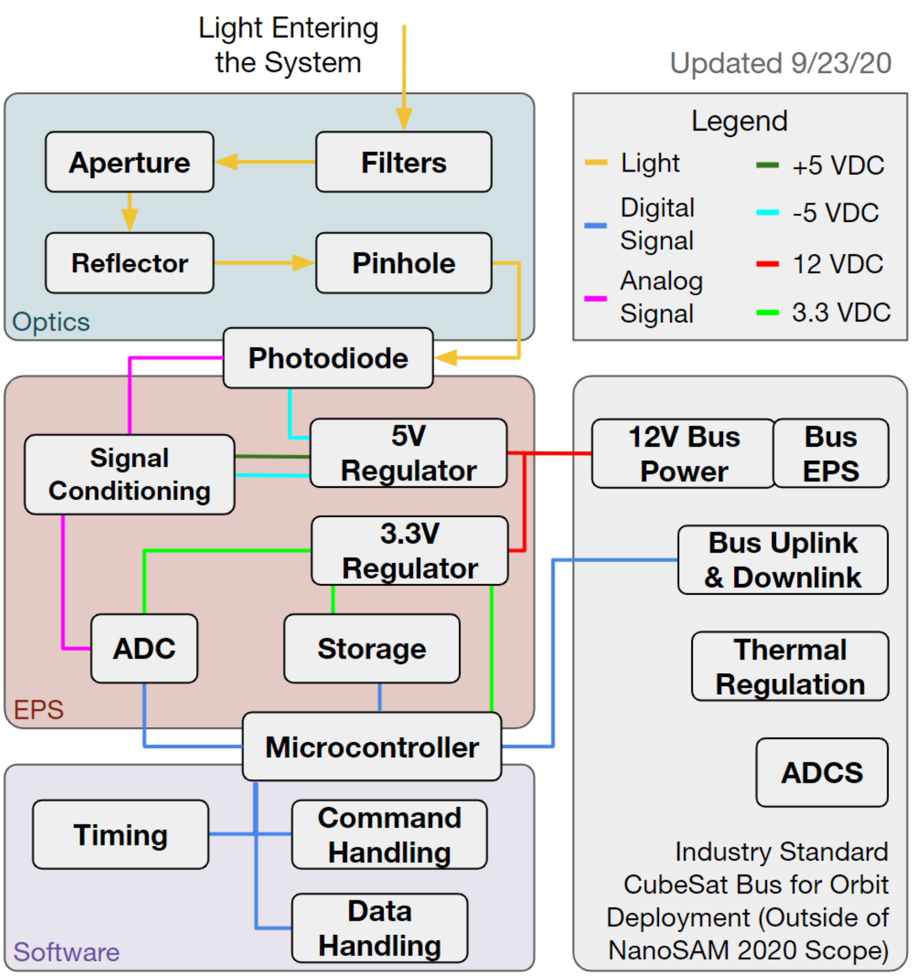

Fig. 4 Functional Block Diagram

III. Design Requirements

NanoSAM II has five major functional requirements (level 0) relating to the system's data capture, communications system, optics capabilities, size, and environmental functions. Tables 3 through 8 show the high level functional requirements and their flow down requirements. Tables 9 through 15 detail their reasoning and path to verification.

L0	L1	L2	L3	Name	Requirement Description
1.0				Data Capture	The supporting electronics and software shall digitize, packetize, and store housekeeping data and information collected from the photodiode.
	1.1			Optics Data	Optical and electronic subsystems shall communicate data through their photodiode connection to collect mission data.
		1.1.1		Sampling Rate	The system shall gather samples at a rate of at least 50 Hz [8] for the duration of the mission.
			1.1.1.1	Processing	The system shall process and store data at a rate higher than the data collection rate of 50 Hz.
		1.1.2		Data Collection Bit Size	Data shall be collected to 10 bit resolution [8].
		1.1.3		Storage Size	The system shall include enough storage space for periods between downlinks.
		1.1.4		Data Collection Timing	Data collection shall start when the optics FOV captures the top layer of the stratosphere and end approximately 34 seconds later at the bottom of the stratosphere.
	1.2			Calibration	System software shall calibrate from sun irradiance measurements prior to collecting data.
		1.2.1		Calibration Timing	Software shall start collecting calibration data when it is tangential to the path of the Earth's orbit .
	1.3			Error Checking	Software shall be able to detect bit errors introduced during data transmission.
	1.4			Housekeeping	Software shall collect and monitor system state data.
		1.4.1		Temperature data	Temperature data shall be collected for the EPS board and optical sensor.
		1.4.2		Power data	Power usage data shall be collected for the EPS board.
		1.4.3		Storage capacity	Storage capacity shall be tracked.
	1.5			Power Consumption	The electronics subsystems shall not draw more than 1 Watt of power, excluding any thermal control[6].

Table 3 Functional Requirements Flow Down: Requirement 1

The data collection timing in requirement 1.1.4 was calculated based on the diagram shown in the CONOPS. Carrying out the geometric calculations of light passing through the stratosphere led to a sweep angle of 21.81° between calibration and the final data capture on the CONOPS. The final 2.181° of this angle corresponds to the section of the orbit where the payload will be in range to gather stratospheric aerosol data. By relating these angles to the orbital period of 5668.144 sec at an altitude of 500km, the times used to label the CONOPS are calculated as 5.72 minutes for the entire mission cycle (calibration to final mesasurement made), with the final 34.4 seconds of this cycle being the window where the payload can observe the light passing through the stratosphere.

L0	L1	L2	Name	Requirement Description
2.0			Communications	The supporting electronics and software shall communicate digitized data to a ground computer during testing, and to a standard bus ICD system for downlink during on-orbit operations. Software shall correct the fault if necessary.
	2.1		SNR	The optical instrument shall have a signal-to-noise ratio of 3500 or greater [6].
	2.2		Fault Mitigation	Warning messages shall be down-linked if software system detects anomalies in housekeeping data.
	2.3		Downlink Data Transfer	Data needs to complete data transfer during downlink period with a maximum transfer rate of 9.6 kbps over a minimum window of 5 minutes [40] [41]

Table 4 Functional Requirements Flow Down: Requirement 2

L0	L1	L2	Name	Requirement Description
3.0			SAM-II Equivalent Optics	NanoSAM II will have optical performance capabilities that are equivalent to or surpass that of SAM-II
	3.1		Wavelength	The optics system shall capture light at a center wavelength of 1.03 μm[14].
	3.2		Vertical Resolution	The optical design shall have a vertical resolution of 1 km [11].
		3.2.1	FOV	The FOV shall be 1.3 arcminutes to achieve a resolution of 1km.
		3.2.2	MTF	The imager shall have a 0.74 MTF in order to meet the resolution and contrast of the SAM-II system [6].
	3.3		Tracking Accuracy	The system shall demonstrate solar tracking accuracy of 1 arc-min/mRad or finer during ground testing [5].

Table 5 Functional Requirements Flow Down: Requirement 3

L0	L1	L2	Name	Requirement Description
4.0			Payload Dimensions	The payload shall have dimensions to allow for integration with an industry standard CubeSat bus in future years
	4.1		Payload Size	The payload shall fit into a 0.5U volume.
	4.2		Payload Mass	The payload shall have a total mass less than or equal to 0.615 kg [3].
	4.3		Payload Interface	The payload enclosure shall have a defined interface for integrating with a CubeSat bus.

Table 6 Functional Requirements Flow Down: Requirement 4

L0	L1	L2	Name	Requirement Description
5.0			Flight Testing	All payload components shall maintain their design requirements through space environment testing.
	5.1		Vibration	The system shall maintain optics performance following exposure to vibration.
		5.1.1	Mirror Alignment	Launch vibration stresses shall not deform the optical alignment such that optical performance measures drop below SAM-II the baseline.
		5.1.2	Natural Frequency	The lowest vibrational natural frequency of the system must be greater than 90 Hz [12].
	5.2		Thermal	The payload shall remain operable over an environmental temperature range of -120 to 120 degrees Celsius [15].
		5.2.1	Thermal Control	Software shall be able to detect when the system exits outside of the lower bound of the acceptable temperature range and activate thermal heating control.
		5.2.2	Payload Temperature	The payload contents shall operate across a temperature range of -20°C to 60°C [12]
	5.3		Vacuum	Electronic and optical components shall remain operable in vacuum conditions.

Table 7 Functional Requirements Flow Down: Requirement 5

L0	L1	L2	Name	Requirement Description
6.0			Cost	The project shall limit all spending to budget of $5,000

Table 8 Functional Requirements Flow Down: Requirement 6

Requirements are useful to the mission because they provide a clear avenue for verifying system capabilities. Tables 9 through 15 detail why the team felt each requirement to be necessary to creating the payload along with how the team plans to verify the requirement. The three possible verification methods are test, analysis, and inspection. A test is a procedure that is carried out under a controlled environment to provide specific output values which characterize some component of system performance. An analysis leverages theoretical models or past data to predict system performances, and is often used in cases where the desired results are not readily gained through a test. An analysis is employed in the case where the desired outcome is simple enough to not warrant an entire test procedure and the verifying team member can determine the verification in a single step, such as measuring the mass of an object.

Requirement	Reasoning	Verification Method	Verification Breakdown
1.0 Data Capture	The successful capture of optical data is crucial to the success of the mission, because aerosol measurement is based off of this information.	Test, Analysis	Run a data collecting test of the system to ensure data is formatted correctly with reasonable results.
1.1 Optics Data	Optical data needs to be transferred to electronics in order for the collected data to be usable.	Test	Run a data collection test and receive data.
1.1.1 Sampling Rate	50 Hz is the sampling rate of SAM-II, which is the performance that NanoSAM II needs to match [8].	Inspection	Data collection test has data points at the correct frequency.
1.1.1.1 Processing	A processing rate higher than the data collection rate will prevent a loss of data.	Analysis	Calculate average processing and collection rates from a data collection test for comparison.
1.1.2 Data Collection Bit Size	Data is needed with 10 bits of resolution in order to be sufficiently accurate [8].	Inspection	Data is observed to be collected at the necessary resolution.
1.1.3 Storage Size	The hardware must have the capacity to store all the data collected between uplinks in order to avoid losing data. The numeric quantity of this data will be decided by trade studies.	Test	Run test with time at least equal to period between each flight uplink. Observe system storage remaining.
1.1.4 Data Collection Timing	Data needs to be collected at specific intervals in order to only capture the atmosphere within the 8-150km range.	Test	Run test such that data collection is triggered and then stopped by software feedback when the optics loses view of the range.
1.2 Calibration	Sun irradiance will create a bias in measurments. Calibrating to this irradiance means the bias can be removied.	Test	Test that the data has the baseline bias removed.
1.2.1 Calibration Timing	Calibration must occur during sunrise and during sunset to confirm the sun bias is specific to the measurements being taken. This timing has the sun in view without atmospheric interference.	Test	Run test such that the software system receives a signal that activates the calibration period and verify calibration starts and stops in the appropriate time.
1.3 Error Checking	Radiation caused errors must be caught as these types of errors are inevitable in an orbit.	Test	Intentionally cause a bit flip and verify that the error checking system finds compensates for this bit flip.
1.4 Housekeeping data	To ensure proper data collection, the status of particular components of the electrical and optics subsystems must be known.	Inspection	Verify that temperature, power, and storage capacity data are being recorded.

Table 9 Justifications: Requirement 1 (Part 1)

Requirement	Reasoning	Verification Method	Verification Breakdown
1.4.1 Temperature data	Temperature variance outside of the allowable range may cause errors in the electronics and optics subsystems and produce errors in the data collected due to resulting deformation	Test	Place the payload in an environment with a known temperature and verify that the system software reads off the correct temperature value.
1.4.2 Power data	Variance in voltages may result in the destruction of components on the electronics board	Inspection	Use a multimeter/voltmeter to manually measure the voltage between two points on the electronics board and verify that the same measurement is produced by the system software.
1.4.3 Storage Capacity	If a downlink error occurs and data is not transferred on time, knowledge of the storage capacity remaining may be necessary.	Test	Install a storage component with known capacity remaining and verify the software reads off the correct capacity.
1.5 Power Consumption	The worst case power draw from NanoSAM 1 was 0.8W [6] and 1W of power allows for 25 percent error in this measurement.	Inspection	Measure the power draw of all electrical components.

Table 10 Justifications: Requirement 1 (Part 2)

Requirement	Reasoning	Verification Method	Verification Breakdown
2.0 Communications	In order for the system to be spaceflight ready, it must be able to communicate to a ground station through a standard bus ICD system.	Test	Perform a wireless ground communication testing.
2.1 SNR	The NanoSAM I team calculated the SNR ratio based off of noise sources, irradiance errors, and SAM-II performance. [6]	Test	Measure the SNR of the system using data collected during the data collection test.
2.2 Fault Mitigation	Knowledge of errors that are occuring is necessary to data analysis or fixing the incoming data.	Test	Verify warning message is received by ground computer when test is performed to trigger a warning message (same test as described for requirement 1.4.4).
2.3 Downlink Data Transfer	Data from the instruments needs to be downlinked within these specifications for the complete data set to reach a ground station	Analysis	Compute the maximum amount of data that can be transferred according to the data rate and downlink window, compare this with the amount of data generated between each downlink window.

Table 11 Justifications: Requirement 2

Requirement	Reasoning	Verification Method	Verification Breakdown
3.0 Equivalent Optics	In order for NanoSAM II to be an improvement to the overall SAM-II system, NanoSAM II needs to meet or exceed the optical capabilities of SAM-II.	Test, Analysis	Extensive ground testing of the system and the individual components as well as simulations accounting for flight-like conditions.
3.1 Wavelength	1.03 µm is a wavelength at which aerosols can be measured [14].	Inspection	Alignment testing of the optical system using an interferometer will test the wavelength being measured.
3.2 Vertical Resolution	The optical system of NanoSAM II needs to match that of SAM-II, which had a vertical resolution of 1km [8].	Analysis	The vertical resolution will be tested through observation of data collected during an overall systems test.
3.2.1 FOV	A FOV of 1.3 arcminutes is needed to achieve the required 1km resolution.	Analysis	The FOV will be confirmed by observation of the data collected during an overall systems test.
3.2.2 MTF	The MTF of .74 was calculated by the NanoSAM I team, based off of the desired optical performance of the lens used in the optical measurement system [6].	Inspection	An interferometer shall be used to measure the MTF of the optical system.
3.3 Tracking Accuracy	The customer requires a tracking accuracy of 1 arc-min/mRad in tracking the sun[5].	Analysis	The tracking accuracy will be verified by observation of the data collected during an overall systems test.

Table 12 Justifications: Requirement 3

Requirement	Reasoning	Verification Method	Verification Breakdown
4.0 Payload Dimensions	The dimensions of the payload need to be integrated with a bus in order to take measurements in space. This requires appropriate sizing and interfacing	Test	Test the system's mkdata outputs when the payload is complete and in it's required dimensions.
4.1 Payload Size	A 0.5U volume is easily attached to a CubeSat system.	Inspection	Measure the volume of the payload.
4.2 Payload Mass	The mass of a 1U CubeSat is recommended by NASA to be 1.33 kg [3], the 0.5U payload should have half that mass.	Inspection	Weigh the payload to confirm the mass.
4.3 Payload Interface	In order for the NanoSam mission to be flight viable, it need to be able to interface with a standard CubeSat bus.	Test	Install payload into a CubeSat and verify data transfer and optics function through ground testing.

Table 13 Justifications: Requirement 4

Requirement	Reasoning	Verification Method	Verification Breakdown
5.0 Flight Testing	Taking measurements in space is necessary to achieve usable measurements from the atmosphere. This environment must be survivable.	Test	Vibration, thermal, and vacuum tests will be performed to verify system functionality is retained during extreme conditions.
5.1 Vibration	The system must withstand vibrations that occur during launch and in orbit.	Test	After vibration testing according to the QB50 guidelines [12], payload functionality will be assessed.
5.1.1 Mirror Alignment	The mirror must remain within a given tolerance of the alignment position to receive accurate measurements.	Test, Analysis	Test the system after vibration and compare to control data collected to estimate the effect on alignment.
5.1.2 Natural Frequency	The payload needs to avoid exciting natural frequencies on launch so that the structure doesn't break.	Test	A vibration test should be performed through a range of 0-200 Hz to verify that not resonant frequencies are excited.
5.2 Thermal	The payload needs to function in its working environment, which involves temperature variation [15].	Test	Test system functionality over the temperature range experienced in flight.
5.2.1 Thermal Control	Thermal control ensures the electronics or optics subsystems don't exceed the allowable lower or upper temperature bounds.	Test	Set the thermal controls such that the lower and upper temperature bounds are well within the allowable range. Test thermal system activation once those bounds are exceeded.
5.2.2 Payload Temperature	The temperature inside the payload will differ from the environmental temperature, and this is the range that the subsystems must be able to survive[12].	Test	Test data collection at each extreme of the temperature range.
5.3 Vacuum	The atmosphere is of such low density at an altitude of 5km that it can be considered negligible and this must be survived.	Test	Test payload in a vacuum chamber and assess thermal performance and degradation of system components due to outgassing effects.

Table 14 Justifications: Requirement 5

Requirement	Reasoning	Verification Method	Verification Breakdown
6.0 Cost	Exceeding the provided budget will prevent the team from acquiring necessary materials.	Analysis	The Expenditure Plan matches the Project Budget.

Table 15 Justifications: Requirement 6

IV. Key Design Options Considered

A. Electronics System

Since functional requirements stem from the design of the NanoSAM I payload, the basic functional block diagram of the electronics system remains largely unchanged. At its core, the electronics system must complete functional requirement 1.0, digitizing and packetizing the information collected by the optical system. Thus, the electronics system requires a photodiode that interfaces with the optical bench to convert gathered light into a current. Following the photodiode is an amplifier and low pass filter combination, to improve and condition the signal. An analog to digital converter (ADC) is then required to convert the current into usable data, which is then packetized in an on board processing unit. Finally, the system will require on board storage to temporarily hold data until it can be downlinked from orbit, and as a form of redundancy for microcontroller storage. All components will require voltage, likely to be regulated to fit the preferences of the ADC and on board computer, as well as noise constraints in analog components.

Thus, the key design options considered for the electronics board are variations of component types that will exist in the manufactured board. Design options here will follow in line with those from the 2019-2020 system, but care is introduced with regards to new design requirements. Particularly, new components will also be discussed along the dimension of thermal qualities, radiation hardening, flight heritage, and vibrational resistance. Still, we note that radiation hardening on components that need it the most is often prohibitively expensive for a student project. A fundamental design consideration when it comes to electronics is simplicity, complicated components often require advanced designs, increased cost, and more board space. Sticking with well defined basics makes debugging easier along the way, and will support a future team in designing a bus or integrating with an industry bus.

Photodiode Options

In the broadest terms a photodiode is an analog semiconductor device that converts absorbed photons and high energy particles into an electrical current as the particles strike the semiconductor surface. In Fig. 5 we see an example of the typical P-N photodiode, noting that the silicon construction is essentially that of a typical diode. The depletion region in the diagram is sometimes called the impurity region, and can be made of different materials with different electrical properties. Striking light on the silicon surface creates electron-hole pairs in the material, which generates an electric signal to be measured. [17].

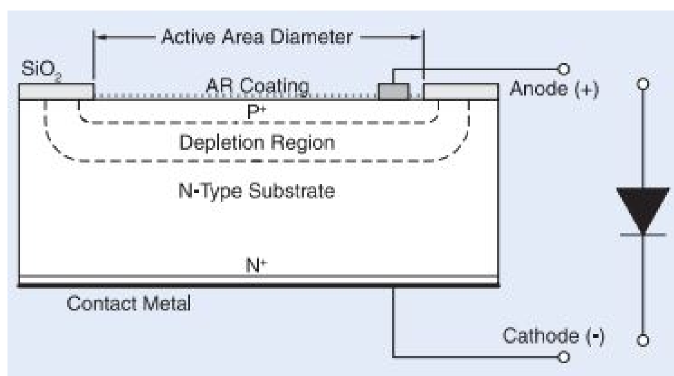

Fig. 5 A planar diffused silicon photodiode [16]

Converting the incoming photons into current allows the irradiance information to be read by the ADC, which can then be converted back from an electrical signal into usable data. Photodiodes have a number of properties of concern to the project, most of which are dictated by the material used. In particular, the noise of the selected photodiode is of primary concern to meet the SNR requirement. Shot noise arises due to statistical fluctuations in the actual generated current, as well as the dark current. The dark current is, as the name describes, the current that flows from the photodiode when there is no light - essentially pure noise to the measurement. Temperature changes affect the dark current drastically, doubling it for every 10 degree change in Celsius [16]. The responsivity of the photodiode will be important for attaining sampling frequency requirements. The responsivity is given by equation 1. Also noted is the operating mode of the photodiode, photovoltaic or photoconductive. Both of these options are inspected when designing the interaction of the photodiode with the larger electrical system, and do not warrant a standalone trade study.

$$R_\lambda = \frac{I_p}{P} \tag{1}$$

Material The right material needs to be chosen by the team to meet our functional requirement for wavelength, whilst keeping the noise and overall cost of the printed circuitry down. Fig. 6 presents common material types of photodiodes sold by Thorlabs, a photodiode manufacturer [18].

Material	Dark Current	Speed	Spectral Range	Cost
Silicon (Si)	Low	High Speed	Visible to NIR	Low
Germanium (Ge)	High	Low Speed	NIR	Low
Gallium Phosphide (GaP)	Low	High Speed	UV to Visible	Moderate
Indium Gallium Arsenide (InGaAs)	Low	High Speed	NIR	Moderate
Indium Arsenide Antimonide (InAsSb)	High	Low Speed	NIR to MIR	High
Extended Range Indium Gallium Arsenide (InGaAs)	High	High Speed	NIR	High
Mercury Cadmium Telluride (MCT, HgCdTe)	High	Low Speed	NIR to MIR	High

Fig. 6 Photodiode Material Characteristics [18]

The most common material type used in photodiodes is silicon. Silicon photodiodes are used for wavelengths between 190-1100 nanometers, and produce lower dark current than most materials, resulting in less inherent noise. Considering these desirable qualities and the relatively low cost on the market, silicon is one of the most common materials for photodiodes in industry. This means we can get a larger active area for the same price as higher-end materials, resulting in overall better measurements. Silicon photodiodes also have flight heritage to our specific project, being used in the SAGE II instrument. InGaAs photodiodes use a combination of indium, gallium, and arsenic to achieve measurement abilities at higher wavelengths than silicon photodiodes, particularly from 800-1700 nanometers [19]. Lastly, germanium photodiodes typically work in the 900-1600nm range. They have the largest active area resulting in stellar sensitivity in this described region, but this comes at an increased price and larger dark current than other variants. Ideally, the bandgap energy of the chosen photodiode material should be similar to the photon energy corresponding to the longest wavelength we expect to encounter. This ensures strong response and low dark current [20]. Thus, the design choice will heavily rely on this quality, but will be affected by inherent dark current generated noise, as well as the material cost. Since all materials cover the 1030 nanometer range, the trade study will look at responsivity curves for photodiodes. We see a sample responsivity curve below in Fig. 7.

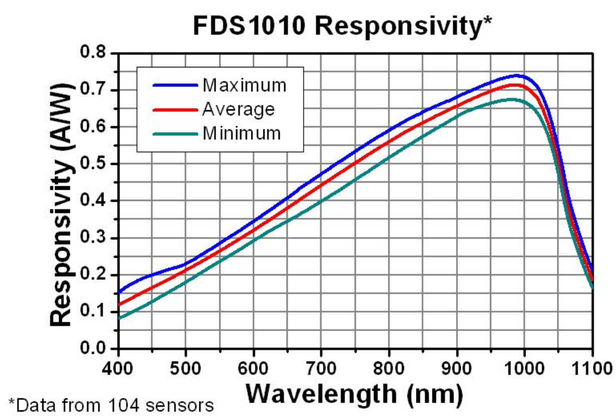

Fig. 7 Silicon Responsivity Curve [18]

Analog to Digital Converter Options

The analog to digital converter is the heart of NanoSAM II's circuitry. It takes the current output from the photodiode and converts it to a digital signal that can be read by the chosen computer system. The choice of ADC will heavily determine the final circuit layout, as each variant of ADC has a different configuration to suit its needs. Our ADC choice ultimately depends on the resolution, conversion speed, power requirements, physical size, compatibility with our computer choice, and the photodiode interfaces [21]. ADCs often require some signal conditioning of the analog signal, which will be accomplished by some form of amplifier and low pass filter depending on the chosen ADC.

Successive Approximation (SAR) A successive approximation ADC works by taking a sample of the electric signal and holding it (sample and hold, or SHA). An internal comparator determines if this SHA output is greater than an internal digital/analog converter (DAC) output, and stores the result in the successive-approximation register. The scale on the internal DAC is then either raised or lowered depending on the SHA return, and the process repeats. This type of ADC is the most popular in most data-acquisition uses, and is used often for multiplexing of varying channels [22]. We see a diagram of the basic internal workings of a typical SAR ADC in Fig. 9. These ADCs consume low power, and are often smaller in board space. Resolutions typically range from 8-16 bits, but it has lower sampling rates for higher resolution applications, and the size of the SAR ADC will increase rapidly as resolution increases.

Sigma-Delta The sigma delta ADC works similarly through a 1-bit comparator and switch, providing strong linearity in the differential digitized signal. The ADC encodes the analog signal using a technique known as delta modulation, where the change in the signal is recorded, as performed by an analog integrator inside the circuity. The results are then sent to a digital filter to perform noise shaping (essentially a low pass and high pass filter combined). The number of internal integrators determines the order of the delta modulating component of the ADC. We see a diagram of the basic internal workings of a typical first order sigma delta ADC in Fig. 8. The benefit of this ADC is high resolution and low noise results due to the inherent oversampling and noise-shaping discussed previously. Similar to the SAR ADC, they have increased in popularity and exist in low cost and low power consumption models.

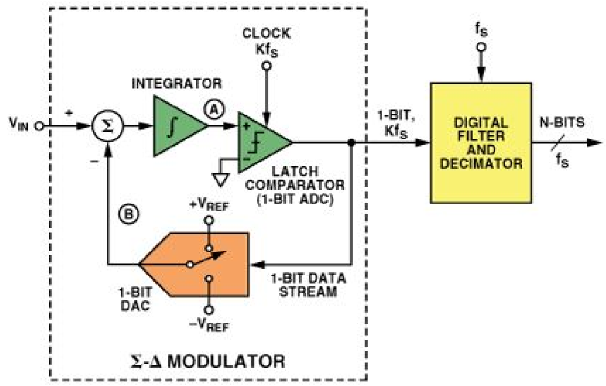

Fig. 8 Basic Sigma Delta ADC [22]

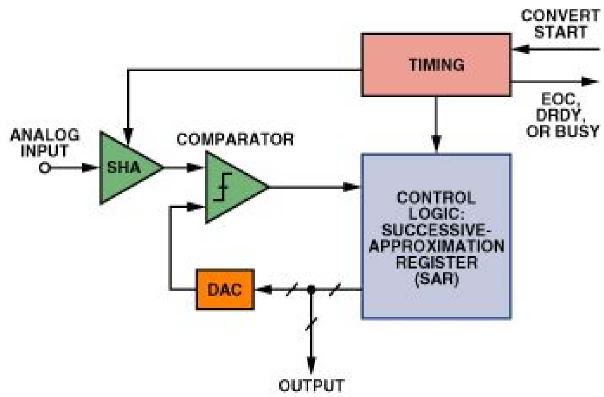

Fig. 9 Basic SAR ADC [22]

Pipelined The pipelined ADC, sometimes referred to as flash ADC, has the simplest internal workings. They use a simple chain of resistors to divide the voltage level of the arriving signal, which is then sent through a comparator to return a binary output. We see a diagram of the basic internal workings of a typical 6-bit pipelined ADC in Fig. 10. The benefit of this simple model is speed, performing much faster than the SAR and sigma delta ADC variants. However, increasing the resolution beyond 8-bits requires a large number of resistors in the chain, and is highly susceptible to temperature changes. Overall, this results in worse accuracy and resolution for this ADC type, and higher noise produced. Due to the number of internal components, although simple, the ADC utilizes higher power consumption than other variants. There is also a subtle disadvantage when working in short bursts of data collection because low sampling rates extended the hold times on the internal track and causes conversion errors [22].

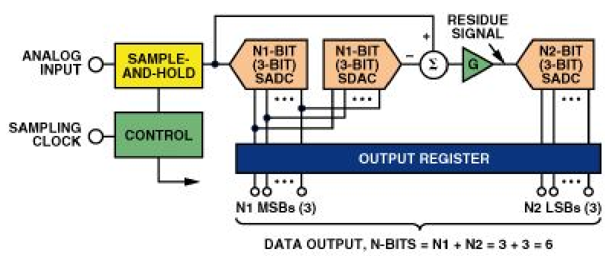

Fig. 10 Basic Pipelined ADC [22]

On Board Computer Options

If the ADC was the heart of our printed circuitry, then the on board computer will be the brain. After light is measured by the photodiode and transformed into a digital signal by the ADC, we need a computer system to packetize, perform any required calculations, and save the data. The on board computer must also communicate with the specified bus communications system, to transfer data for eventual downlink back to ground systems on Earth. There are three traditional types of computers used on board CubeSats. All of these options are susceptible to radiation damage and single event upsets (SEUs). Choosing an OBC that has multiple connection varieties will simplify transfer of data on the board, as well as simplify testing by allowing for easy access to data. Ideally, we would like USB for real time testing, and something straightforward like a serial bus interface (SBI) between individual board components.

Field Programmable Gate Array (FPGA) The field programmable gate array is essentially a large collection of small logic gates that can be configured to the needs of the user. The FPGA is divided into groups of logic blocks that are connected through simple routing channels, and have input/output pads that surround them to take in data and run it through the complex logic. The logic gates within a modern FPGA are typically controlled by high level programming through Verilog or VHDL. The major benefit of using an FPGA is specificity and versatility, they can be programmed for almost any usage, and to an extremely precise level [24]. They thus have strong flight heritage for interaction with multiple parts of the electronic block, including data collection, storage, communication, ADCS, etc. The downside to the FPGA is that they are difficult to program, and may be overkill depending on the inherent challenge of the mission.

Microcontroller Moving up the chain of abstracted complexity, we have the microcontroller. The microcontroller is a chip that contains a small CPU, memory, I/O ports, timers, and other accoutrements. Essentially, it is a small computer. Microcontrollers lower the complexity associated with performing data handling, often at the cost of versatility. However, they are strong at doing straightforward and repetitive tasks, and can still be used in a variety of applications, often through a higher level programming language like C. The small size makes them good for size limited applications like CubeSats, but comes at the cost of limited computational power. Most microcontrollers with significant flight heritage use ARM processors [25]. Most hobbyist microcontrollers typially use USB I/O, which is good for ground testing applications, but can communicate via a serial programming interface with other active electronics, such as traditional op-amp ADCs. An example of a microcontroller is the Teensy 4.0, employed by the NanoSAM I electronics design, and shown in Fig. 11.

PCB Computers Finally, we arrive at the top level of printed circuit board computers. These are also sometimes referred to as single board computers. Following the same logic as before, these devices abstract out more complexity associated with programming the computers applications. These devices are larger than microcontrollers, and have greatly increased processing power. They often come with additional features, such as multiple ADCs, different I/O options, and specialized attachments. The issue with these additional features is that often they must be selected ahead of time and increase the cost of the computer [26]. The most popular example of the on board computer is the Raspberry Pi, often used by hobbyists for a variety of simple projects, and sometimes for student projects in space. One model of the Raspberry Pi is shown below, in Fig. 12. Although the Raspberry Pi is a cheap option, most PBC computers with flight heritage are radiation hardened and cost thousands of dollars.

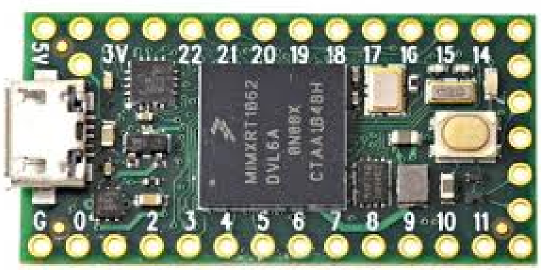

Fig. 11 Teensy 4.0 Microcontroller

Fig. 12 Raspbery Pi On Board Computer

Storage Options

With all satellites on orbit, data can only be downlinked back to Earth in very specific windows. Thus, most satellites must have a form of on-board storage to hold collected data before it can be downlinked. The selection of on-board computer has a large part in determining the type of storage, since the two must communicate with each other. Although some microcontrollers and OBCs contain their own internal storage, it is strong redundancy to have a backup form of external storage, as the OBC internal storage can be used for housekeeping data not related to the mission crucial data [27]. The previous team's storage trade study focused on the differences between SSD, microSD, USB, and flash storage. Although USB and the SSD/microSD storage options are useful for testing with a computer, the electronic design for NanoSAM II will require external storage that exists within integrated components (IC's) for placement on the PCB. IC's providing external storage fall within four categories: flash, SRAM, DRAM, and EEPROM [31].

Flash Flash storage is made of memory cells that use MOSFET transistors to operate as either NAND or NOR gates [28]. The differences between NAND and NOR flash are irrelevant at this stage, and will be determined by exact electrical characteristics required during the design phase. Flash memory is non-volatile, which means that if the power to the external storage is lost, the data will not be lost. However, the network topology of flash memory is such that individual bits cannot be erased, and require erasure of a block of memory. Furthermore, removing data is physically destructive due to the voltage required to remove trapped electrons from the MOSFETS [30]. Flash memory is cheap, small, fast, and provides some inherent radiation resistance to single event upsets. Also, flash memory has increasing usage in OBCs with flight heritage.

SRAM and DRAM Random access memory (RAM) is a volatile storage type, meaning that if the IC chip loses power, data is lost. Thus, RAM is typically used for temporary storage, and could be used to store collected data before being downlinked, depending on difference between downlink times. DRAM stands for dynamic RAM, and it consists of a transistor and a capacitor. DRAM in particular is destructive during the read operation, and will require another write operation to save data that is read. SRAM consists of six transistors in a flip-flop latch as opposed to the single transistor and capacitor. This latch removes the DRAM flaw of destructive reads, making it faster. However, the increased number of transistors makes it more expensive than DRAM [30]. Some modern day variants of DRAM include synchronous dram, which allows the memory to be synced with the clock speed of a microprocessor, but this is more complex in an external storage configuration.

EEPROM Electrically Erasable Programmable ROM (EEPROM) is a type of read only memory (ROM), and one of the older type of external memory out of the options here. Although not often used with modern electronics, it is included in the potential design options to show depth of research. EEPROM utilizes two transistors that activate based on their threshold voltage, applied during the read operation. The driven current goes through a sense amplifier to return a 1 or 0 during the read [29]. EEPROMs are programmed by the IC manufacturer to specifications as determined by the part listing. Although EEPROM is a viable form of read only memory, one of the requirements of our external storage is that it provides write capabilities to store the data that is collected on orbit. Thus EEPROM is not included in the trade study because it does not meet our requirements.

B. Optics System

Previous Design Overview

Last year, the NanoSAM I senior project team designed and manufactured an optical sensor, a radiometer, to measure the intensity of 1.03 μm light. A radiometer has three distinct stages: Filtering, Focusing, and Sensing. In order to accomplish each stage, NanoSAM I designed and manufactured an OAP Telescope which uses an OAP Mirror to focus filtered 1.03 μm light onto the photodiode.

Due to time constraints, NanoSAM I was never able to fully align the radiometer and the performance of this instrument and the system as a whole was never verified nor tested. Despite this, the process of designing, manufacturing, and aligning yielded a wealth of lessons and analysis which will be applied this year to create an improved radiometer specifically with regards to alignment tooling. Additionally, this radiometer will be aligned, tested, and validated, a process which NanoSAM I was unable to complete due to circumstance.

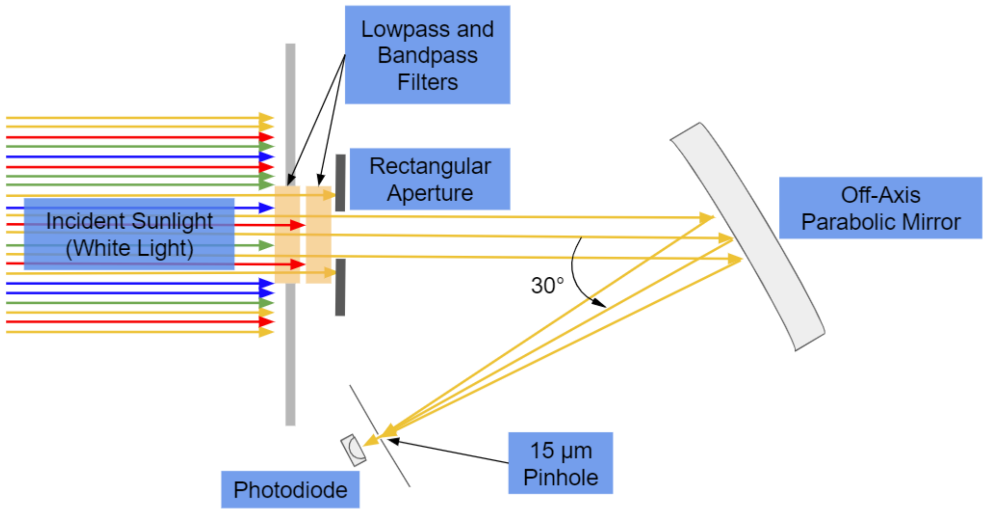

Fig. 13 NanoSAM I Radiometer Diagram

Previous Design Analysis

The baseline design of the Herschelian telescope designed by NanoSAM I will be used by NanoSAM II. A complete redesign of the optical system was considered, but it was decided to be out of the scope of the NanoSAM II project. Instead, NanoSAM II will improve the alignment and alignment tooling of the existing optical system. Several optical components were purchased by NanoSAM I, and are now available to NanoSAM II for no cost. Due to the low cost, reduced logistical risk, and reduced design complexity of using already provided components, NanoSAM II will be reusing several components from NanoSAM I. These are described in detail below.

Telescope Selection NanoSAM I considered four different types of telescopes: Schmidt-Cassegrain, Newtonian, Herschelian, and Prime Focus. These four telescopes were compared through a trade study that evaluated each on the basis of cost, manufacturing complexity, optical aberrations, effective focal length, and obstruction. Based on these metrics, the Herschelian telescope was determined to be the optimal design choice. The trade studies and analysis performed by NanoSAM I are shown in Tables 23,54-56, and Section 6.2.3 of NanoSAM I's Conceptual Design Document [42], and are summarized below.

The Herschelian telescope has a relatively simple design when compared to the other design options considered (shown in Figure 12 of source [42]). The main reason for this is that the Herschelian telescope only uses one mirror, while some of the other design options considered use pairs of mirrors. Shown in figure 13, the main component of the design is the OAP mirror, which reflects the incoming incident light and focuses it to a focal point off the optical axis. Due to the presence of a single, off-axis mirror, there are no obstructions. Therefore, the Herschelian telescope accepts the most light for a given aperture size. The simplicity of the design also vastly reduces the amount of manufacturing complexity, because there is only one mirror that needs to be aligned. Even with the simplicity of a single mirror, NanoSAM I proved that alignment is still very difficult, to the point where NanoSAM I failed to reach mission-critical alignment. Due to the complexity that would be added by the addition of a second mirror, NanoSAM II has decided to remain with a telescope design that utilizes a single mirror. Additionally, the Herschelian telescope designed by NanoSAM I has a focal length of 54.45 mm, which fits within the NanoSAM II payload size requirement of 0.5U without introducing additional complexity. Finally, the major components for the Herschelian telescope designed by NanoSAM I (mainly the OAP mirror) have already been purchased by NanoSAM I, lowering the cost and logistic risk of the optical system for NanoSAM II if this design is used. Because of the low cost, relatively low manufacturing and alignment complexity, sufficiently short effective focal length, and lack of obstructions, NanoSAM II has chosen to remain with the telescope design selected by NanoSAM I. The Herschelian telescope does have the possibility of optical aberrations which is true of all telescopes, but the aberrations of this type of telescope are manageable and the other selection parameters favor the use of a Herschelian telescope.

Filter Selection Originally, NanoSAM I intended to isolate a pass region at a central wavelength (CWL) of 1.02 µm, the wavelength of light measured by the SAM II instrument, but the team could not find COTS filters to accomplish this. Aerosols are not specifically correlated with absorption of 1.02 µm light. Aerosols absorb light with a large range of frequencies in the low IR spectrum. When measuring aerosol density by solar occultation, a quiet portion of the spectrum is all that is necessary. NanoSAM I found COTS filters to isolate 1.03 µm light. In this wavelength, aerosol absorption is the dominant change in signal wavelength, and scattering due to other sources is negligible. Additionally, there are minimal amounts of chemical reaction in this region [46]. Finally, NanoSAM II's photodiode is sufficiently sensitive to 1.03 µm light to detect aerosol absorption with an SNR of at least 3500 [6].

NanoSAM I purchased a bandpass and lowpass filter that together isolate a CWL of 1.03 µm light with a bandwidth of 0.0239 µm. The light outside of the passband is excluded by stacking a ThorLabs FLH1030-10 Bandpass filter and a ThorLabs FELH1000 Longpass (Lowpass) filter. The 1030 nm wavelength is optimal to measure aerosols because at this wavelength the aerosol concentration is higher than that of other atmospheric molecules (such as $N0_2, O_2$, and H_2O) by approximately an order of magnitude [46]. As is explained in Tables 66-68 in NanoSAM I's Conceptual Design Document [42], these filters are hard-coated, and so they offer the best transmission when compared to the other filters. This increased transmission leads to more light entering the measurement instrument, and therefore a higher sensitivity for solar occultation. Additionally, these filters produce high optical density compared to other filter choices, which will also improve the instrument's sensitivity by reducing the amount of light received outside of the desired wavelengths [42]. Because these filters accomplish their purpose and are available to NanoSAM II at no cost, they will be used in NanoSAM II's design.

Mirror Substrate and Coating Selection Because NanoSAM II has elected to use NanoSAM I's legacy components, the substrate and coating of the OAP Mirror has been decided; Aluminum will be used for both. Use of the same material throughout the optics system is optimal because it ensures that all components will have the same CTE, which will eliminate thermal stresses. NanoSAM I chose protected aluminum as the optimal mirror coating due to the cost, reflectivity at 1.03 µm, and durability. As is outlined in the trade study analysis performed in section 6.2.3 of NanoSAM I's Conceptual Design Document [42], protected aluminum is a popular mirror coating for devices measuring wavelengths in the required spectrum. Additionally, protected aluminum is relatively durable (when compared to other possible coatings such as protected silver or gold). Because smoothness of the mirror surface is critical to taking successful measurements, using a material that is resistant to scratches can increase the likelihood of proper measurements being taken. While protected aluminum is not as reflective as other possible mirror coatings, this is outweighed by the optimization of protected aluminum for the desired wavelength. Finally, protected aluminum was also the least expensive of the options considered. Once protected aluminum was chosen as the mirror coating, the mirror substrate material was chosen to be Aluminum 6061-T6 in order to have a continuous CTE across the mirror [42].

Optical Axis - Interferometer Beam Alignment Method NanoSAM I used two tilt micrometers, controlling yaw and pitch, to precisely dial in the alignment of the OAP mirror's optical axis to the interferometer's beam. NanoSAM II will continue to use tilt micrometers to control pitch and yaw and add a kinematic base [**?**] which will allow the radiometer to be removed and replaced throughout the alignment process without disturbing its orientation relative to the interferometer's beam.

Photodiode Block Translation Tunability Options

NanoSAM II's alignment procedure will follow the same concept as NanoSAM I's procedure, identically if shims are the selected option, similarly if rails or translational mounts are the selection. A brief overview of each alignment process is given below.

Alignment Procedure using Shims The interferometer's beam will be aligned along the OAP mirror's optical axis, Z-axis (See Fig. 14), using tilt micrometers and reflected along the Z'-axis. Next, the photodiode block, the structure which holds the pinhole field stop and photodiode, is mounted to a 3-axis stage. A chrome half sphere is centered on top of the pinhole so that interferometric measurements can be made to move the pinhole closer to the focus of the OAP. The 3-axis stage is used to position the chrome half sphere at the focus point using the interferometric measurements minimize the aberrations. During each step, the required offsets along each axis are calculated, and the equivalent shims are placed. These steps are repeated until the radiometer is aligned and aberrations are below the acceptable maximum.

Alignment Procedure using Rails or Translational Mounts The interferometer's beam will be aligned along the OAP mirror's optical axis in the same manner as the case for shims. Divergently, the rails and/or mounts are attached to the optical bench. The photodiode block is attached to the rails and/or mounts. A chrome half sphere is centered on top of the pinhole for interferometric measurements. The rails and/or mounts are used to position the chrome half sphere at the focus point using the interferometric measurements. These half sphere steps are repeated until the radiometer is aligned.

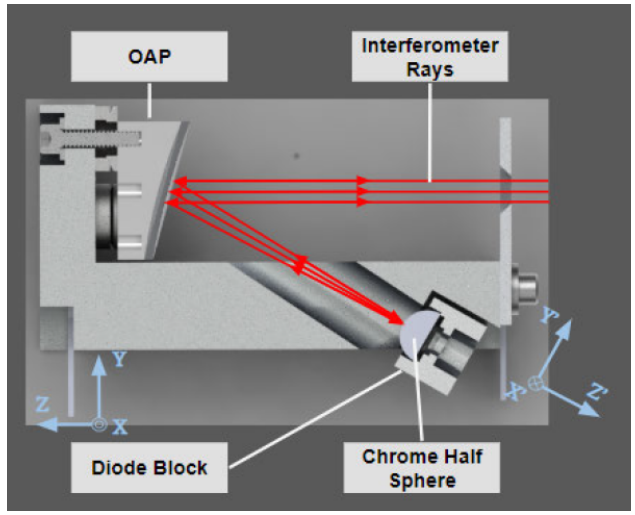

Fig. 14 Alignment Diagram [6]

As seen in the overview of the alignment process, the pinhole assembly must be adjusted to be directly centered on the focus produced by the OAP of the interferometer beam. Because the pinhole is rigidly mounted to the photodiode block, the photodiode block's mounting points on the optical bench must be adjustable relative to the OAP mirror. Descriptions of each option to adjustably mount the photodiode block are listed below.

Shims Shimming is the most simple, industry practice for offsetting components precisely in optical engineering. By placing shims of well-characterized thickness in gaps between rigidly mounted components, off-sets can be achieved with relative ease with tens of micrometers of precision. NanoSAM I's shim sizes ranged from 25.4μm to 254μm.

Rails By placing the photodiode block on COTS optical rails, adjusting offsets would be as simple as sliding components to the desired location and securing position via set screws during testing. Prior to flight, adhesive is applied to reinforce the orientation. Rails would reduce the amount of time adjustments take during the alignment process. [35]

Translational Mounts The photodiode block could be translated along the axes using a COTS translational optics mount. These mounts use high-thread count bolts to precisely dial translational displacement with single micrometer precision. The orientation is held by set screws during testing. Prior to flight, adhesive is applied to reinforce the orientation.

The three possible options are shown in Fig. 15 below.

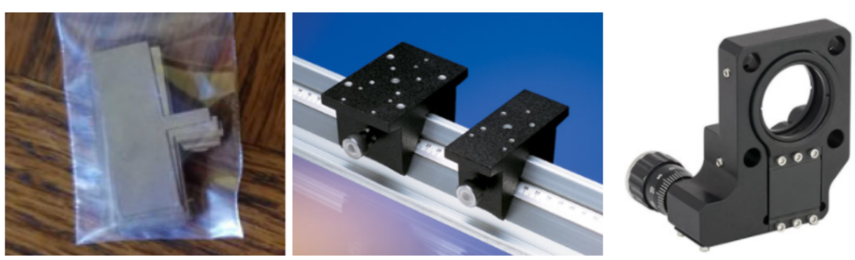

Fig. 15 From left to right: NanoSAM I Shims [6], Ealing Optical Rails [43], Thorlabs Z-axis Translational Mount[44]

Reducing Diameter of OAP Mirror

Due to the anchor points deforming the mirror, NanoSAM I's OAP mirror introduces tilt aberrations, which causes the wavefront to displace (WFE), which decreases the MTF value of the radiometer. Minimizing these aberrations yields a more acceptable MTF value. This can be done by increasing the diameter of the OAP, since the deformation at the center of the mirror due to the anchor points is smaller as the anchors are farther away.

Current COTS OAP Mirror By keeping NanoSAM I's OAP mirror, significant financial costs and technical bottlenecks are avoided. The current OAP mirror is a well-characterized COTS component supplied by Edmund Optics. This is the largest, COTS, OAP mirror within the team's budget. Keeping the current OAP mirror will not decrease the amount of WFE.

Custom OAP Mirror Replacement By custom ordering a new OAP mirror with a larger diameter, the tilt aberrations can be reduced. Ordering a custom part may have significant financial cost/lead time, which may cause budget issues and project delays.

Photodiode Shield Geometry

A light blocker must be placed directly in front of the photodiode to select the desired field of view of the radiometer. The geometry of this blocker determines the shape and dimensions of the field of view. A pinhole will result in a circular FOV. A slit will result in a rectangular FOV.

Pinhole NanoSAM I selected a pinhole as their field stop. The pinhole selected was a circular opening 15 µm in diameter, which resulted in a circular field of view with a diameter of .95 arcminutes. According to the NanoSAM I calculations, the pinhole should have allowed in the necessary amount of power to achieve the required signal-to-noise ratio [6].

The field of view of the field stop is calculated using the equation

$$FOV = \frac{Ocular\ Field\ Stop\ Diameter}{Telescope\ Focal\ Length} * 57.3 \tag{2}$$

Slit Alternatively, a slit could be used instead of a pinhole. Because NanoSAM is only interested in vertical resolution, a slit geometry would allow for a greater amount of light to be collected. The slit would be a rectangular opening, with a maximum height of 20 µm, as this is the diameter needed to achieve the desired 1.3 arcminutes field of view using Equation 2. The length of the rectangular opening would be 3 mm [50].

C. Structures System

1. Previous Design Overview

Previous designs for the structures system were poorly documented, as few of the NanoSAM I design choices were motivated by clearly defined requirements. The result of this is that the NanoSAM I design is functional and low cost, while only being applicable for a ground solar tracking test. This design is essentially a set of four rails with the key components on separate platforms aligned on the rails [Fig 16]. The rail system is then enclosed in a simple aluminum shell.

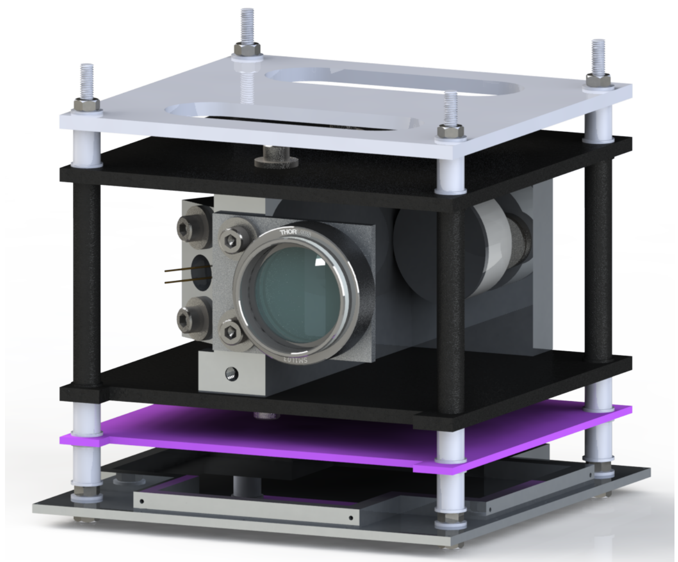

Fig. 16 NanoSAM I Internal Structure

While the structure met the previous requirements of fitting the payload within 1.5U, the driving requirement for the NanoSAM II structural design is that the payload needs to fit within only 0.5U, while also providing adequate protection during space environment testing (requirement 5.0). Fitting within 0.5U will make the product more compact and therefore more marketable.

2. Structural Design Elements

The structure of the NanoSAM payload performs three main functions. The first is that it attaches the NanoSAM payload to some exterior structure, such as an external satellite. The second is to give the structure an exterior of its own to protect the internal devices from dust on the ground and the environment of space while in operation. Third, the structure houses the internal components and must provides a rigid base to prevent vibrational and thermal harm to the sensitive electronics and optics. The mechanics of how the NanoSAM payload is attached to the exterior structure is addressed in the Payload Integration section.

Main Structural Material

The structure may need to be compatible with the CubeSats, so a requirement from the CubeSat Design Specification document, REV 13 [32], that states "Aluminum 7075, 6061, 5005, and/or 5052 will be used for both the main CubeSat structure and the rails." (CubeSat Requirement 3.2.15) will be applied. This limits the structural design space to one of these materials or some combination thereof. While these materials are all aluminum, some differences exist in their densities, shear moduli, and coefficients of thermal expansion, as well as cost and availability.

Integration of Internal Components to Structure

Perhaps the most obvious role of the structure is to provide support to the electronics and optical systems, reducing the effects of vibrations and thermal effects. This is essential to the success of the payload, since the electronics and optics must be mounted so that they can be integrated as a whole.

Direct Bracket Mount Often used in CubeSats, electronics boards and other payloads are commonly mounted directly to aluminum brackets as part of the larger structure. These integration methods are easy to design and implement, and have been well studied for CubeSat applications. One such example can be seen in figure 17 below, which is a CAD design of the 2U UPSat (University of Patras Satellite)[33].

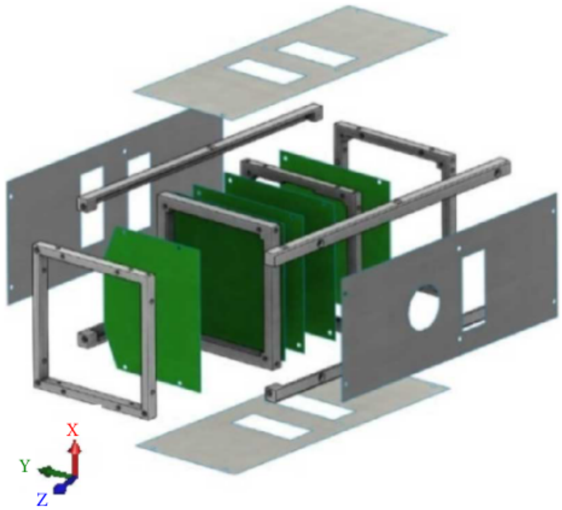

Fig. 17 Example of Direct Bracket Mount

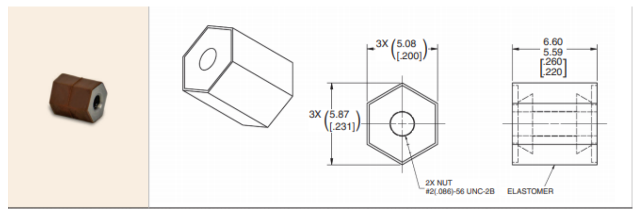

Fig. 18 An elastomer isolator available from Parker LORD

Spring Isolator Mount One mounting system that would reduce the effects of vibration and shock is a spring mounting system for the optical device. Typical small scale mounts tend to use rubber or other elastic products to form an artificial spring, as opposed to an actual metal spring. These spring mount systems isolate the mounted side from each other, reducing mechanical shock and vibration. One example of one such isolator can be seen in figure 18 above.

Shock Mounts Shock mounts provide more protection against mechanical shock and thermal extremes than a straightforward bracket mount would by itself, however the core of the structure would still utilize the bracket method. The key difference is that these mounts provide thermal insulation from the bulk of the structure and and reduce potential misalignment issues due to vibrations or shocks on launch. Delrin (a polymer) shock mounts were used on The Cal Poly State University CP1 CubeSat [34]. These shock mounts would most likely need to be designed by the Structures lead, as micro shocks for space applications are not readily available. These differ from the spring isolator mounts above in that there is a central rod that connects the two platforms, so most of the mechanical vibration damping occurs along one direction.

D. Software System

Software design choices will be coupled with the electronics system to handle data processing, storage, and transmission, thereby fulfilling requirements 1.0-1.3, and 2.0. The nature of the electronics system will shape the specifics of software implementation, but the key software design choices will be independent of electronics.

Previous Design Overview

Previous software was designed specifically for ground testing without consideration to potential in-orbit operations, thus it does not include functionality for in-orbit data capture or robust error checking. Fig. 19 illustrates the basic functionality of the previous software system [6].

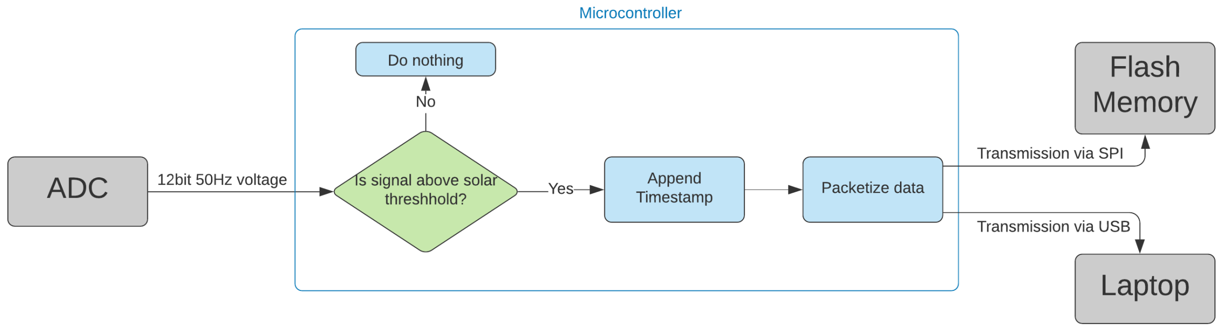

Fig. 19 High level design of previous software

Data Capture Timing

NanoSAM II will collect optical data sets twice each orbit: once during sunrise and once during sunset. The software must be able to capture data in both scenarios by defining an accurate data collection window of consistent duration. See the CONOPS section for more information on these optical data collection windows.

Continuous Data Collection In this configuration, data will be continuously recorded and temporarily stored, but only data of interest will be marked for transmission. In the case of a sunrise the photodiode will detect some threshold value at the beginning of the collection window, and data collected over the following period will be marked for storage and transmission. In the case of a sunset the photodiode signal will drop below the threshold value at the end of the collection window, and data collected over the preceding period will be marked for storage and transmission.

Triggered via Integrated Clock with Calibration via Photodiode In this configuration, data will only be collected and stored during predefined windows measured by the hardware-integrated clock. The timing of the data collection windows will be periodically adjusted by measuring the time of sunset and sunrise via the photodiode signal.

Calibration

To ensure the accuracy of data, NanoSAM II will measure a reference value when the photodiode's line of sight to the sun is outside the atmosphere. This reference measurement will be at the maximum solar intensity, and gives a baseline against which the data will be compared. Its magnitude will determine the precision of all following data. For ground testing the calibration value shall be measured at solar noon and the actual extra-atmosphere value will be extrapolated.

In Situ Calibration With this method NanoSAM II will re-calibrate at each data capture window. The calibration data will be stored internally and all incoming data will be modified relative to the calibration value before it is stored and transmitted.

On Ground Processing An alternative method is to store and transmit the raw, unmodified photodiode data as well as the calibration value. The data will then be analyzed relative to the calibration data once it has been transmitted to ground systems.

Error Detection

To identify and potentially correct data corrupted by interference, an error detection method will be implemented in all transmission packets. Additionally, an error detection method will be implemented within NanoSAM II's internal data storage to mitigate the effects of single event errors caused by charged particles.

Longitudinal Redundancy Check (LRC) With this method, also known as two dimensional parity, data units are grouped into blocks. Each data unit is appended with a single parity bit, and additionally each column of bits is assigned a parity bit. The column parity bits are then appended to the data stream as a redundant unit. LRCs are capable of detecting burst errors and single bit errors, but can easily miss two bit errors in any column [38].

Cyclic Redundancy Check (CRC) With a Cyclic Redundancy Check, data blocks are subjected to polynomial division and the remainder is appended to the block as a check value. The receiving hardware performs the same polynomial division accepts the data only if the check values match. CRCs are capable of detecting burst errors [38].

Hamming Code A Hamming code consists of parity bits placed within the data unit at all positions that are powers of two. Each parity bit considers only a portion of the total data unit according to its position, thus allowing the receiver to both detect and correct a single bit error. By appending a single parity bit to each data block a two bit error may also be detected, but not corrected. Hamming codes can detect errors up to two bits with certainty, and are capable of correcting single bit errors [37].

Repetition Code A simple-to-implement method of error detection in which data units are redundantly transmitted a fixed number of times. An error is detected whenever repeat data units are not identical, and by taking the majority of the units to be the correct data, errors can be ignored. Repetition codes can correct errors of any size, but cannot handle simultaneous errors in more than one identical data set [36].

E. Payload Integration

For the scope of this project, the NanoSAM II team has decided to focus primarily on creating a flight-ready payload instead of designing a full spacecraft. To ensure the success of the optical payload, the relevance of each sub-system and the critical design aspects for this year's team have been highlighted in the Multi-Year Design Breakdown, figure 3. This means that the team will not be working on attitude determination and control, communications with a ground station, or any mission critical elements at a spacecraft-level. Therefore, referencing the requirements stated in tables 6, 7 and recognizing that the optical payload will one day be integrated with a bus system that would not be designed by the current team, four key design options were formulated and researched. These design options are to help identify how to design to industry standards and make integration in the future as seamless as possible.

	Single	**Joint**
Commercially Bought	This design option involves the interaction with an external company and designing the payload to interface with a specific, commercially available, CubeSat bus.	In this design consideration, the team would collaborate with another in-development or soon to be in-development CubeSat mission that is using a commercially bought CubeSat bus.
Team built	This design option involves a future NanoSAM team focusing on a high level design of a spacecraft that will interface with this year's NanoSAM II optical payload.	This design consideration involves a future NanoSAM team collaborating with another mission and developing a bus with the overall focus of integrating the optical payload.

Table 16 Payload Integration Design Options

Table 16 shows all the design options for the NanoSAM II payload integration. There are four main design considerations each falling into 2 categories; the external collaboration and the required design. The first category of design options highlight that the team can either choose to collaborate with another team in what would ultimately be a joint mission, or work individually. Working with another team would allow for resources to be shared and collaboration on a complex project is always welcome. However, the amount of flexibility in the design would have to be dynamic and certain variables such as timeline and availability may present conflict with the teams. The second category involves the amount of design required. A commercial bus system could be purchased through an external company like Blue Canyon or Endurosat, or be built by a future team. Buying a commercial bus would include ICD and lots of information that would help the current payload design, but a future team built design would allow for a much for flexible payload design. The important distinction to make is that the current team will be using this design consideration to make integration easier in the future.

V. Trade Study Process and Results

A. Electronics System

It is often difficult to determine exact quantitative values for certain metrics without conducting the full electronics design. Often parts are specifically chosen out of hundreds of manufacturer options for extremely specific characteristics. Thus, the quantitative numbers used in the following metric categories are not exact specifications of any one part, but are averages created from browsing the Digikey part website [31]. Although these averages do not reflect the exact part specifications, they provide a quantitative means to compare broad part categories.

1. Photodiode Options

Metric	**Weight**	**Driving Requirements**	**Description and Rationale**
Dark Current	0.4	2.1, 5.2	The leading cause of noise for photodiodes is the dark current. Reducing dark current sources is vital to collecting accurate data and maintain a high signal to noise ratio. Dark current is proportional to temperature and active area.
Responsivity	0.4	1.1	Responsivity is a measure of the effectiveness of converting light into current. It is important to select a photodiode material that exhibits high responsivity in the bandwidth region closest to 1030 nm. Different photodiodes work best in different wavelength ranges, so picking a material that expresses high responsivity in a wavelength range closest to 1030 nm is crucial.
Active Area	0.1	5.1.1	A larger active area provides more surface for light to hit the semiconductor material and be converted into current, which allows for redundancy in optical system alignment, giving room for error introduced in vibrational scenarios.
Cost	0.1	6.0	In NanoSAM I, the optical system took a significant portion of the budget. Any replacement of optical parts will consume a large portion of the budget, and thus, keeping electronics pieces cheap and simple is crucial to maintaining the 5000 dollar budget. Photodiode cost can range heavily, and can be quite expensive.

Table 17 Photodiode Metrics and Weighting

Metric	**1**	**3**	**5**
Dark Current	1-5	1-5 nA	1-5 pA
Responsivity	0-0.5 A/W	0.5-1.0 A/W	>1.0 A/W
Active Area	0-1 mm^2	1-5 mm^2	>5 mm^2
Cost	>$100	$50 - $100	$5 - $15

Table 18 Photodiode Metric Values

Dark current is proportional to active area, and any material can be made with feasibly any active area, to differ between materials here, we discuss general trends in available parts. Particularly, the dark current value is compared between photodiodes with the same area. Responsivity values are taken at the designed wavelength for the part reported from manufacturer data sheets. Still, the overall responsivity curve for multiple photodiodes in the material classification were analyzed to make sure that the responsivity at 1030 nanometers was similar to the responsivity at the designed wavelength.

Metric	Weight	Si	InGaAs	Ge
Dark Current	0.4	5	3	1
Responsivity	0.4	3	3	1
Active Area	0.1	1	1	5
Cost	0.1	5	3	1
Total	1.0	**3.8**	2.8	1.4

Table 19 Photodiode Trade Study Results

2. Analog to Digital Converter Options

Metric	Weight	Driving Requirements	Description and Rationale
Resolution	0.4	1.1.2, 2.1	The ADC must digitize the continuous photodiode current into data with discrete measurements. The bit resolution of the ADC must be enough to resolve aerosol concentrations from the irradiance measurements, meeting the customer set requirement.
Power Consumption	0.2	1.4.5	Active circuits on the PCB will contribute to a large sink of total power budget, which is defined by the batteries aboard the selected bus design.
Conversion Speed	0.1	1.1.1, 2.1	The speed of conversion will consequently determine the data sampling rate, meeting the 50 hertz requirement. Low weight is assigned here however, because almost all modern ADCs can reach this requirement.
Size	0.1	4.0	The optical bench will take up a majority of 0.5U space for our payload. The ADC will be one of the larger elements on the PCB, and reducing size of the overall PCB to fit along the optical bench is crucial to the 0.5U requirement.
Computer Compatibility	0.1	1.0	It will be necessary for the ADC to communicate digitzed data with an on board computer system for data operations, transfer to storage, and downlink. This joint necessity is shared by the trade study for OBCs, and communication capability is typically versatile, so weight here is reduced.
Cost	0.1	6.0	ADCs are more expensive than photodiodes, but also relatively small compared to the on board computer, and thus weighted lower. Overall rationale for keeping costs low is described in the photodiode trade study, and is not repeated here.

Table 20 Analog to Digital Converter Metrics and Weighting

Metric	1	3	5
Resolution	< 8 bits	< 16 bits	< 24 bits
Power Consumption	> 0.01 W	0.001-0.01 W	< 0.001 W
Conversion Speed	< 1 kHz	1-10 kHz	> 10 kHz
Size	> 10 mm^2	3-10 mm^2	< 3 mm^2
Computer Compatibility	Parallel	SPI	SPI and DSP
Cost	> $100	$10-$100	< $10

Table 21 Analog to Digital Converter Metric Values

Similar to the photodiode section, with the thousands of options you can typically find an ADC in each of the three categories that will fit the needs of the project. To differentiate, ADC qualities are compared in relatively similar price ranges. To determine cost metrics, the average individual digikey part costs are estimated per category. Power consumption here was calculated based on maximum input voltage and current, using equation 3. For computer compatibility, parallel connections were deemed the lowest level as they are less common. SPI interfaces are the most common, so they were deemed middle, and additional points were given if the ADC also had DSP interfaces.

$$P = V_{dd} * I_{dd} \tag{3}$$

Metric	Weight	Successive Approx.	Sigma-Delta	Pipelined
Resolution	0.4	3	5	1
Power Consumption	0.2	3	3	1
Conversion Speed	0.1	3	3	5
Size	0.1	3	3	1
Computer Compatibility	0.1	5	3	1
Cost	0.1	3	5	1
Total	1.0	3.2	**4.0**	1.4

Table 22 Analog to Digital Converter Trade Study Results

3. On-Board Computer Options

Metric	Weight	Driving Requirements	Description and Rationale
Versatility	0.3	1.0	The selected option must be able to communicate with the ADC, storage, and with the selected bus design. Since each of these items are dictated by trade studies, it will be important to select an option that has multiple I/O types and has strong redundancy with other PCB components.
Size	0.2	4.0	The size of the on board computer will be the largest element of the final PCB design, and thus it is vital that we choose options that allow our PCB to fit in the 0.5U requirement.
Cost	0.2	6.0	The OBC contributes to the largest individual element cost on the PCB. Overall rationale for keeping costs low is described in the photodiode trade study, and is not repeated here.
Complexity	0.1	1.0	With any time constrained project such as this, we seek a solution that meets requirements with minimum complexity. The OBC can be difficult to program in the FPGA case, or could come with existing open source software solutions in the case of some microcontrollers.
Processing Power	0.1	1.0, 1.1.1.1, 1.1.2	The selected OBC must be able to handle the data from the ADC, and store the data at a rate below the sampling rate to ensure no lost information. It also must be able to simultaneously handle bus interfacing, and any payload handling programs that are put on it. The weight here is lower however, because most OBCs should easily be able to handle our needs.
Power Consumption	0.1	1.4.5	OBCs are actually typically quite power efficient, but the power consumption, which is defined by the batteries aboard the selected bus design, must still be considered.

Table 23 On-Board Computer Metrics and Weighting

Metric	1	3	5
Versatility	1-3 I/O	3-5 I/O	> 5 I/O
Size	PCB Sized	-	IC Sized
Cost	> $1000	$100-$1000	$10-$100
Complexity	Custom/Proprietary Software	Standard Hardware (RS232)	Open Source (C++)
Processing Power	0-100 MHz	100-1000 MHz	> 1 GHz
Power Consumption	> 1 W	0.1-1 W	< 0.1 W

Table 24 On-board Computer Metric Values

The OBC section is much harder to define hard quanitative metrics for. Versatility, the most important metric here, is often driven by cost as much as it is by category. The ADC section was ranked in compatibility by having SPI interfaces, so ideally, we look here for SPI interfaces in the OBC. Since almost every OBC here has an SPI interface, we rank versatility by total number of I/O streams. Complexity is dictated by the typical software used for programming. Power consumption is dictated by equation 3. Processing power is determined by internal clock speed. Cost is determined by the average cost between commonly used parts. For size, we only differentiate between items roughly the size of a typical printed circuit board (PCB), or the size of a typical integrated circuit (IC), like an op-amp.

Metric	Weight	FPGA	Microcontroller	PCB Computer
Versatility	0.3	5	5	3
Size	0.2	1	5	1
Cost	0.2	3	5	1
Complexity	0.1	1	5	3
Processing Power	0.1	3	3	5
Power Consumption	0.1	5	3	1
Total	1.0	3.2	**4.6**	2.2

Table 25 On-Board Computer Trade Study Results

4. External Storage Options

Metric	**Weight**	**Driving Requirements**	**Description and Rationale**
Computer Compatibility	0.4	1.0	Similar to the ADC, the memory must be compatible with the on board computer system for reading and writing of data. This joint necessity is shared by the trade study for OBCs. Modern storage requirements should handle our capacity and speed needs readily, so compatibility with the down selected ADC and OBC is most important here.
Storage Capacity	0.2	1.1.3	The memory storage capacity must be able to hold all the gathered data in the time difference between downlink periods.
Read/Write Speed	0.2	1.1.1.1	The memory internal read/write speed must be able to keep up with the ADC's sampling rate requirements, as well as the OBC's transfer requirements.
Size	0.1	4.0	On board storage sizes will be smaller than the OBC, but still not negligible on a PCB where every milimeter will count. Size in the presented storage design options varies significantly.
Cost	0.1	6.0	Memory costs will be lower than the PCB active components, so the weight is lower here. Overall rationale for keeping costs low is described in the photodiode trade study, and is not repeated here.

Table 26 Storage Metrics and Weighting

Metric	**1**	**3**	**5**
Computer Compatibility	Parallel	SPI	SPI & DSP
Storage Capacity	< 64 mB	64-128 mB	> 128 mB
Read/Write Speed	< 100 MHz	100-200 Mhz	> 200 MHz
Size	> 10 mm^2	5-10 mm^2	0-5 mm^2
Cost	> $5	$3-$5	$1-$3

Table 27 Storage Metric Values

Metric	**Weight**	**Flash**	**SRAM**	**DRAM**
Computer Compatibility	0.4	3	1	1
Storage Capacity	0.2	3	1	5
Read/Write Speed	0.2	3	1	5
Size	0.1	5	1	3
Cost	0.1	5	3	1
Total	1.0	**3.4**	1.2	2.8

Table 28 Storage Trade Study Results

B. Optics

1. Photodiode Block Translation Tunability

Metric	Weight	Driving Requirements	Description and Rationale
Material Complexity	0.3	5.2.2	The effects of thermal stresses on complex components are more difficult to control for than on simple components. Components with varying material type are more apt to have mechanical or structural relationship changes when subject to temperature changes than single material components. These changes adversely affect the optical alignment.
Friction Interactions	0.3	5.1.1	Mechanical and structural assemblies held in orientation by friction (e.g. set screws) are prone to change when subjected to vibrational stress. These potential changes in orientation would adversely affect the optical alignment.
Alignment Precision	0.2	3.2.2	NanoSAM I determined acceptable alignment errors last year which informs the metric of Alignment precision. These acceptable alignment errors were found by backsolving MTF estimates to ensure a particular error resulted in a minimum MTF of 0.74. As NanoSAM II's optical design progresses, the acceptable alignment errors may shift, but NanoSAM I's calculations offer a reasonable estimate.
Cost	0.1	6.0	The successful translation tuning of the photodiode block to the OAP mirror image is mission critical. However, the least expensive of equal options should be pursued.

Table 29 Photodiode Tuning Metrics and Weighting

Metric	1	3	5
Material Complexity	>3 unique materials	2-3 unique materials	1 unique material
Friction Interactions	Orientation fully dependent on Friction	Orientation dependent on Friction but reinforced with glue	Orientation independent of Friction
Alignment Precision	>25 µm	10 - 25 µm	<10 µm
Cost	>$300	$150-250	<$150

Table 30 Photodiode Tuning Metric Values

Metric	Weight	Shims	Rails	Translation Mounts
Material Complexity	0.3	5	3	3
Friction Interactions	0.3	5	3	3
Alignment Precision	0.2	3	1	5
Cost	0.2	3	1	1
Total	1.0	**4.2**	2.2	3.0

Table 31 Photodiode Tuning Trade Study Results

Information for this trade study came from the specifications provided by the manufacturers, and NanoSAM I's Project Final Report, shown in Sources [43],[44], and [6]. The price of shims are based on NanoSAM I's expense breakdown [6] while the price of rails and translation mounts are based on the estimated number of each component needed multiplied by the unit cost of that component, [43] and [44]. Alignment precision was sourced from [6] for shims, [43] for rails, and [44] for translation mounts.

2. OAP Mirror Selection

Metric	Weight	Driving Requirements	Description and Rationale
Diameter	0.2	3.2.2	A large source of wavefront error (WFE) is due to the anchor points that are used to mount the reflector. The anchors cause the surface of the reflector to deform which contributes WFE as the wavefront is also deformed. A reflector with a larger diameter has the anchor points farther away from the center of the mirror, which is where the light hits it, which means that the center is less deformed. Keeping WFE as low as possible will allow for it to be easier to meet requirement 3.2.2. In order to get a part with the same focal length (FL) and a larger diameter, a custom part would have to be ordered and created as there are not suitable COTS parts that would meet these requirements.
Cost	0.4	6.0	The cost of part is also important as a custom part will cost a significant portion of the budget whereas continuing to use the current OAP mirror will not have any cost associated with it. This will likely be the most prohibitive of the metrics as losing a large chunk of the budget could cause major issues down the line if the team does not have sufficient funding left to complete the project.
Production Time	0.4	1.0, 3.0	A custom part also will take a while to be made, which may cause project delays and will increase the project risk overall as not having the reflector will impact many aspects of the project.

Table 32 OAP Diameter Increase Metrics and Weighting

Metric	1	3	5
Diameter	<20 mm	20-25.4 mm	>25.4 mm
Cost	>$1000	$501 - 1000	$0 - 500
Production Time	61-120 days	30-60 days	0-30 days

Table 33 OAP Diameter Metric Values

A diameter of less than 20 mm is less than nominal as the aperture dimensions are 20mm by 5mm. In essence, this wastes light that is entering the system as some of the light entering the aperture would travel past the OAP. The current OAP has a diameter of 25.4 mm, an FL of 54.45 mm, and an incident-to-reflection angle of 30° and an Aluminum coating [6]. The proposed custom OAP would have a diameter of 38.1 mm, to keep the mirror around the same size, and maintain a FL of 54.45 mm and incident-to-reflection angle of 30° and the Aluminum coating [45],[46],[47]. The cost of using the current OAP is $0 since it was made available from the previous team's inventory. The rough cost estimate received for a custom OAP from Edmund Optics was found to be around $1000-$1200, which is a significant chunk of the team's budget and the production time was estimated to be a 12-17 week lead time. Using this information, the following table was compiled to complete the trade study giving each option values for each metric and computing the weighted average to determine the optimal strategy.

Metric	Weight	Custom OAP	COTS OAP
Diameter	0.2	5	3
Cost	0.4	1	5
Production Time	0.4	1	5
Total	1.0	1.8	**4.6**

Table 34 OAP Diameter Trade Study Results

3. Field Stop Geometry

Metric	Weight	Driving Requirements	Description and Rationale
Field of View	0.4	3.2.1	To meet requirement 3.2.1, the field of view must be 1.3 arcminutes in order to achieve a resolution of 1km. If the field stop is too small to achieve this requirement, the data taken will not meet the minimum accuracy to be useful.
SNR	0.4	2.1	The field stop must let in enough light to allow for a SNR of 3500 or greater in order to satisfy requirement 2.1
Cost	0.1	6	While cost is important, the cost of the field stop is relatively low compared to other optical systems. Therefore, cost is a consideration but is not weighted as heavily as the previous metrics.
Design Complexity	0.1	3	The system designed by NanoSAM I used a pinhole field stop, and so the design is already built for a pinhold field stop. If a pinhole is used by NanoSAM II the design will not need to be changed. If a slit is used the design will need to be modified to account for the change in field stop.

Table 35 Field Stop Metrics and Weighting

Metric	1	3	5
SNR	<3150	3150-3500	>3500
Field of View	<1.3 arcminutes	N/A	>1.3 arcminutes
Cost	> $100	<$100	$0
Design Complexity	Field Stop Redesign	Field Stop Modification	Use previous Field Stop

Table 36 Field Stop Metric Values

NanoSAM I used a 15 μm pinhole, and calculated that this was a sufficient diameter to meet the SNR requirement [6]. The field of view of a pinhole was calculated using the information found in source [48], assuming the same 15 μm diameter pinhole. The pinhole used by NanoSAM I does not meet the 1.3 arcminute field of view requirement. Instead, a 20.6 μm pinhole would need to be used, as was calculated using Equation 2. Because a slit will let in more light that a pinhole, a slit will also meet the minimum field of view and SNR requirements that the pinhole does. Additionally, costs for the pinhole and slit field stops can be found in sources [49] and [50].

Metric	Weight	Pinhole	Slit
Field of View	0.4	5	5
SNR	0.4	5	5
Design Complexity	0.1	4	1
Cost	0.1	4	1
Total	1.0	**4.8**	4.2

Table 37 Field Stop Trade Study Results

C. Structure

1. Structural Material

Metric	Weight	Driving Requirements	Description and Rationale
Cost	0.3	6.0	Cost of the material is a driving factor since the structure is one of the main places to incur costs, especially due to manufacturing hours.
Density	0.3	4.2	The density of the material is directly related to the total mass of the system. In order to reduce the mass of the system, density must therefore be minimized. This assumes that all structures will have approximately the same volume.
Shear Modulus	0.2	5.1	The shear modulus of the material is directly related to its ability to resist deformation, and is critical in damping vibrations encountered during launch.
Coefficient of Thermal Expansion	0.1	5.2	The coefficient of thermal expansion (CTE) is related to requirement 5.2, which indicates that the entire payload shall remain operable over -120 to 120 C. Minimizing the CTE will reduce the effects of thermal swings and provide a more consistent structure for the payload.
Availability	0.1	5.0	The availability of materials is a driving metric separate from cost. The reason for this is that a material should be readily available in order to facilitate the completion of the project on time.

Table 38 Material Metrics and Weighting

Metric	1	2	3	4	5
Cost	>3.52$/$in^3$	3.52-2.82$/$in^3$	2.82-2.11$/$in^3$	2.11-1.40$/$in^3$	<1.40$/$in^3$
Density	>2.78g/cc	2.78-2.75g/cc	2.75-2.73g/cc	2.73-2.70g/cc	<2.70g/cc
Shear Modulus	<26.0 GPa	26.0-26.2GPa	26.2-26.4GPa	26.4-26.6GPa	>26.6GPa
CTE	>23.02 $\mu m/mK$	23.02-22.68 $\mu m/mK$	22.68-22.34 $\mu m/mK$	22.34-22.00 $\mu m/mK$	<22.00 $\mu m/mK$
Availability	Not Widely Available and/or not in form factor needed	N/A	Widely Available, but not in form factor needed	N/A	Widely Available and in form factor needed

Table 39 Structural Material Metric Values

Cost was determined based on the cost of the material per cubic inch, in the bar size closest to .25"x1"x12". After finding all costs, the range is binned into five groups, these bins form the five metrics. A similar method was repeated for all metrics with numerical values. The metrics for availability were based on previous experience with ordering parts.

Metric	Weight	Al 7075	Al 6061	Al 5005	Al 5052
Cost	0.3	1	5	3	2
Density	0.3	1	4	4	5
Shear Modulus	0.2	5	2	1	1
CTE	0.1	1	1	5	4
Availability	0.1	5	5	3	4
Total	1.0	2.2	**3.7**	3.1	3.1

Table 40 Material Trade Study Results

2. Integration of Internal Components

Metric	Weight	Driving Requirements	Description and Rationale
Thermal Isolation	0.25	5.2	A mounting method that thermally isolates the key components from the rest of the structure will help to meet requirement 5.2, as it will facilitate the use of resistive heaters or other elements to reduce the temperature variation due to conduction on orbit.
Vibration Isolation	0.25	5.1	A mounting method that reduces vibrations that reach the optics helps to meet requirement 5.1.1 in particular; reducing these vibrations will help to prevent misalignment in the optics.
Availability	0.2	6.0	Using widely available components that have been demonstrated to be useful for the desired application reduces risk in the project and increases overall confidence.
Modeling Confidence	0.15	5.0	A mount that can be accurately modeled is preferred, as it will increase confidence in simulations.
Probability of Success	0.15	5.0	A mount that is proven and has few points of failure is preferred.

Table 41 Internal Integration Metrics and Weighting

Metric	1	3	5
Thermal Isolation	Provides no thermal isolation	Provides minimal thermal isolation	Provides a significant amount of thermal isolation
Vibration Isolation	No vibration isolation	Isolation in less than three degrees of freedom	Isolation in three degrees of freedom
Availability	Needs to be designed in-house	Demonstrated, but needs additional work to implement	Commercially available off the shelf
Modeling Confidence	Cannot be accurately modeled without major simplifications	Can be modeled with a few simplifying assumptions	Can be modeled with high fidelity
Probability of Success	Several points of failure and low technology readiness	Several points of failure but can be mitigated	Few points of failure and can be readily tested/replaced

Table 42 Structural Internal Integration Metric Values

The above table for the internal mounting method describes many qualitative metrics, which is necessary since some of the mounting methods are speculative and would need to be designed by the structural team. As such, many of the metrics are presumptive and chosen with the intent to determine if the potential cost of designing a mounting method would be acceptable. Cost was not a differentiating factor, as the team expects all methods to have about the same cost. Instead, the normal cost considerations are included in availability and probability of success.

Metric	**Weight**	**Direct Mount**	**Spring Mount**	**Shock Mounts**
Thermal Isolation	0.25	1	5	5
Vibration Isolation	0.25	1	5	3
Availability	0.2	5	5	1
Modeling Confidence	0.15	5	3	3
Probability of Success	0.15	5	3	2
Total	1.0	3.0	**4.4**	2.95

Table 43 Internal Integration Trade Study Results

D. Software System

1. Data Capture Timing

Metric	**Weight**	**Driving Requirements**	**Description and Rationale**
Timing Accuracy	0.8	1.1.4, 1.2.1	The ability to maintain an accurate data collection window over several hundred orbits will assure that data is reliably captured, while maintining a consistent data capture window duration will simplify the storage and transmisson processes. Reliable data capture is at the core of NanoSAM II's mission and is thus accurate timing is weighted highly.
System Resource Use	0.2	1.1.1.1	The usage of onboard memory and computation time must be optimized such that data can be processed at a minimum sample rate of 50Hz given by Requirement 1.1.1.1. Excess memory usage may unnecessarily increase the frequency of single event errors, potentially compromising data quality.

Table 44 Data Capture Timing Metrics and Weighting

Metric	**1**	**3**	**5**
Timing Accuracy	Collection window is prone to drift over time, potentially resulting in a total loss of science data	Data collection process may be susceptible to partial data loss over time	Data collection process is not susceptible to data loss.
System Resource Use	Resource load could necessitate a reduction in data processing speed	Resource load is nontrivial but unlikely to affect data processing speed. Additional storage space may be required	Resource use is trivial

Table 45 Data Capture Timing Metric Values

Metric	Weight	Continuous Data Collection	Integrated clock with calibration via photodiode
Timing Accuracy	0.8	5	3
System Resource Use	0.2	5	5
Total	1	**5**	4.6

Table 46 Data Capture Timing Trade Study Results

2. Calibration Method

Metric	Weight	Driving Requirements	Description and Rationale
Downlink Data Volume	0.7	2.3	Transmission of unnecessary information will inflate the data volume of each downlink, potentially increasing transmission time and the volume of transmission errors.
System Resource Use	0.3	1.1.1.1	The usage of onboard memory and computation time must be optimized such that data can be processed at a minimum sample rate of 50Hz given by Requirement 1.1.1.1. Excess memory usage may unnecessarily increase the frequency of single event errors.

Table 47 Calibration Method Metrics and Weighting

Metric	1	3	5
Downlink Data Volume	Method adds significant data volume to downlink	Method adds some additional data to downlink	No additional data is included in the downlink
System Resource Use	Resource load could necessitate a reduction in data processing speed	Resource load is nontrivial but unlikely to affect data processing speed. Additional storage space may be required	Resource use is trivial

Table 48 Calibration Method Metric Values

Metric	Weight	In-Situ	Via Ground Equipment
Downlink Data Volume	0.7	5	3
System Resource Use	0.3	3	3
Total	1	**4.4**	3

Table 49 Calibration Method Trade Study Results

3. Error Detection Method

Metric	Weight	Driving Requirements	Description and Rationale
Maximum Correctable Error	0.35	1.3, 2.0	Uncorrected single event upsets in programming variables could cause software systems to malfunction and fail, thus it is essential that the error detection method includes some degree of error correction.
Maximum Detectable Error	0.3	1.3, 2.0	Error detection is required both for data transmission and memory to catch and ignore corrupted data packets which could compromise data quality and software operations.
System Resource Use	0.2	1.1.1.1	The usage of onboard memory and computation time must be optimized such that data can be processed at a minimum sample rate of 50Hz given by Requirement 1.1.1.1. Excess memory usage may unnecessarily increase the frequency of single event errors.
Downlink Data Rate	0.1	2.3	The ratio of total transmitted data that is not redundant. A low data rate may unnecessarily increase the size of each downlink.

Table 50 Error Detection Method Metrics and Weighting

Metric	1	3	5
Maximum Correctable Error	None	1 bit	> 1 bit
Maximum Detectable Error	1 bit	2 bits	> 2 bits, potentially burst errors
System Resource Use	Resource load could necessitate a reduction in data processing speed	Resource load is nontrivial but unlikely to affect data processing speed. Additional storage space may be required	Resource use is trivial
Downlink Data Rate	<50%	50% - 95%	>95%

Table 51 Error Detection Method Metric Values

Metric	Weight	Longitudinal Redundancy Check	Cyclic Redundancy Check	Hamming Code	Repetition Code
Maximum Correctable Error	0.35	1	1	3	5
Maximum Detectable Error	0.3	5	5	3	5
System Resource Use	0.25	3	3	5	1
Downlink Data Rate	0.1	3	5	5	1
Total	1	2.9	3.1	**3.7**	3.6

Table 52 Error Detection Method Trade Study Results

E. Payload Integration

Metric	Weight	Driving Requirements	Description and Rationale
Flexibility	0.3	4.0, 5.0	The ability for one design to be integrated in many systems or easily adapted. The more documentation provided and the closer to an industry standard one design method presents will have the better score.
Reliability and Uncertainty	0.2	Class timeline	Flight heritage and thorough documentation provide reliable information that will allow the team to complete the necessary design in the timeline of the class.
Required Research	0.2	Class timeline & 4.3	Design options must be readily available so that focused design can begin.
Customer Input	0.3	4.3	What are the goals of the customer and are they realistic with the timeline of the class.
Cost	0.1	6.0	In this stage of the design process, no money is anticipated to be spent on integrating the payload with an external bus. However, it is still an important factor to consider when deciding which design option is best.

Table 53 Payload Integration Metrics and Weighting

Metric	1	3	5
Flexibility	No ability to change current design	Some freedom to re-design	Complete freedom to re-design and optimize
Reliability and Uncertainty	Many unknowns regarding to timeline, resources, or availability	Less unknowns and more physical information readily available	Little to no unknowns regarding the timeline, available resources, and availability
Required Research	Requires lots of research and time to find actionable design options	Less research needed to find design options	Little research required to gather clear design options
Customer Input	Customer gives no direct instruction on integration	Customer has some information and definition about interfacing	Clear design requirements for payload integration
Cost	Cost is very large and way outside the scope of this project	Cost is more reasonable but requires most if not all the budget	Does not require all the budget and reasonable

Table 54 Error Detection Method Metric Values

Metric	Weight	Single Commercial	Joint Commercial	Single Team Built	Joint Team Built
Flexibility	0.4	4	2	5	3
Reliability and Uncertainty	0.2	4	1	3	1
Required Research	0.2	3	1	2	1
Customer Input	0.3	3	2	3	2
Cost	0.1	1	2	1	3
Total	1.0	**4**	2	**4**	2.5

Table 55 Payload Integration Trade Study Results

The weights for each metric are given above in table 55. Metric weights ranged from 0.1, the lowest, to 0.4, the greatest. Each metric was weighed based on its importance to mission success. For example, the flexibility of the design was given the highest weight. Flexibility in this section refers to how robust the design choice is to change and how easily the design could be altered in case re-designs were required. The lowest weight was given to cost. Since the project has a budget this year of $5,000, most of the bus system components lie outside the scope. The team will not be focusing design time towards the development of a spacecraft bus and therefore, purchasing/building/contributing to a bus will not happen this year.

Each design option, single commercial, joint commercial, single team built, and joint team built, were all given a numeric score from 1-5 on how well that design option fulfills the metric; 5 being the highest score. The results of the payload integration trade study can be found in table 55. The results indicate that the team should pursue a design option of either a future team commercially buy a spacecraft bus system or a future team build a design. In review, the reason the "tag-along" options got low scores for reliability and uncertainty is because there are too many unknowns for this type of a design. The amount of research needed to find a mission compatible with NanoSAM, the available resources and budget, and unknown development timelines makes this design option far less desirable than the latter. There is too much uncertainty in finding a good mission in time. We cannot wait to see if a good mission will appear in our research. We must have the ability to design in the near future and there are options available now that will provide high flexibility and reliability. Without specific guidance from the customer on this year's project integration, the team has to decide on the scope of the NanoSAM II project. This is another reason why the two design options, commercially bought and team built, had the best scores in the trade study.

VI. Selection of Baseline Design

A. Electronics System

Trade studies were performed on four essential elements of the electronics system: the photodiode, the analog to digital converter, the on board computer, and the external storage. We note that these trade studies, and their results, are closely related to the trade studies performed by the previous year's team. The purpose of this was two fold: because the current electronics design poses no major issues, the trade studies were taken to help validate maintaining current design element, but additionally, these trade studies allow a redesign to focus on individual part selection and sizing. Although the element categories have the same results, redesign efforts will likely end up with different individual part selection based on the need to reduce the board size in a new structural configuration, and from the effort to improve electrical characteristics of the overall system.

Photodiode Selection

The selected trade study option for the photodiode will be a silicon photodiode running on a photoconductive system. As expected, silicon's low dark current, high responsivity, and low cost make it ideal to collect strong data within the program budget. The differences between the photoconductive and photovoltaic system are small, but the photoconductive system will provide better responsivity and result in a more straightforward circuity design. The downside to silicon is that the wavelength range is typically more suited for smaller wavelengths than 1030 nm, so depending on the signal to noise ratio achieved in other parts of the circuit and the available budget, the team should not be opposed to exploring the InGaAs photodiode.

ADC Selection

The selected trade study option for the analog to digital converter will be the sigma-delta type. Sigma-delta ADCs typically offer most resolution at similar price ranges over the other ADCS, at a relatively low power consumption and size. They offer good compatibility with a serial programmable interface, and have more than enough conversion speed to meet design requirements. Although the do cost more on average than the other variants, they are not expensive compared to the electronics system at large, and the increase in quality and signal to noise ratio from the larger resolution is worth the cost.

On Board Computer Selection

The selected trade study option for the on board computer will be the microcontroller. This is the expected outcome for a student project, and matches a variety of other CubeSat projects that members of the team have had experience in. Both FPGA's and full single board computer systems are too costly, especially since the ones with good flight heritage are often thousands of dollars. The complexity to code of the FPGA's puts them outside of the design scope with the number of other elements to work on between the electronic and software designs. Microcontrollers provide great versatility, working with the ADC and external memory selections, easily interfacing with a laptop for ground testing, and provide solutions to standard bus interfacing for future teams. They are also small, cheap, and require low power, making them perfect for small CubeSats that seek to perform in constellations.

External Storage Selection

The selected trade study option for the on board computer will be flash memory. Flash is reliable, cheap, provides large storage, and easily meets our speed requirements. Flash memory has flight heritage both in external storage, as well as on most radiation hardened on board computers. It can easily interface via SPI, making it perfect for redundancy and communication with the microcontroller.

B. Optical System

NanoSAM II will build off of the system designed and built by NanoSAM I. In order to reduce cost and logistical risk, NanoSAM II will reuse several parts ordered by NanoSAM I. New components will be added in order to improve the alignment and the alignment process.

Photodiode Block Translation Tunability

In order to tune the Photodiode Block Translation, the trade study demonstrated shims to be the optimal design choice. Shims can be made of a single material which reduces thermal deformation uncertainty. Additionally, shims do not rely on friction interactions, which could be disrupted when subjected to vibrational stress. Shims are not quite as precise as translational mounts, but the disadvantage here is outweighed by the low material complexity and lack of friction interactions. Shims are a less expensive tuning method than rails or translational mounts which further reinforces the results of the trade study.

OAP Mirror Selection

There were two options for the OAP mirror diameter: to continue using the OAP mirror ordered by NanoSAM I or to replace it with a custom OAP mirror with a slightly larger diameter in order to reduce wave front error resulting from the slight deformation due to the mirror's mounting points. The NanoSAM I OAP mirror is available immediately at no cost, while a custom mirror was estimated to be around $1200 (more than a fifth of NanoSAM II's budget), and to have a 12-17 week lead time. Even though a custom OAP mirror could improve the quality of optical measurements, the cost and lead time of attaining one prohibits this option. Therefore, NanoSAM II will be using the OAP mirror purchased by NanoSAM I.

Field Stop Geometry

Two field stop geometries were considered, that of a pinhole and that of a slit. NanoSAM I used a 15 μm pinhole, that was calculated to meet a satisfactory intensity for the functional requirement of SNR. However, a 120 μm pinhole will be needed to meet the required field of view of 1.3 arc minutes. Because a slit will let in more light than a pinhole, a slit will also meet the requirements for SNR and field of view. Therefore, the decision came down to design complexity and cost. The system designed by NanoSAM I is already designed for a pinhole field stop requiring no major changes to the overall design. A new pinhole of the appropriate size (20 μm) will need to be purchased, but will be less expensive that purchasing a slit field stop. In contrast, NanoSAM II would have to buy a slit, which is about twice the cost of a pinhole, and adjust the optical system to account for a slit instead of a pinhole. These factors make a pinhole the optimal design choice, because it meets the necessary optical requirements with minimal additional cost and design complexity.

C. Structure

Trade studies were performed on two essential elements of the structural system: the main material used for the structure, and the primary method for mounting the internal hardware. These trade studies were motivated by the functional requirements of the structural system, which drove design options that were compatible with the thermal and vibrational requirements to be selected.

Material Selection

The selected trade study option for the main structural material is Aluminum 6061, which is commonly used in student-built projects for similar applications. Due to its widespread availability, low cost, and lower density, it edges out over the other Aluminum alloys.

Integration of Internal Components

The selected trade study option for the primary method for integration the internal components is a spring isolator mount, which is selected based on its ability to provide thermal and vibrational isolation while still maintaining lowered costs and confidence of success. Additionally, these mounts are commercially available, which reduces the engineering strain and time on the structures team.

D. Software System

NanoSAM II will feature a much expanded software system compared to that of NanoSAM I, adding data capture capability for both sunrise and sunset, as well as a more robust error detection system for onboard data storage and transmission. The primary functions of the software system include data capture, instrument calibration, data storage, and data transmission. From these functions, three critical design choices were extracted.

Data Capture Timing

Continuous data collection was chosen primarily for its robustness when faced with variations in the time of sunset and sunrise. Timing the data capture window via the integrated clock may provide a similar level of timing precision, but the accuracy of the timing may become compromised if the software must pause for any reason, affecting subsequent data capture windows. Though continuous data collection utilizes extra data storage, a buffer of approximately 60 seconds of data is more than sufficient, corresponding to approximately 5kB at the minimum sampling rate and precision.

Calibration Method

Calibration will be performed by software onboard the instrument prior to data transmission. This method will not consume significant system resources and is preferable to performing calibration with ground equipment as it reduces the number of data types that must be stored and transmitted.

Error Detection Method

Hamming codes will be used as the primary method of error detection and correction. While Hamming codes do not always detect burst errors, they are capable of detecting and correcting single bit errors, which account for the majority of single event errors [37]. Hamming codes are thus suitable for use in both data transmission and data storage.

E. Payload Integration

The results of the payload integration trade study are shown in Table 55. Two design considerations were found to have equal merit. These design options were a single mission with either a commercially bought cubesat or team built cubesat. However, after connecting with a representative with Blue Canyon Technologies and discussing the possible options with our customer, the team has decided that the single mission with a commercially bought cubesat would allow for the most flexibility in designing the NanoSAM II payload. Pursuing this path will also enable clear requirement definitions for this year's design instead of having to define for a range of possible busses.

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