NanoSAM IV

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NanoSAM (Nano Stratospheric Aerosol Measurements) is an optical instrument in a 0.5 U CubeSat form factor tasked with measuring aerosol density as a function of altitude within the Earth's atmosphere via solar occultation. This database allows for studies of aerosol changes due to seasonal and short-term meteorological variations, atmospheric chemistry, cloud microphysics, volcanic activity, and other perturbations. Previous iterations have focused on designing the instrument's electronics, optics, reducing the overall dimensions of the instrument, and testing the assembly with vibration analysis. So far, earlier iterations of NanoSAM have neither collected nor reported data; producing useful optical data is the primary goal of NanoSAM IV. This optical data is modeled and predicted to imitate the intensity of the sunlight the instrument would observe in orbit. The light intensity data will be detected through a photodiode, and the output analog signal will then be amplified via a transimpedance amplifier. The analog signal will then be passed through an analog-to-digital converter and finally passed to a computer via USB to store and record data. The entire system's data collection process will be automated to simulate an orbital cycle. This automation will inform the onboard microprocessor when to begin stop data collection. The success of this project is dictated by having repeatable optical data with a signal-to-noise ratio greater than 200.

Nomenclature

	Solar Beta Angle
λ_{680}	Wavelength of 680 [nm]
μ	Gravity Parameter
θ	Allowable Viewing Angle
a	Semi-major axis
AM	Allowable Distance Movement Opposite the Viewing Angle
e	Eccentricity
I	Intensity of Light from LED
i	Inclination
I_{PD}	Photocurrent (i.e. current output of photodiode)
P	Incident light power

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r Distance Between LED and Photodiode

R_f Feedback Resistor

$R\lambda$ Responsivity of Photodiode at a specified wavelength (NOT a resistance value)

S LED Output Power

SNR_{low} bare minimum signal to noise ratio NanoSAM IV must achieve

$theta$ Vector of Offset Angles of Light from LED

V_{ADC} ADC quantization noise

$V_{dark,PD}$ Dark Current Noise (i.e, the noise of the photodiode when no light is incident on the sensor and is dependent on temperature)

$V_{Johnson}$ Johnson Noise of the (largely dependent on temperature and the resistance of the circuit, and is the highest source of noise in the circuit due to a high resistance value)

V_{noise} quadrature sum of $V_{shot,PD}$, $V_{dark,PD}$, $V_{Johnson}$, V_{OpAmp}, V_{ADC}

V_{OpAmp} Noise from the operational amplifier

$V_{shot,PD}$ Photodiode Shot Noise

$V_{signal,desired}$ Desired Voltage signal at ADC

$V_{signal,high}$ Upper limit of ADC voltage signal

$V_{signal,low}$ Lower limit of ADC voltage signal

A	=	amplitude of oscillation
$CU - LATR$	=	Colorado University Light Aerosol Trace Recognition
$NanoSAM$	=	Nano (0.5 U cubesat) Stratospheric Aerosol Measuremnents
ADC	=	Analog-to-Digital Converter
$Beta$	=	Solar Beta Angle
θ	=	Spacecraft altitude angle

I. Introduction

The Colorado University Light Aerosol Trace Recognition (CU-LATR) project is a team of 9 undergraduate seniors at the University of Colorado, Boulder. This project is the fourth iteration of the NanoSAM cubesat project.

The NanoSAM mission is based on placing a Stratospheric Aerosol Measurement (SAM) instrument on a small cubesat in orbit around the Earth. The SAM instrument itself measures and characterizes aerosols present in the Earth's stratosphere. The greater NanoSAM mission CON-OPS is shown in Fig. 1 Reliable and accurate data from an instrument like SAM is incredibly useful to scientists studying the atmosphere and the physical processes leading to the composition of gases in the atmosphere. Having access to readily available and reliable atmospheric observation data is critical in an era of global warming, where climate and atmospheric conditions are changing rapidly.

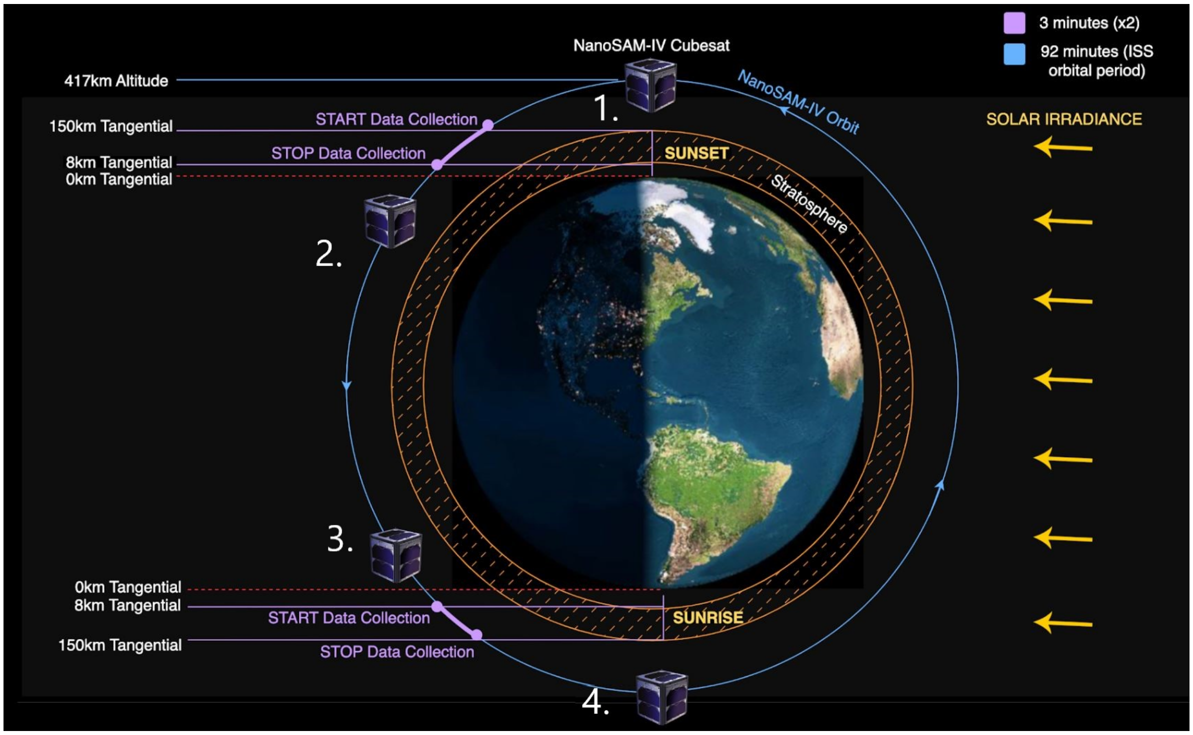

Fig. 1 NanoSAM CubeSat Mission CONOPS

II. Mission

The NanoSAM IV team has been tasked with creating a laboratory simulation of the Ball Aerospace SAM program missions focusing specifically on collecting and processing simulated solar irradiance data at zero aerosol attenuation in an automated fashion. The primary goal of NanoSAM IV is to produce irradiance data similar to the data produced by a SAM instrument on orbit. Previous CU senior project NanoSAM teams have done everything from designing the optical bench of the instrument to vibration testing, however no team has ever collected irradiance data before. The NanoSAM IV design will consist of a laboratory setup with a light source. A model of the NanoSAM IV laboratory benchtop design can is shown in Fig. 2 This setup will serve as a test bench for all necessary components, including electronics and software, designed to achieve the goal of collecting data. The NanoSAM IV designs will be useful in continuing to model and progress the greater NanoSAM mission.

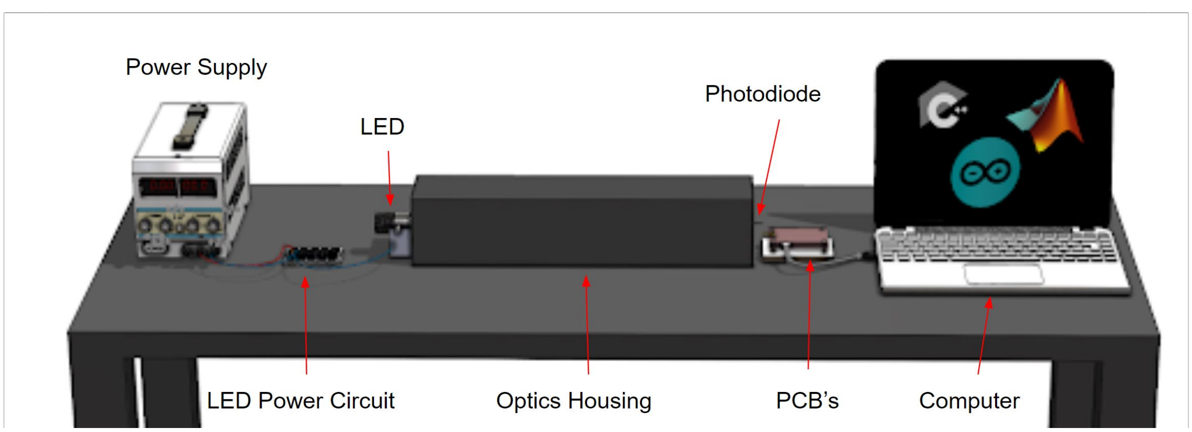

Fig. 2 NanoSAM IV

III. Software

The software team was chiefly tasked with automating the data collection and storage of scientific data via simulated satellite bus. This task breaks down to the embedded system payload being required to take in voltage data representing scientific photodiode/irradiance data from a light source and associated housekeeping data. This analog data must be converted to a digital format and be timestamped, to be sent to the satellite bus for storage and processing. These broad requirements break down further into specific requirements for the software team. These requirements include sending data at 50 Hz rate, creating an orbital model to simulate NanoSAM position on orbit to automate the start and stop of irradiance data collection, detecting when irradiance data drops below a threshold value, stopping data collection when irradiance data is below a threshold value for a set period of time, stopping data collection after a finite period of time, monitoring if we exceed the 8W payload power limit, plotting irradiance, temperatures, and power versus time, and ensuring communication and data flow between the payload and satellite bus.

Based on these requirements, the software design enables back and forth communication of the embedded system through USB protocol. The embedded system is comprised of a Teensy microprocessor which is running code in C++. This code samples data from the ADC and packages into data packets, which will be discussed later. Data is sent over USB which is saved locally as binary data on the computer. Matlab code is also running on the computer which commands the start and stop of data collection.

The functional block diagram of the software is shown in Fig. 3. There are 4 collection modes shown in the software FBD, each serving a different purpose. Mode 1 (M1) simulates a NanoSAM orbit and controls the collection based on orbital position and desired collection windows as shown in Fig. 1. Mode 2 (M2) is just a manual start and stop from the software. Mode 3 (M3) is a manual start, and then commands the embedded systems to stop data collection when the signal falls below a certain threshold. Finally, mode 4 (M4) sends a single command to the embedded systems with a specified amount of time for data collection.

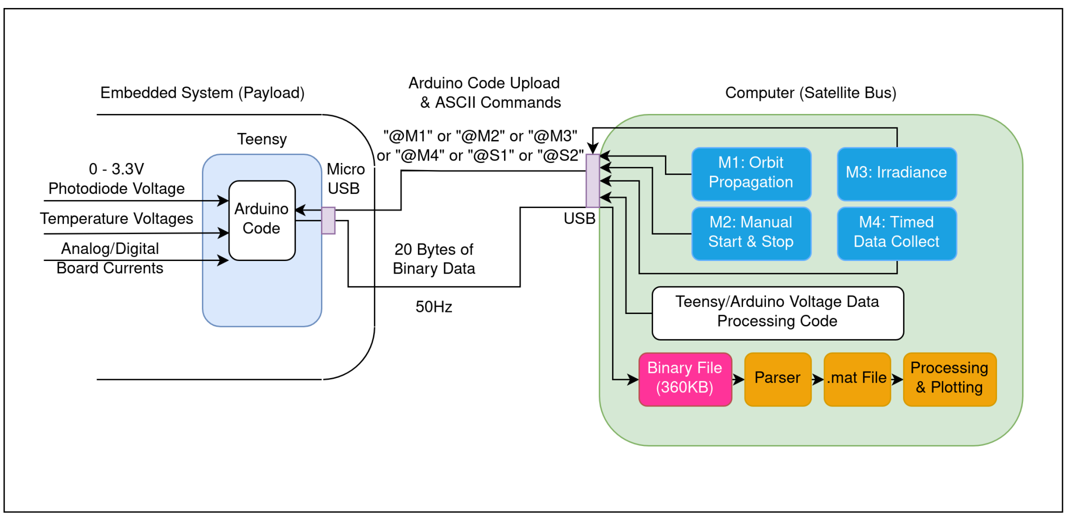

Fig. 3 NanoSAM-IV Software Functional Block Diagram.

The figure below better shows Teensy's IO with the laptop and electronics, which are further detailed in a later section. The important aspects of SPI and USB communication are of upmost importance.

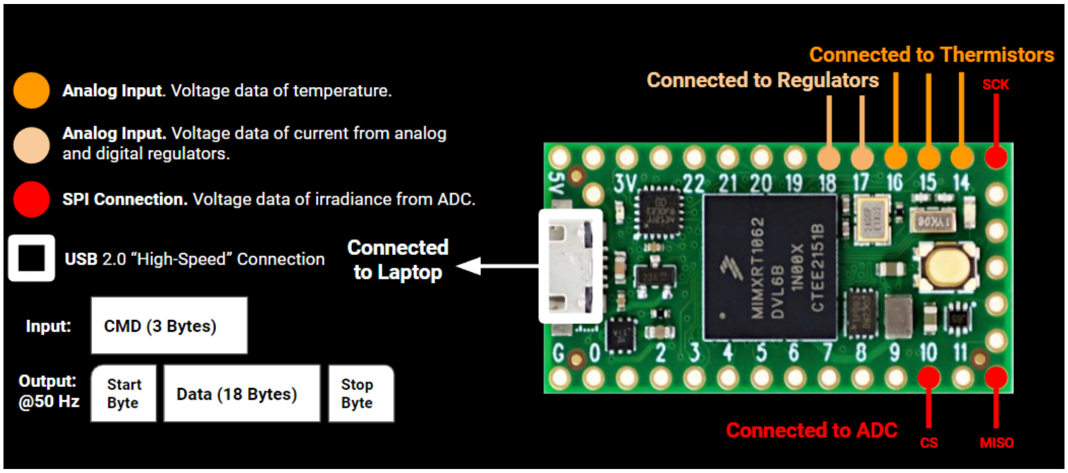

Fig. 4 Teensy Inputs and Outputs Diagram.

With this in mind, the following figure shows three diagrams of the Teensy code flow. This is the main loop that Teensy and the two main functions' design–the command handling function and the collect data function. Note, that the "Data Collection Loop" block calls collect data 50 times with a delay of less than 20 milliseconds between each call to obtain the 50 Hz rate.

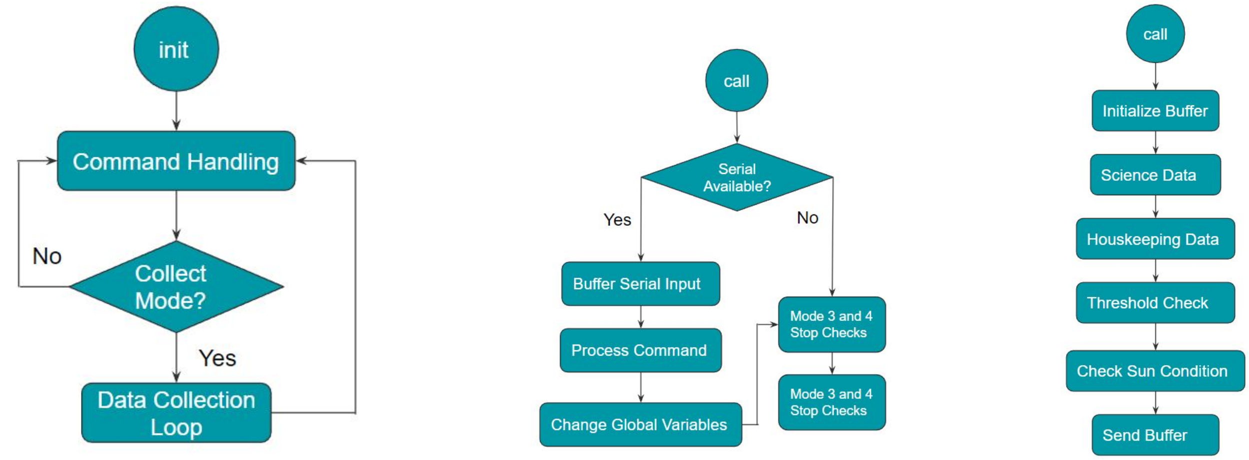

Fig. 5 Teensy Main Code Loop, Command Handling Function, and Data Collect Function

This code's design satisfies the previously mentioned requirements and all four modes of operation. It is also important to further expand on our data, the buffer and other important information can be seen below.

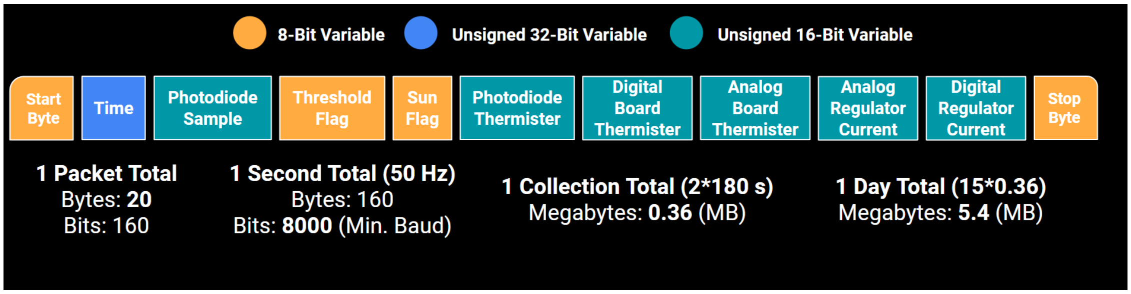

Fig. 6 Detailed Data Buffer and Important Sizes and Rates

A. Orbital Simulation

The orbital simulation (Mode 1) is a key aspect of the design and the most important of the 4 Matlab scripts and is tied to a larger orbital mechanics models. The orbital simulation will take in circular orbit parameters: a, e, and i and use these defined parameters to propagate NanoSAM's position on the chosen orbit with time. The values we will be using are a = 6795.5 km, e = 0, and i = 51.6 degrees [10]. These values are based off of the mean ISS orbit parameters, since NanoSAM and other cubeSats would likely be launched off of the ISS and put into a similar orbits. Since we are using a circular orbit, the parameters: ω, Ω, and v will not be defined. Instead, we will set our starting position in the orbit based on the angle of NanoSAM relative to the sun. This is a more relevant metric as the angle of NanoSAM relative to the sun is what we are using to define when to start and stop data collection.

Data collection happens at two intervals during an orbit as seen in Fig. 1. The first interval is at sunset for NanoSAM, which begins when the simulated NanoSAM position is at 150 km tangential to the surface of the earth. As NanoSAM's position drops behind the earth it will hit 8km tangential to the surface of the earth, which marks the end of of data collection. This process repeats at sunrise when NanoSAM comes from behind the earth and can "see" the sunlight. The locations are reversed from sunset, where data collection begins at 8 km tangential and stops at 150km tangential. Each of these events last about 3 minutes. Fig. 1 does not tell the full 3D story of NanoSAM but serves as a useful visual reference.

Fig. 7 describes the 3D geometry necessary to solving this problem. The orbit simulation is a very challenging problem if trying to traditionally propagate the orbit to get an [x,y,z] position in space and then convert that position into a tangent altitude. Rather, the position of the cubesat in orbit is based off of the angle made between the spacecraft and the sun.

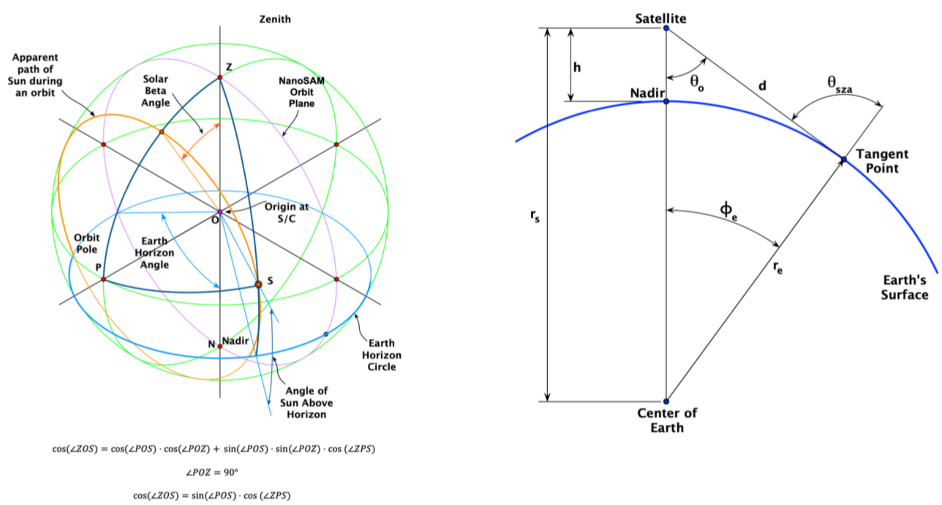

Fig. 7 NanoSAM orbit Modeled in a Spacecraft Fixed Frame.

There is one major important angle for this model that relates our known values to when our orbit is at 150 or 8 km tangential altitude.

$$cos(\angle ZOS) = sin(\angle POS) \cdot cos(\angle ZPS) \tag{1}$$

In this equation we know that the $sin(\angle POS) = 90-$ where Beta is the angle between the orbit plane and the position of the sun. We also know that $cos(\angle ZPS)$ is related to where the sun is relative to our spacecraft, which will go from 0 to 360 degrees over the course of one orbit. Knowing $sin(\angle POS)$ is a fixed value and iterating through $cos(\angle ZPS)$ values based on our orbit parameters we can know $cos(\angle ZOS)$. We also know that the angle θ is the angle between our tangent altitude and satellite as seen in 7 on the right. This remains a fixed value for each tangent altitude of interest, so we will have a θ_0 for 0 km tangential, θ_8 for 8 km tangential, and θ_{150} for 150 km tangential. These values depend on the shape and size of the NanoSAM orbit but remain fixed values for a fixed set of orbit parameters. If we know $cos(\angle ZOS)$ and our theta values of interest θ then we can use use the equation below to solve for when we are at our tangent altitude.

$$cos(\angle ZOS) + \theta = 180 \tag{2}$$

When $cos(\angle ZOS) + \theta = 180$ then we are at our tangent altitude of interest. This method will be implemented into our code.

The actual orbital simulation code will first find the orbital period, and then discretize that into individual timesteps. As time progresses, at each timestep, the necessary angles will be calculated and a check will occur if the spacecraft has entered the region of interesting (150km to 8km tangent altitude). When the spacecraft first enters this period, a command will be sent to the Teensy to begin collecting data, and again to stop collecting when the simulated spacecraft first leaves the specified region. Within this time period, data will be collected at the regular 50 Hz as dictated by the embedded systems requirements, and also will be stored the same way.

A major component of this orbital mechanics model is the solar Beta angle. For the purpose of propagating just one orbit, it will be assumed that Beta remains constant. In real life, due to the tilt and motion of the Earth, Beta actually will vary significantly throughout the year. As Beta increases, the data collection window time also increases, up to approximately 70 degrees, when the orbit plane will be such that there won't be a sunrise or sunset event. The orbital simulation will also take in Beta angle as a parameter, and is automated to use this in the calculation. Observing how the data collection time changes as we change Beta angle will help to verify the functionality of this script during full system integration and test.

IV. Electronics

The electronics team was chiefly tasked with designing a light source circuit to emulate the power that would be incident on the photodiodes active area previously designed and manufactured by the NanoSAM-II team. The photodiode was selected by the previous NanoSAM teams. The electronics team will also be tasked with the re-design of two boards. These two boards are the NanoSAM-II's analog board and digital board that will be detailed later in this report. Below, Fig. 8 depicts the overall FBD of the electronics design. Overall, the electronics system will have two inputs and one output. The Lab computer will input commands to the Teensy via USB that will command data collection, and a bench top triple power supply will supply the electrical power required for the light source circuit and the signal processing analog and digital boards of 12V. The output of the system will be the raw irradiance data and housekeeping information sent from the Teensy to the lab computer via USB. The Software section of this report will detail the Lab computer code, and data breakdown. Overall, the electronics team is required to design a light source that is able to output between 29 and 586 milliwatts with an expected power output of 210 milliwatts. That will correspond to an incident optical power on the photodiode active area between 0.118 and 2.37 microwatts with an expected power of 0.1184 microwatts. The photodiode will respond within bound of 0.0533 and 1.07 micro amps with an expected current of 0.857 microamps. All of these requirements flow from the Ball requirements to emulate the signal that this instrument would have if it were to operate in LEO. Lastly, the boards must convert the photodiode current into a voltage, amplify, filter, and convert it to a digital signal all while drawing less then 8 watts of power and achieving an SNR of 200 to satisfy a customer requirement.

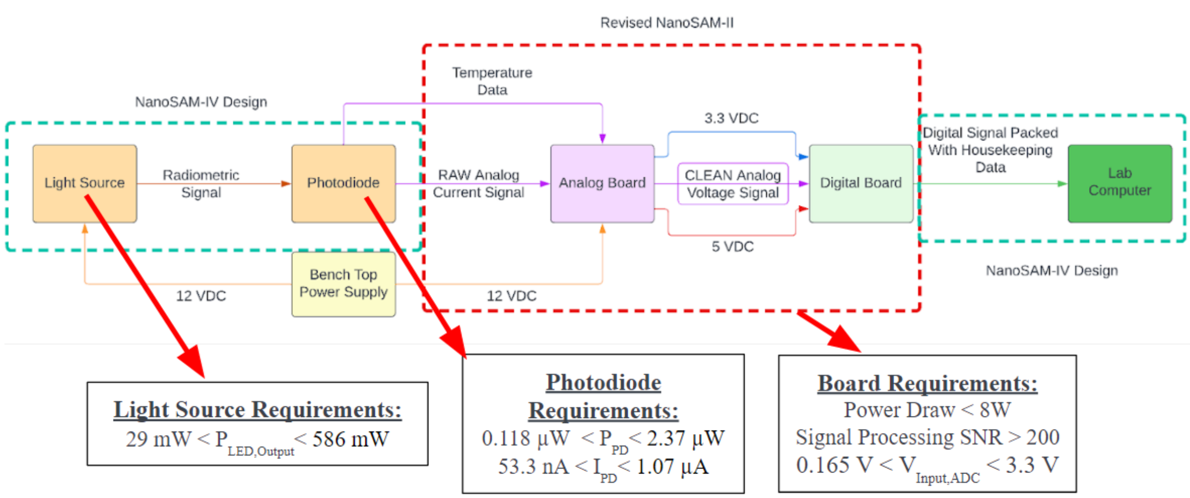

Fig. 8 Overall System FBD

1. Light Source Circuit

After the overall system and requirements have been defined a light source circuit was designed shown in Fig. 9. Starting with the light source optical power output bounds between 29 and 586 milliwatts with an expected power output of 210 milliwatts. The Thorlabs M680L4 mounted LED was selected, as it has a wavelength of 680 nanometers and a output angle of 20 degrees (the wavelength and output angle and distance from the photodiode will be detailed in the following sections). With the specific LED selected it was calculated that a voltage of 2.5 volts at 600 milliamps was required to be supplied to the LED in order to output an optical power matching the 210 milliwatt optical power requirement. To ensure that the voltage and current supply from the XPH 35-4T power supply is within the required bounds, the power from the supply is passed into the Texas Instruments TLV767 linear regulator, thus reducing the 10 millivolt noise to 60 microvolts. Furthermore, a passive (RC) low pass filter is put in series to eliminate extraneous frequencies outputted by the linear regulator's noise set at 10 kilohertz.

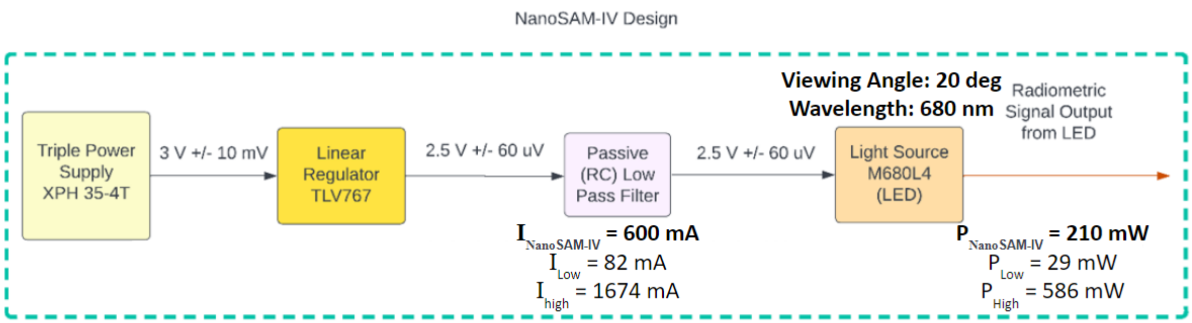

Fig. 9 Light Source Circuit FBD

With the voltage and current requirements defined, as well as modeling the noise output of the Texas Instruments linear regulator, the R1 resistor and C1 capacitor in Fig. 10 are sized to drive the LED within nominal bounds. The respective values are 0.9 kiloOhms and 18 nanofarads corresponding to the required output current of 600 milliamps to match the output frequency of the Linear regulator. Lastly a potentiometer with ten (x10) 100 Ohm steps will be used to vary the LED's power input and optical output within the required bounds (outlined in yellow).

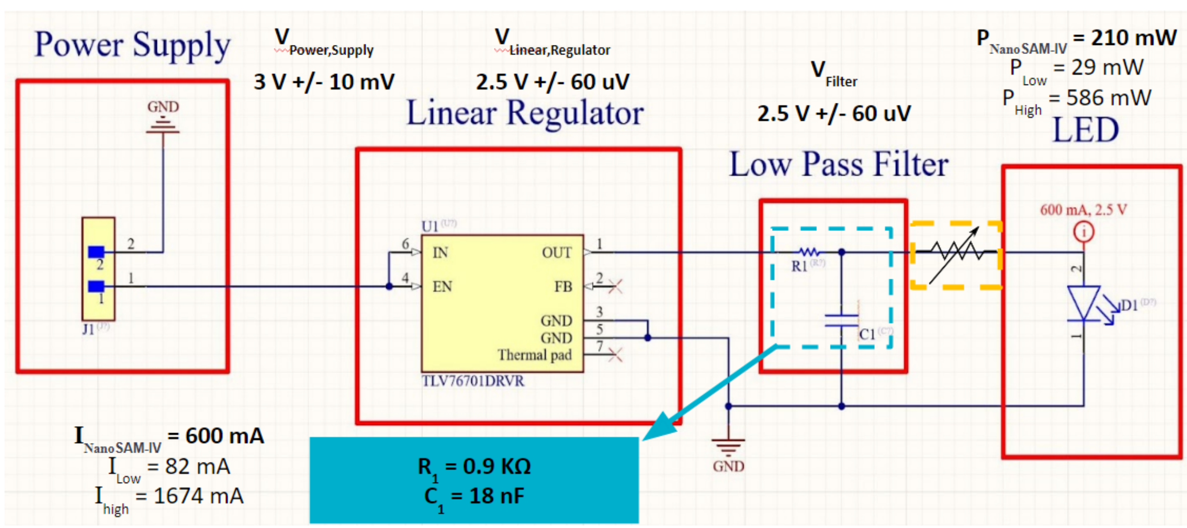

Fig. 10 Light Source Circuit Schematics

2. NanoSAM-II Instrument Board Revisions

Following the design of the light source circuit the instrument FBD shown in Fig. 11 below depicts that the instrument's photodiode will receive an incident optical power on the photodiode active area between 0.118 and 2.37

microwatts with an expected power of approximately 0.1184 microwatts. The photodiode will respond within bound of 0.0533 and 1.07 microamps with an expected current of 0.857 microamps. This current is passed into a transimpedance amp converting the current to a voltage and amplifying it. The signal is then passed into a low-pass filter to match the ADC reference voltage and frequency input requirements of the ADC such that the ADC can discern the signal without aliasing. The voltage is inputted into the ADC with a expected voltage of 2.640 volts and a lower bound of 0.165 volts corresponding to the 200 SNR requirement, and an upper bound of 3.3 volts corresponding to the reference voltage of the ADC.

The power draw of both of the boards and the photodiode will is monitored by current monitors placed on the outputs of the linear regulators allows for the discernment of power usage. There are thermistors placed on the photodiode and both the analog and digital board to model the temperature of the system ensuring it is within nominal operating temperature ranges, defined by the SNR calculation noise assumptions that will be discussed in a following section.

Finally the digitized irradiance signal is passed to the Teensy micro processor on the analog board along with the current and temperature measurement data, where it is uploaded via USB to the Lab computer and passed to the software team. (detailed in the software section).

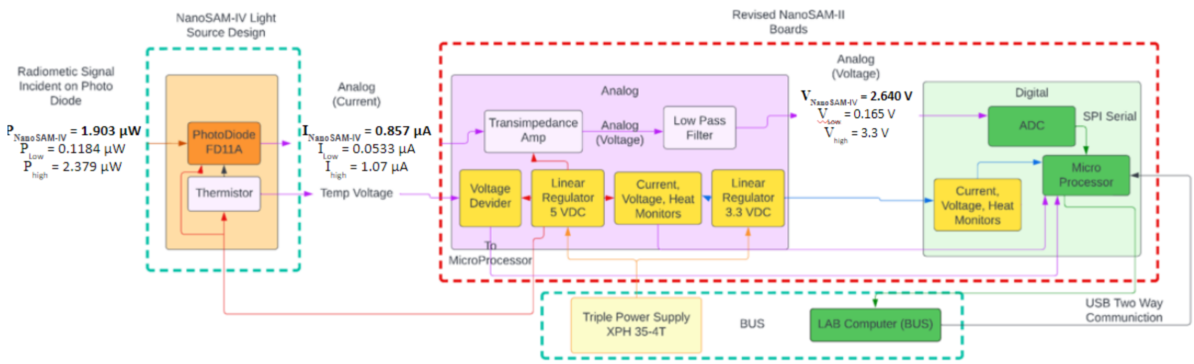

Fig. 11 Instrument FBD

Following the determination of the required signal bounds at each given component, the revision of the sizing (shown in Fig. 12 below) of the feedback resistor is based on the ADC input, its lower voltage bound corresponds to 0.165 volts to satisfy the SNR requirement, and an upper bound of 3.3 volts to match the reference voltage. The capacitor size is based on the ADC's sampling rate of 208 hertz taking into account the nyquist frequency of 104 hertz to prevent aliasing. The resistor is to be 3.08 megaOhms and the capacitor is 408 picoFarads completing the redesign of the analog signal processing board. With the resistor and capacitor sized an SNR model is able to be created.

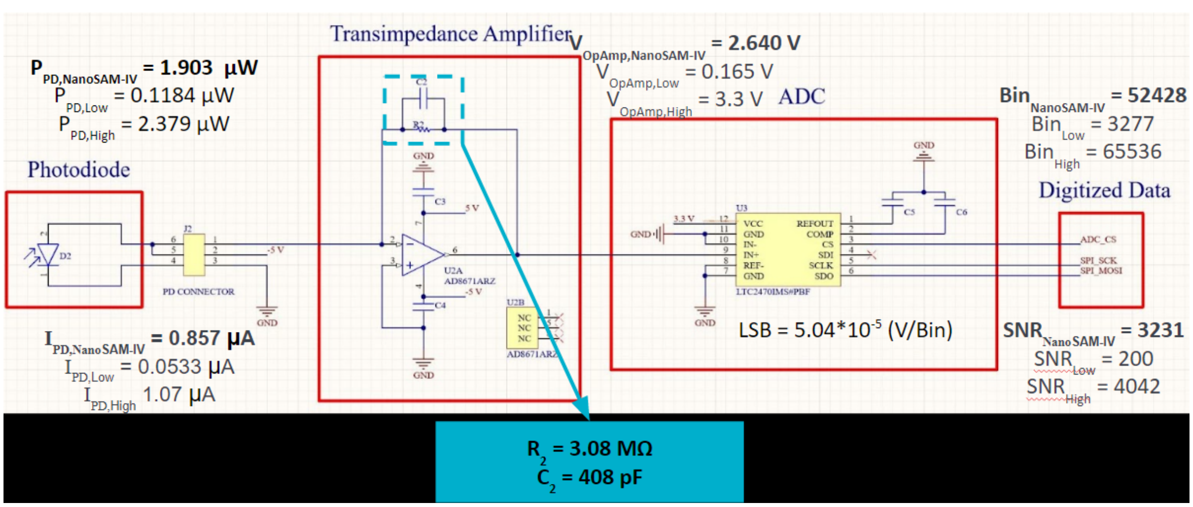

Fig. 12 Instrument Schematics

V. Optics

The optical and mechanical portion of NanoSAM IV is focused on the testing box outlined in Fig. 2. The purpose of the test box is to isolate the LED and photodiode from ambient light sources. This allows the system to get a baseline one hundred percent irradiance measurement to replicate an on-orbit reading of the sun without any attenuation. Future NanoSAM projects may use this baseline for comparisons when collecting attenuated signals. The isolated signal also allows the electronics subteam to confirm the SNR model, thus proving the functionality of the embedded systems. Exterior ambient light may cause the signal from the photodiode to not match the expected un-attenuated signal, skewing the baseline measurement.

To isolate the signal, NanoSAM IV will use an Aluminum 6061 cuboid. The design of this cuboid is governed by an adapted Inverse Square Law, ISL, equation. It is important to note that two key assumptions have been made in applying this model. The first is the surface area of the interior of the box is hundreds of times the size of the photodiode sensor The second is that there are negligible reflections from the interior's material that would allow light to reflect into the photodiode sensor. The reflections would cause the signal to be outside the determined power tolerances. To make these assumptions, several steps were taken. The first is the width of the box will be 10 centimeters, so with the calculated length and the two end caps being 10 cm x 10 cm, the surface area will be almost 2,000 cm^2. The photodiode sensor area is 1.21 mm^2, so the assumption of the surface area being hundreds of times the size of the photodiode is valid. The next assumption, about reflections, will be mitigated by painting the inside of the cuboid with Musou black paint; this black paint absorbs 98.2% of light (according to the manufacturer's specifications). The combination of the black paint and the surface area of the test box allows the ISL to be used.

Once the necessary steps are taken, and the assumptions are now valid, the following adapted ISL can be utilized:

$$I = \frac{S}{4\pi(r * tan(theta))^2} \tag{3}$$

where I is the intensity of light from the LED in Watts/deg^2 on the photodiode, S is the LED output power in Watts, r is the distance between the LED and photodiode in millimeters, and θ is a vector of offset angles from -85^o to 85^o.

The intensity of light from the LED is a known value determined by a previous NanoSAM mission to be I = 1.0763*10^{-4} Watts/deg^2. This value can decrease by 1.0167*10^4 Watts/deg^2 while still remaining within requirements and represents the expected intensity of light on the photodiode and is a requirement on mechanical from electrical. When the intensity of light is within these tolerance bounds the electrical boards are capable of achieving a SNR over the required 200. The vector of offset angles are provided in the data sheet for the LED provided by the manufacturer Thorlabs. Their data sheet states that light beams spread out from the LED in a triangle with half-angles of 85^o. So, the two variables that NanoSAM IV can solve for are S and r. For the chosen M680L4 LED, Thorlabs provides a typical output power of 0.21 Watts based on providing typical current and voltage values. Since Thorlabs has provided a clear value for S when using a certain current value and voltage, the value of 0.21 Watts for S will be utilized. Leaving only r to solve for.

Solving for r shows:

$$r = \frac{\sqrt{\frac{S}{4\pi * I}}}{tan(theta)} = 635mm \tag{4}$$

Now, knowing the required distance, a design for the test box can be drawn up, shown in Fig. 2. On the left is the M680L LED, supported by an aluminum 6061 brace. On the right is the FD11A photodiode and thermistor. The two endcaps where the LED, photodiode, and thermistor are installed have holes cut into them that are slightly larger than the diameters of the LED and Photodiode. The slightly larger diameter will allow Loctite to be used to set and hold the LED and photodiode in place so that there is no variation in alignment, and repeated tests will provide similar signals. The two holes are aligned so that the LED and photodiode will be on the same plane with a viewing angle of zero degrees between the two. The two endcaps will be attached to the main body by utilizing external L-brackets and screws attached to the test box. Once this has been done, aluminum tape will be used to further seal the edges between the endcaps and the main body. The brace for the LED will be bolted to the endcap so that no variation in alignment is allowed.

Acknowledgments

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