University of Colorado Boulder

Department of Aerospace Engineering Sciences

NanoSAM - Project Definition Document

ASEN 4013 - Senior Design

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Approvals

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I. General Information

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II. Problem, Need, & Purpose

The goal of the Nano-Stratospheric Aerosol Measurement (NanoSAM) project 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 manned aircraft. High aerosol concentration is also an indication of poor air quality that could affect human health. On a larger scale, aerosol concentration is used to measure the radiative balance of the Earth which has implications on Earth's climate and environmental change. A more advanced particle detection system known as SAGE II (an evolution of the SAM system) was able to determine the cause of the depletion of the ozone layer and led to the banning of CFCs (chlorofluorocarbons) allowing the Antarctic ozone to recover.

NanoSAM seeks to use solar occultation to measure the aerosol concentrations, similar to SAM-II. 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]. However, this project will be scaled down such that the measurement devices can be launched in a constellation of CubeSats to increase the resolution of the data and produce more accurate models. The NanoSAM CubeSat is designed to weigh 1.33 kg, significantly less than the current SAGE-III system which weighs 473 kg and is the latest evolution of the initial SAM system. Furthermore, if the NanoSAM CubeSat can meet or exceed the technical specifications from SAM-II, which already produced scientifically valuable data, then it can be assumed that the NanoSAM CubeSat will also produce valuable data.

The 2020-2021 NanoSAM team will work together with Ball Aerospace Corporation to build off of the previous year's design, with the overall goals of improving the optical resolution and making the system space flight ready. The refined optical system will detect wavelengths of light corresponding to aerosols specifically while operating in conditions experienced in low earth orbit. The team will develop modifications to the electronics board and optics subsystem as required to meet this optical improvement.

In order for the system to be space-flight ready, it must be able to survive fluctuations in temperature, function in a vacuum, and produce measurements with an improved signal to noise ratio from the previous NanoSam team's design. Furthermore, supporting software will be improved as required to verify that it can acquire, digitize, packetize, and download this data to a computer during testing. Additional software will be developed as required for further flight testing. A flight ready housing that supports the fully integrated payload will be designed, built, and tested, improving on the previous housing design that was built for ground testing. Overall, the deliverables for this project will be the refined optical system, electronics system, the software needed to operate NanoSAM, and payload integration in a validated, flight capable enclosure.

III. 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 [1]. SAGE-I capabilities were improved upon with the SAGE-II project, which used a spectrometer to measure aerosol concentration across seven different wavelengths. 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 [1]. Although a successful project, the SAGE-III instrument is large, expensive, and has a small data density for measurements, collecting only 30 aerosol measurements per day [9].

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 that allows for greater data density while collecting aerosol concentration profiles in the upper stratosphere. SAM-II measured aerosol concentrations aboard Nimbus-7, which had an altitude of 950 km with an orbital period of 104 minutes [6]. 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 [7]. SAM-II collected light intensity data with a bandwidth of 0.038 μm at a sample rate of 50 Hz [7]. 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 NanoSAM was done by the University of Colorado NanoSAM 2019-2020 senior project team. The 2019-2020 NanoSAM project team designed a system to measure aerosol concentration in the stratosphere, but stopped short of designing a flight-ready system. Progress was interrupted by the 2020 pandemic before validation testing could be performed [9]. Among the main subsystems in the project (electronics, hardware, software, and optics), the previous team held their heaviest focus on optics. This means the requirements for this previous project were focused almost entirely around the functionality of the optical system. These requirements included successful solar irradiance data collection, achieving a specific signal to noise ratio threshold, and collecting accurate data with a particular vertical resolution. The 2019-2020 team succeeded in creating and manufacturing 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) [9] 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 the electronic board's analog to digital converter and the optical system's pinhole alignment. Across the board, project systems were not completely validated before the end of the academic year due to the global pandemic.

IV. Specific Objectives

Specific objectives of the project are the tasks and specifications that the NanoSAM project seeks to meet for a successful mission. These objectives are broken into three levels of success to support the NanoSAM project requirements and build from similar project elements as the previous year's project.

	Level 1 (NanoSAM 2019-2020 Solar Test)	**Level 2** (Improved Ground Performance)	**Level 3** (Flight Capability Testing)
Optics	The optics design is improved to perform the NanoSAM 2019-2020 solar tracking test while matching SAM-II performance measures.	The optics alignment and focus are improved while matching SAM-II performance measures. These exact improvements will be selected through trade studies.	The improved optics are functional across the entire operating temperature range (TBD). Optical testing following vibration testing shows that the instrument matches SAM-II performance measures.
Payload Housing	The payload housing contains the fully integrated electronics board and optical bench, both of which fit inside a 1.5U CubeSat enclosure.	The payload housing supports the fully integrated payload being successfully mated within industry standard bus ICD specifications.	The payload housing stays within the operating temperature range (TBD) and does not encounter resonant frequencies during vibrational testing.
Data Capture	Supporting electronics and software acquires, digitizes, packetizes, and downloads raw data from a photodetector to a computer.	Same as level 1	Supporting electronics and software acquires, digitizes, packetizes, and downloads raw data from a photodetector to a computer. Data can be transferred from the payload to an industry standard CubeSat bus RF/comms system, within ICD specifications. [3]
Electronics & Control	The redesigned electronics board has a compatible analog to digital converter and successfully controls and powers all on-board operations.	The redesigned electronics board supports optical improvements, and is composed of radiation hardened components.	The redesigned electronics board stays within the operating temperature range (TBD), and does not encounter resonant frequencies during vibrational testing.

Table 1 Specific Objectives

Many of the level three objectives from the previous team have been moved to level one (or even below level one) due to the significant progress that has been made on these objectives despite the lack of testing performed. This year's team has added new project elements that correspond to additional design work that will be performed. Thus, level one requirements are those that must be completed for the NanoSAM project to meet the previous year's goals, with the addition of designing a payload housing and fully-functional electronics board. 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 to finalize the design choices necessary to meet the 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. Finally, the insight gained from testing the first two levels will help the team develop strong test procedures for environmental requirements. These environmental tests will 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 validate the level three flight capable objectives.

Finally, the optics performance is largely based on the performance of SAM-II (discussed in Section III). Since NanoSAM is designed to be a CubeSat-sized payload with similar capabilities to the much larger SAM-II, it is essential that NanoSAM possesses the same capabilities as SAM-II. Therefore, the first specific objective is well-defined by SAM-II metrics [9] which have informed Functional Requirements 0.3 and 0.4 in the next section. The specifics of the improvements to be made will require trade studies to narrow down, and will be completed during the next design phase.

V. High Level Functional Requirements

The following high level functional requirements are derived from the specific objectives laid out in section IV. In subsequent documents, these requirements will be elaborated on further in a hierarchical organization to flesh out their specificity and ensure that the system performance can be verified. The goal of these functional requirements is to leave no specific objective uncovered.

Number	**Name**	**Requirement Description**
0.1	Data Capture	The supporting electronics and software shall digitize and packetize information collected from the photodiode, downloading it to on-board storage.
0.2	Communications	The supporting electronics and software shall communicate digitzed data to a ground computer for testing, and to a standard bus ICD system for downlink during on-orbit operations.
0.3	Monochromatic Imager	The optical device implementation collects data on the aerosol density in the stratosphere from the wavelength desired while achieving an MTF of at least 0.74 after manufacturing and alignment.
0.4	Vertical Resolution	The optical design shall have a vertical resolution 1 km or less
0.5	Tracking Accuracy	The solar tracking ground test shall demonstrate TBD accuracy in Sun tracking from the ground
0.6	Payload Size	The payload shall fit inside of a 1.5U CubeSat
0.7	Flight Testing	All payload components shall maintain their design requirements through thermal, vacuum, and vibration testing

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 requirements 0.3-0.5 relate to a successful design on the optics system, meeting the SAM-II performance and improving it. An explanation of these three requirements is given below.

The modulation transfer function (MTF) is a mathematical construct that represents the relationship between the resolution and contrast of an image produced by an optical system. Specifically, an MTF is the plot of the measured contrast of an optics setup over the space of resolutions [11]. The MTF is dependent on the wavelength of the incident light and the focal ratio of the optical setup. Generally, a shorter wavelength or a smaller focal ratio reduces the slope of the MTF curve which increases the contrast at a given resolution.

Resolution is typically measured in units of length or "lp/mm," line pairs per millimeter. Line pairs are adjacent sets of black and white lines that can be used as a standard when performing MTF characterizations. Contrast is measured on a unitless scale from 0 (0% contrast) to 1 (100% contrast). A measurement of 0 at a particular resolution means none of the contrast information was collected; a measurement of 1 at a particular resolution means that all contrast information was collected [4].

The 0.74 MTF value was determined by the previous year's team to best imitate SAM-II functionality at a 1 km vertical resolution [9]. The values ensures sufficient spatial resolution. The 1 km vertical resolution was chosen to imitate SAGE-II functionality [10]. The tracking accuracy of the NanoSAM testing will depend on design choices made, but it will need to follow the path of the sun to take measurements. A completed NanoSAM in space will have tracking performed by the industry standard bus.

Lastly, functional requirements 0.6 and 0.7 relate to the level three specific objectives of a flight capable payload. For this project, the payload will fit in a 1.5U package, or 10 cm x 10 cm x 15 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. These functional requirements also lead to the need for flight testing, including thermal range, vacuum testing, vibration endurance, and radiation. For a successful payload in a CubeSat, the space environment must be accounted for in order to create a robust design. For the scope of this project, the NanoSAM payload will include space qualified components and will be tested for functionality through vibration and thermal testing.

A. 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. However, the 2020 mission was only designed to perform on the Earth's surface, while this year's project will be designed to carry out the desired operation in space.

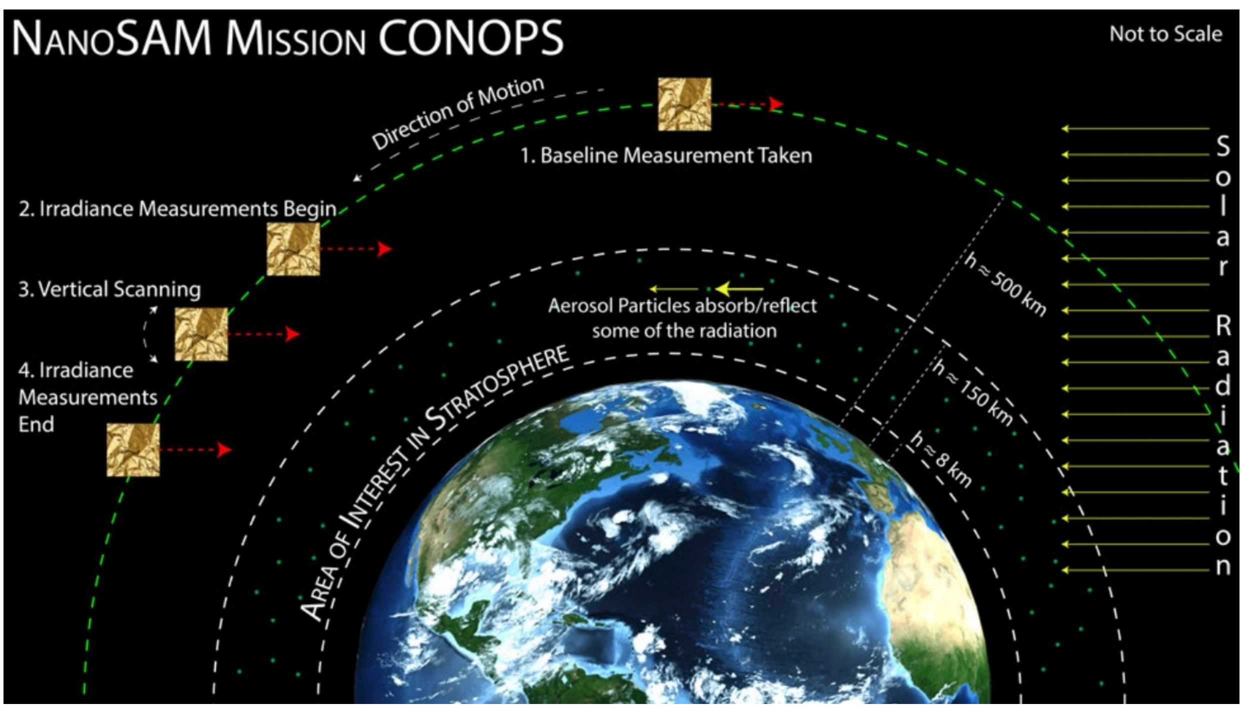

Fig. 1 2019/2020 NanoSAM team CONOPS

VI. Critical Project Elements

These elements are the physical pieces of the NanoSAM project that are critical to success of the specific objectives laid out in section IV. Table 3 lists the elements and describes potential technical, logistic, and financial constraints that the team must address. These project elements are specifically used in following sections to ensure the team has the knowledge and resources to tackle them.

Number	Name	Element Description
E1	Previous NanoSAM Test	The solar tracking test was planned by the previous NanoSAM team and is necessary to verify that the operational capabilities of the electrical and optical systems meet solar irradiance, instrument SNR, data capture and optical quality requirements. The solar tracking test will require an flat, open area and a clear, mostly sunny day, such that the data can be most representative of the data that might be attained in an orbit. The team will utilize previous testing hardware to complete this test early in order to validate design decisions of the previous payload.
E2	Optical Bench and Radiometer	The Optical Bench is the central structure that holds and aligns NanoSAM's Radiometer, the optical instrument which measures the intensity of a particular wavelength(s) of incident light. In order to improve these components, the previous Optical Bench and Radiometer must be realigned and tested in order to set baseline requirements for a redesigned Optical Bench and Radiometer. Optically-purposed facilities to realign the optical system are difficult to find due to current circumstances. Therefore, additional planning will be required to successfully align and test the design.
E3	Electronics Board	Previous 2019-2020 testing showed that the ordered electronics board had issues with its analog to digital converter. A redesign of the electronics board to fix previous issues, and to meet needs from any optical improvements will be critical to a fully working payload. This redesigned board will also be improved with radiation hardened components to facilitate flight readiness. The solar tracking test will help us pinpoint flaws in the current design, and further integration tests during the Spring semester will validate the redesign. Of logistical concern is the need to order electronics parts early due to backlog and slower shipping caused by the pandemic.
E4	Flight Software	Software was previously created for the solar tracking test, but was not tested. There will likely be a need to improve software before running that test, and fix bugs encountered during early test runs. An electronics board redesign may also prompt a full redesign in testing software if the microcontroller is changed. Depending on typical bus ICD specifications, the team may need to design software to communicate with bus systems, including transfer of data from flash storage on the electronics board to a downlink system on the bus. It will be important for the team not to underestimate the need for strong software in a project that will be mostly dominated by physical design work.

Table 3 Critical Project Elements [1 of 2]

Number	Name	Element Description
E5	Integrated Enclosure	In order for the NanoSam to be flight ready, it must have housing designed such that the overall housing fits in a 1.5U enclosure. Also the electronics must be able to integrate with the already established CubeSat communication, power, and attitude control systems. This may require identifying an industry standard bus and obtaining its ICD specifications or finding another CubeSat mission that the NanoSAM can be integrated to be a part of. Both of these options will likely require a significant time and monetary commitment in the case where an industry standard CubeSat needs to be purchased/built. Once again, due to the nature of the pandemic, it may be difficult to perform any integration testing with an actual bus.
E6	Enclosure Testing	Vibration testing will be necessary to verify the flight capable enclosure requirement as well as ensure the mirror and optical equipment remains sufficiently aligned after a launch into space. Similar to the vibration testing, the flight capable enclosure must undergo thermal testing to verify that systems remain inside their operating temperature range during on-orbit operations. Equipment for these tests may be difficult to find and book for use due to the current pandemic, so it is key that a suitable testing plan is established early on.

Critical Project Elements [2 of 2]

VII. Team Skills and Interests

Critical Project Element	Team member(s) and associated skills/interests
E1: Solar Tracking Test	Jashan Chopra: test procedure generation, data analysis, thermal chamber testing Emma Tomlinson: test procedure generation, data analysis, test equipment manufacturing Axel Haugland: Test procedure generation, test data analysis Ryan Smithers: Interested in test design, implementation, and data analysis Abigail Hause: Interest in test procedure generation and data analysis
E2: Optical Bench	Emma Tomlinson: Experience in machining and manufacturing, interested in optical design Jackson Kistler: Interested in optical engineering, optical physics, and space instrumentation in general David Perkins: Some experience with basic optics, interested in scientific optics for use in space. Ryan Smithers: Interested in optics and its applications to spaceflight Abigail Hause: Interested in optics and use in satellite data collection Daniel Wagner: Interested in optical design, interested in learning Zemax Optical Design Software and alignment processes
E3: Electronics Board	Jashan Chopra: analog & digital mechanics, Eagle PCB design, soldering, previous work on CIRBE CubeSAT circuits Daniel Barth : Interest in electronics design Ryan Smithers: Has experience with digital electronics Daniel Wagner: Experience in PCB design and construction, Experience in photoelectric circuits
E4: Flight Software	Jashan Chopra: MATLAB, python, ruby, unit testing, ground system telemetry and commanding, 1.5 years industry work in software Jaret Anderson: C, Python, MATLAB, Software V&V industry experience Donavon Schroeder: C++, MATLAB, ADCS flight software for MAXWELL/COSMO Daniel Barth : C++, Matlab, Python Jackson Kistler: C, C++, C#, MATLAB, python Axel Haugland: MATLAB, C++, C, Python Ryan Smithers: MATLAB, C, Java, Small amount of Python
E5: Integrated Enclosure	Donavon Schroeder: Industry experience researching and integrating CubeSat subsystems Emma Tomlinson: Industry experience with systems engineering and integration of complex instruments Axel Haugland: Experience integrating and testing subsystems, Experience preparing system for high atmosphere environments David Perkins: Experience/interest in CAD. Ryan Smithers: Experience with CAD (Inventor) Daniel Wagner: Experience with CAD (CSWA) and ANSYS software
E6: Enclosure Testing	Jaret Anderson: TVAC and VAC testing for a BalloonSat payload Daniel Barth: Interested in structural testing and design Axel Haugland: Experience in thermal and vacuum testing. Donavon Schroeder: Interest in thermal and vibration testing. Abigail Hause: Interest in structural and thermal testing Daniel Wagner: Experience in COMSOL, ANSYS simulation softwares

Table 4 Team Skills and Interests

VIII. Resources

Critical Project Elements	Resource/Source
E1: Solar Tracking Test	Jaykob Velasquez and Connor Mcleod are both good resources for determining exactly how the solar tracking test should be performed since the test was formulated by them. No special facilities will be necessary to perform this test. The hardware and software needed to perform this test were created by the 2019-2020 team, and can be accessed by the 2020-2021 team.
E2: Optical Bench	Optical system alignment will likely need to be done at JILA facilities if at all possible due to the current pandemic barring access to Ball's facilities. JILA facilities will provide the necessary interferometer to perform the alignment according to the procedure provided by the previous NanoSam team. Jim Baer and Connor Mcleod will be the primary resources used for verifying the procedures necessary to align the optical system.
E3: Electronics Board	Electronics board redesign likely wont require external resources beyond lab space at CU for final integration of a redesigned board. LASP contains facilities for electronic assembly and testing if more detailed work is required. Jared Catalina, the primary designer of the 2019-2020 electronics assembly, has expressed willingness to provide guidance and support with electronics work.
E4: Flight Software	Similar to the solar tracking test, for verification on flight software Jaykob Velasquez and Connor Mcleod will both be good resources since they have hands on experience with the currently designed software. PlatformIO was used to interface the C++ code with the current hardware components and will likely be required for the initial testing that will be performed like the solar tracking test and also to verify that the integration was successful.
E5: Integrated Enclosure	Obtaining an ICD from Blue Canyon or another source will be possible with the help of Jim Baer. Blue Canyon does work with Ball Aerospace, as well as LASP, so they are familar and friendly with CU research projects. In the case that it is decided to attempt a joint CubeSat mission, many research teams on the CU boulder campus utilize CubeSats so it may be possible to find a TBD source on campus.
E6: Enclosure Testing	Vibration testing could potentially be performed in the PILOT lab on campus, thermal-vacuum testing could also potentially be performed on campus at LASP (Laboratory for Atmospheric and Space Physics)

Table 5 Resources

References

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