NanoSAM II

Nano-Stratospheric Aerosol Measurement

Critical Design Review

November 24, 2020

Ball Aerospace

University of Colorado Boulder
Department of Aerospace Engineering Sciences

Agenda

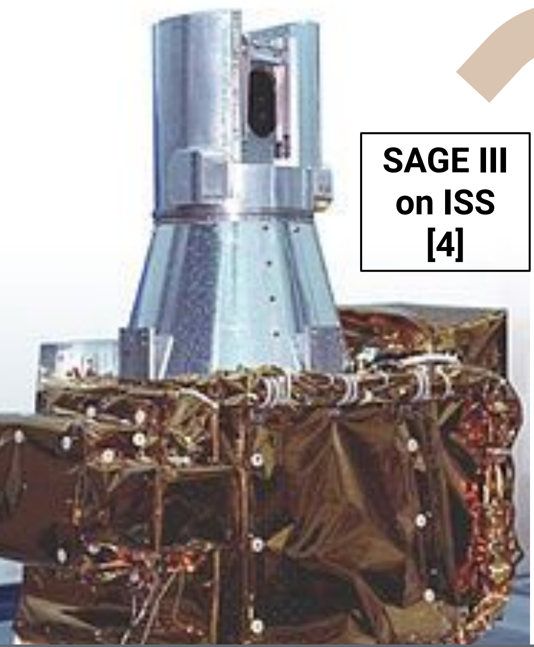
NanoSAM II
CDR

Project Purpose and Objectives

Jaret Anderson

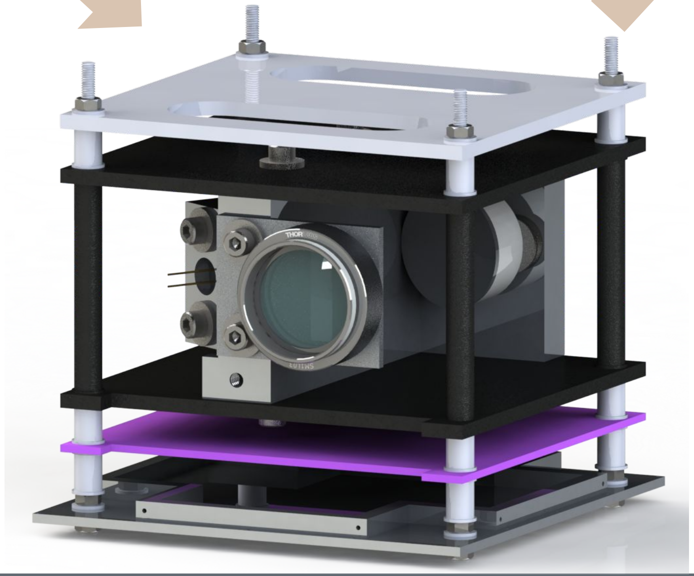
Project Background & Purpose

SAM/SAGE Instruments
(1979-1984, 2001-2006, 2011-Current)
Bulky, High Cost, Low Data Volume

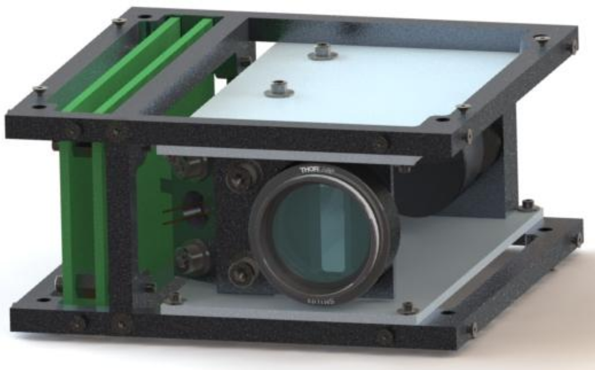


SAGE III on ISS [4]

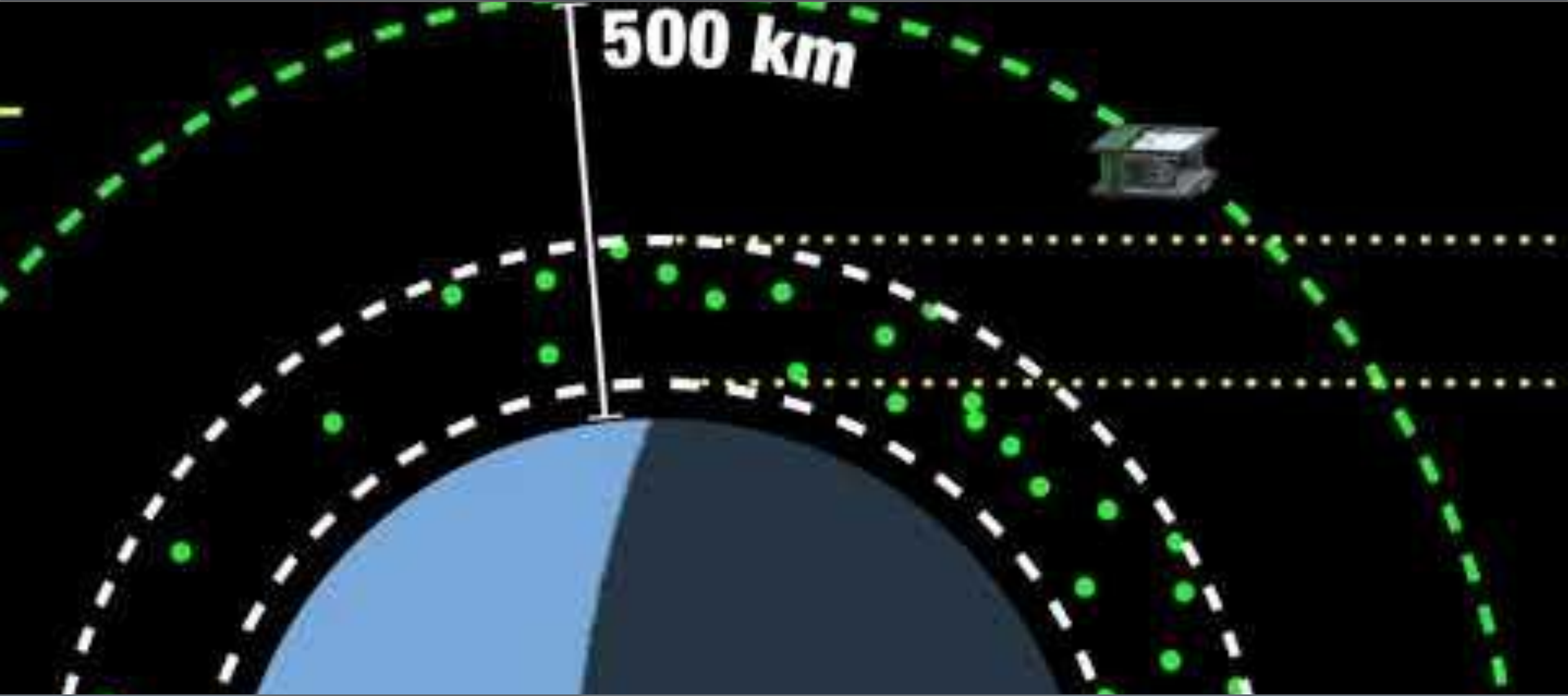
NanoSAM I
(2019-2020)
Optical Instrument for CubeSat Footprint



NanoSAM II
(2020-Current)
Integrated 0.5U CubeSat Payload



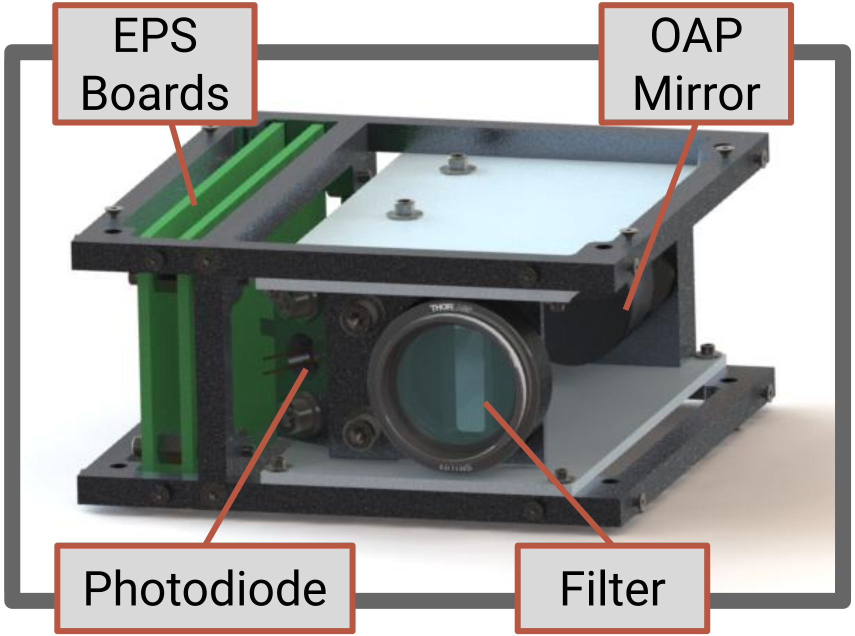
NanoSAM Mission CONOPS

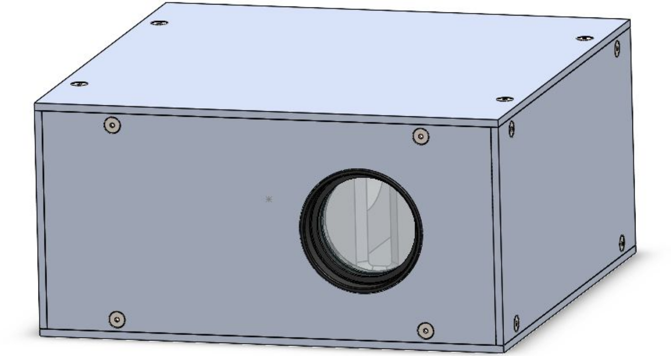


Design Solution

Emma Tomlinson

NanoSAM II CAD

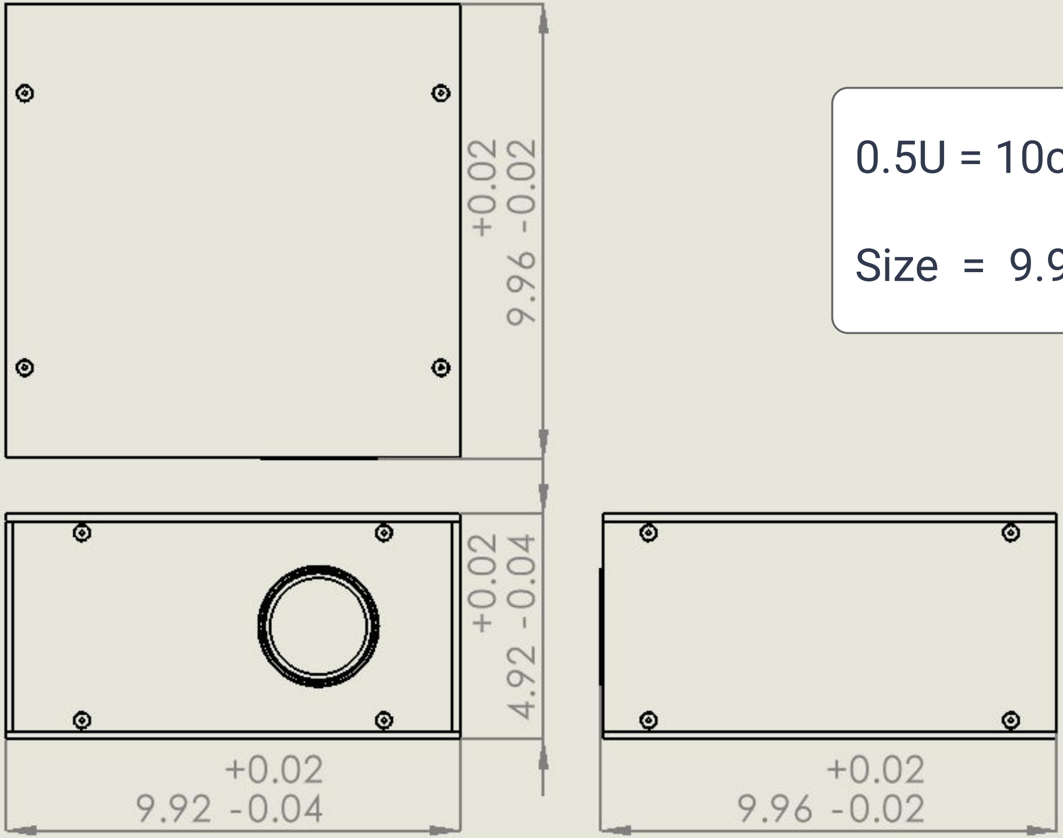




Mass: 0.48 kg
Size: 0.5 U

Gathers Irradiance Measurements at 50 Hz

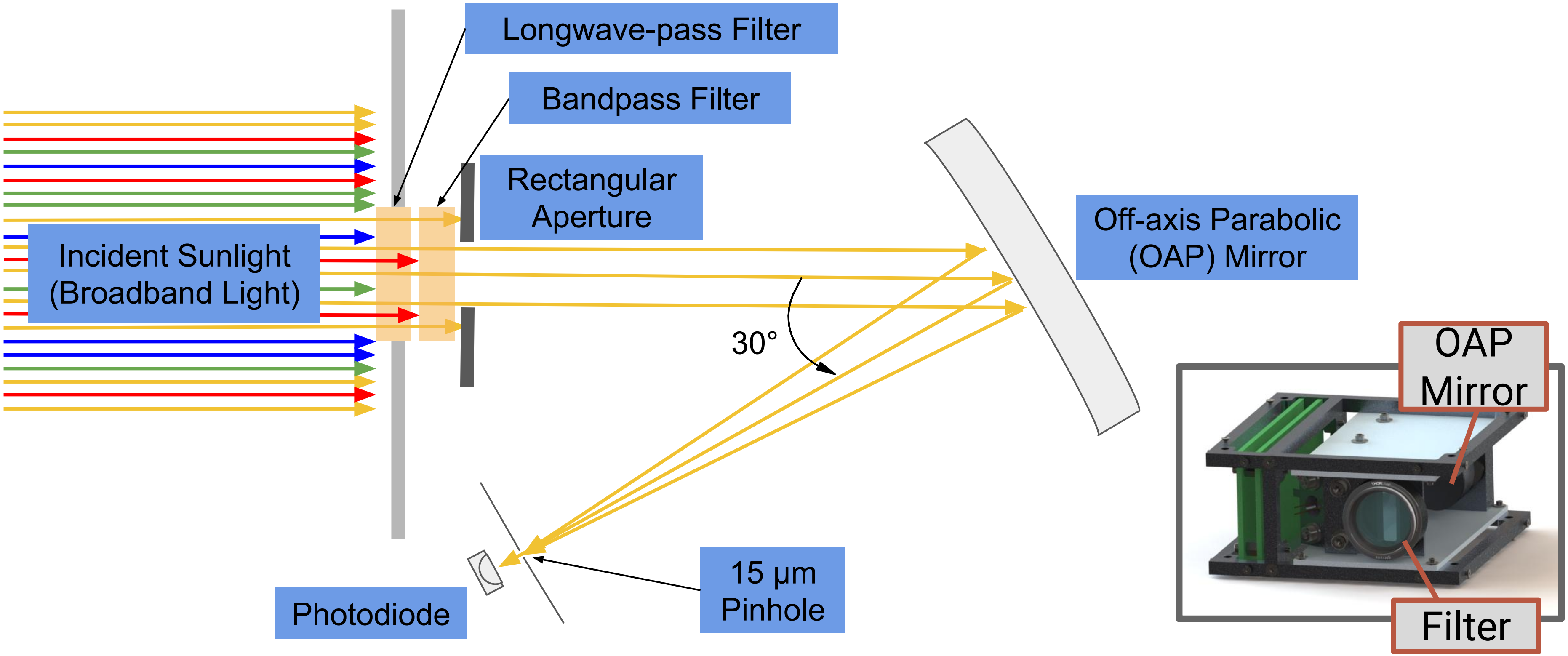
NanoSAM II Dimensioned Drawing



0.5U = 10cm x 10cm x 5cm

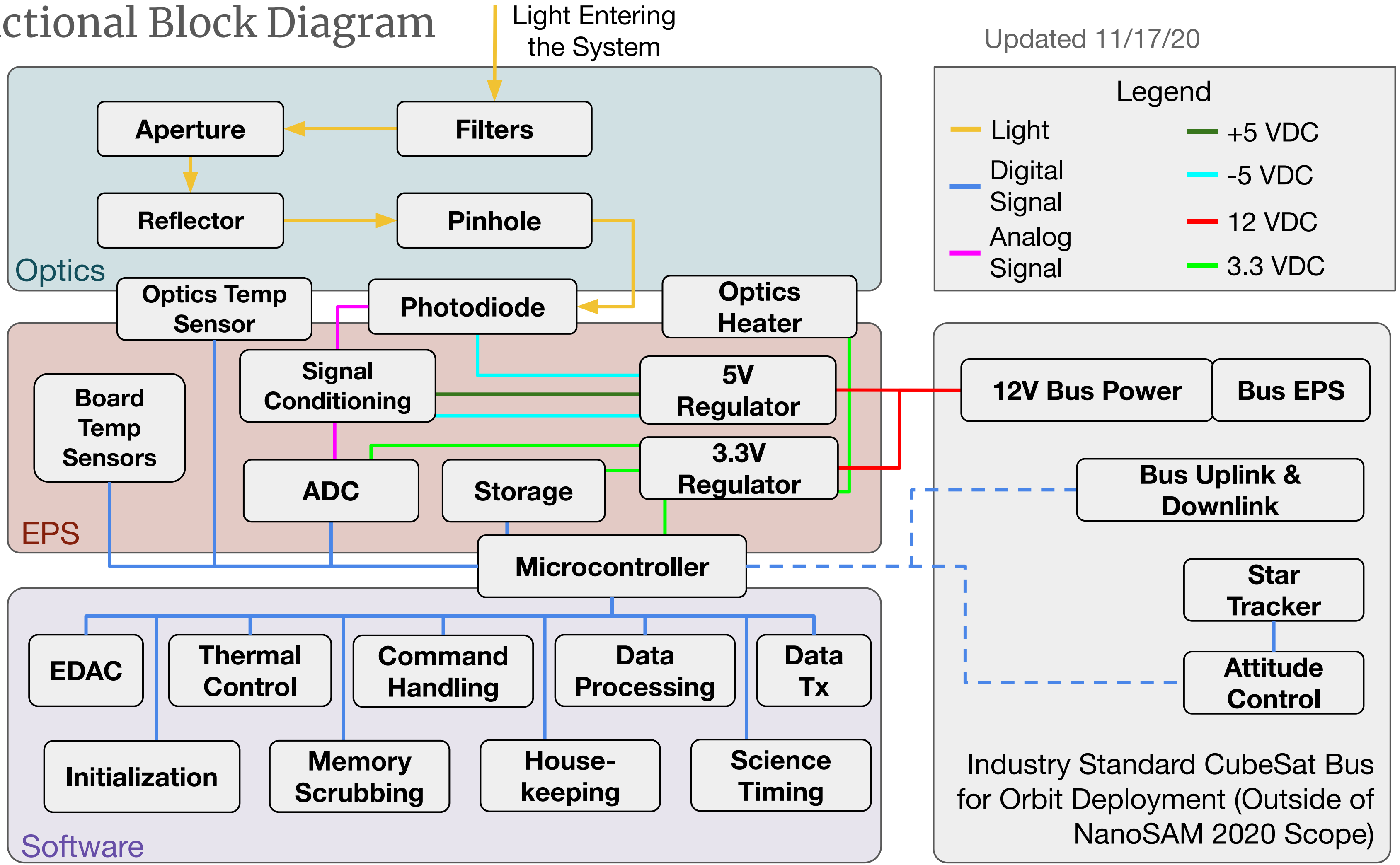
Size = 9.96cm x 9.92cm x 4.92cm

Optics Instrument Overview



Functional Block Diagram

Updated 11/17/20

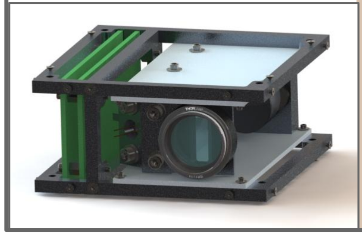


Critical Project Elements

Donavon Schroeder

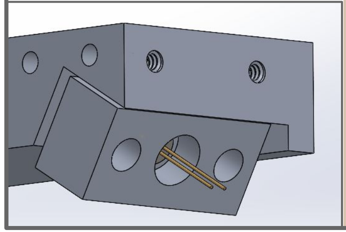
Critical Project Elements

Structure



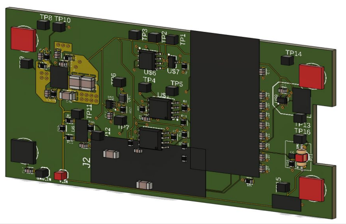
Vibrational Modes
Simulation & Testing

Optics



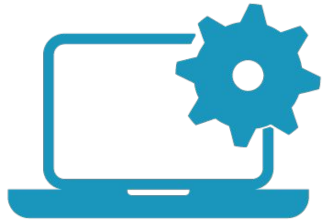
Match SAM-II
Instrument Legacy
Performance

Electronics



Low-Noise
Signal Processing

Software



Timely and Reliable
Data Collection

Design Requirements and their Satisfaction

Ryan Smithers

Jaret Anderson

Donavon Schroeder

Emma Tomlinson

Structure Relevant Requirements

4.0: Payload Dimensions

- Payload size must be less than 0.5U
- Payload mass less than 0.615 kg

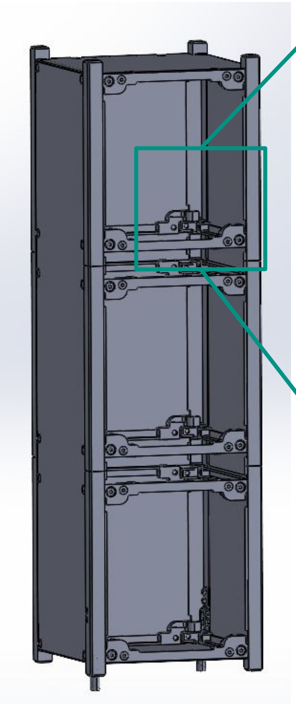
5.0: Flight Testing

- Payload can survive vibrational, thermal, and vacuum testing
  - Survives a temperature range of -20°C to 50°C [1]
  - No resonant frequencies below 100Hz [1]

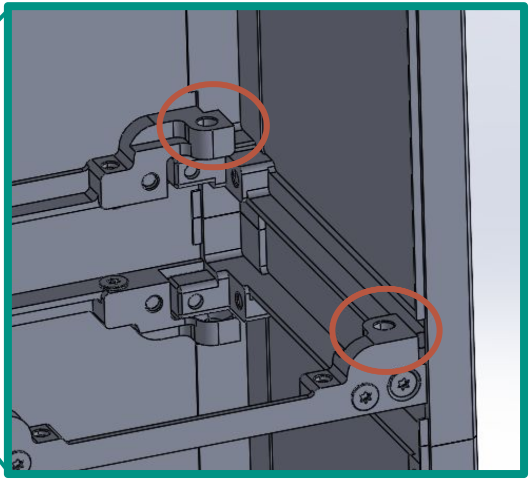
Requirements Satisfaction

- Current dimensions, with walls: 9.92cm x 4.92cm x 9.96cm
- Current mass of .480 kg
- P_{heater} = 3 W
- Lowest structural resonant frequency: 904 Hz

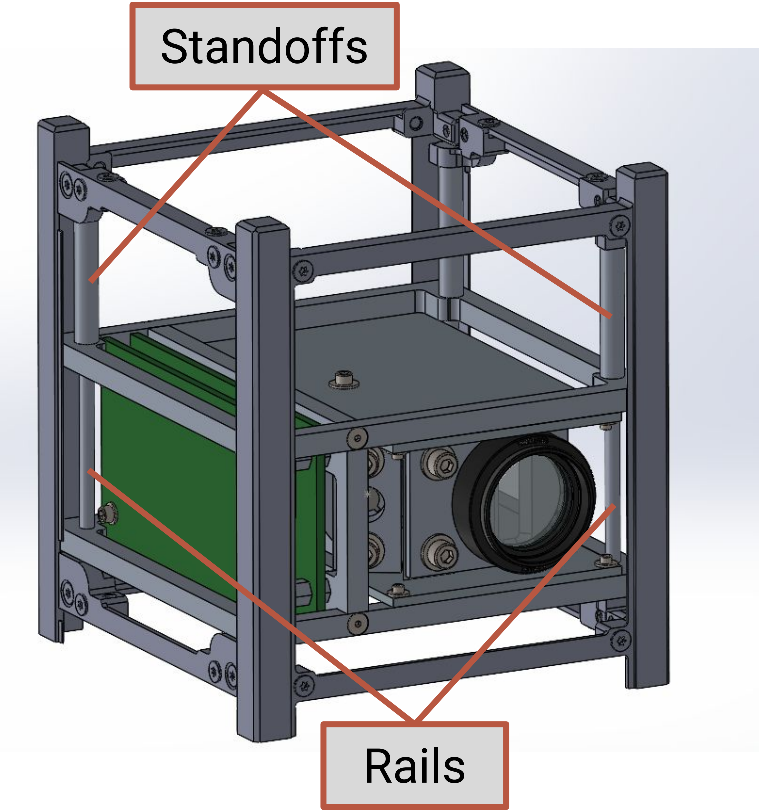
Vibrational Study – CubeSat Mount



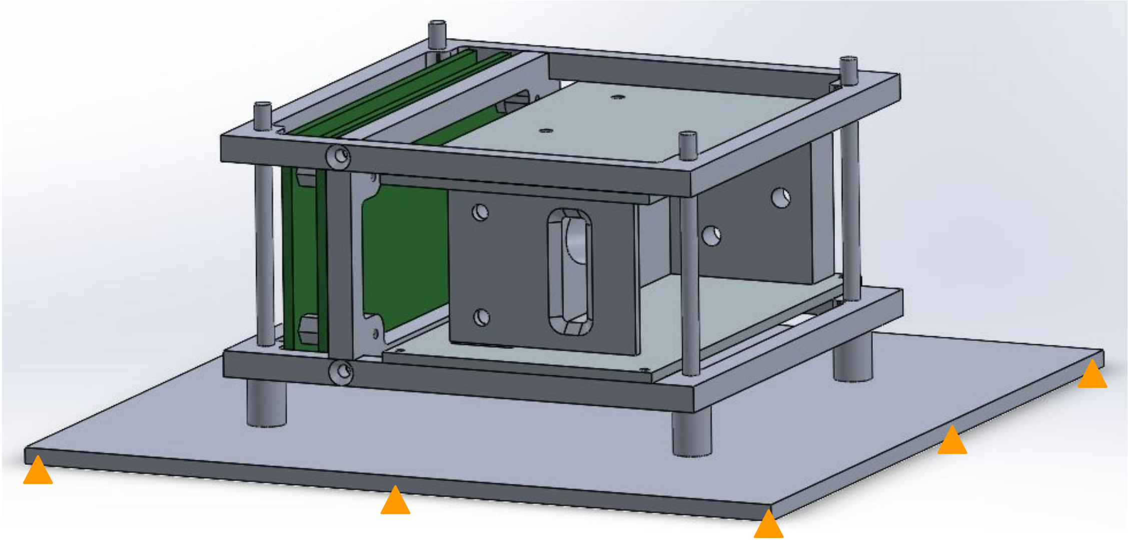
ISIS 3U CubeSat Structure [7]



PC104 Standard Attachment [8]



Vibrational Study – Structural Vibe Test FEA



Commercial CubeSat Interface Mount - PC104 Specs [8]

Boundary Condition:

▲ Fixed Vibe Table Plate

Lowest Frequency: 906 Hz

No resonant frequencies below 100Hz requirement

Optics Relevant Requirements

1.0: Data Capture
- Optical and Electrical Subsystems shall communicate mission data through the photodiode connection

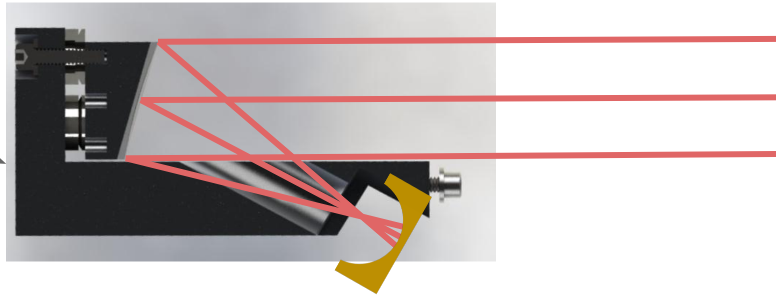
3.0: SAM-II Equivalent Optics
- The optics system shall capture light at a center wavelength of 1.02 μm
- The optical design shall have a vertical resolution of 1 km
- The FOV shall be 1.3 arcminutes to achieve a vertical resolution of 1 km
- The imager shall have a MTF of 0.74 at the chosen spatial frequency in order to meet the resolution and contrast of the SAM-II system

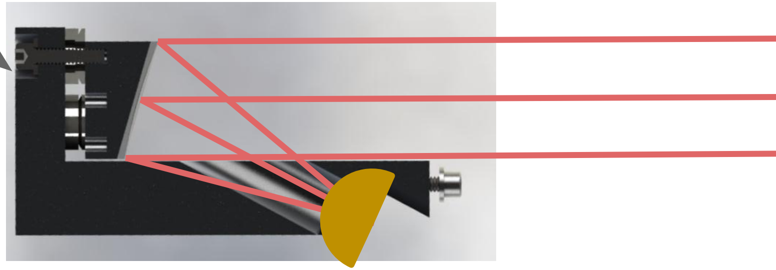
4.0: Payload Dimensions
- Payload size must be less than 0.5U
- Payload mass less than 0.615 kg

Requirements Satisfaction
- Bandpass filter and longwave pass filter to isolate 1.02 μm light
- Herschelian Telescope with 25.4 mm diameter, 30° off-axis angle OAP mirror, focal length of 54.45 mm
- 20 x 5 mm aperture, pinhole of 15 μm diameter
- Fits within dimensions described

Optics Modifications for Alignment

- Previous Alignment Procedure: Concave Return Sphere
  - Unable to borrow or buy a Concave Sphere
- Modify Alignment Procedure: Convex Return Sphere (very smooth Steel Balls)
  - Easily acquired
  - Requires Tooling to be placed on the focus of the OAP
- Large ball bearing is better for alignment

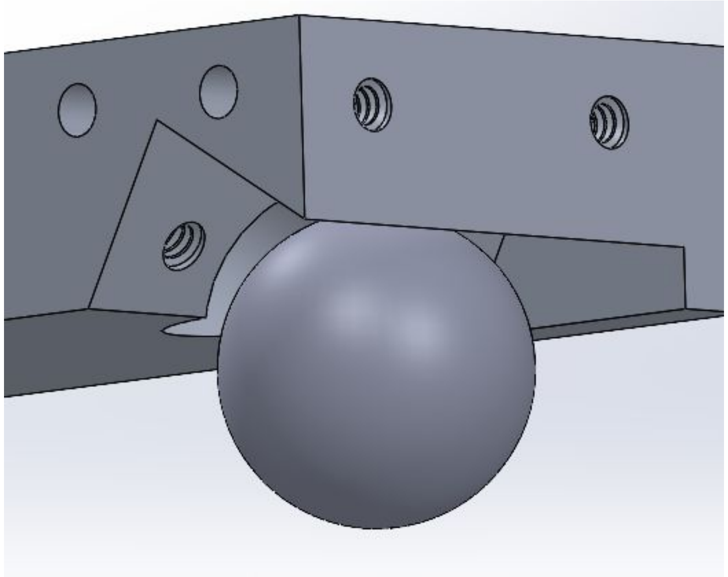




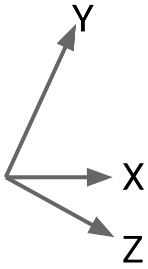
*Above Diagrams not to scale

Optics Modifications

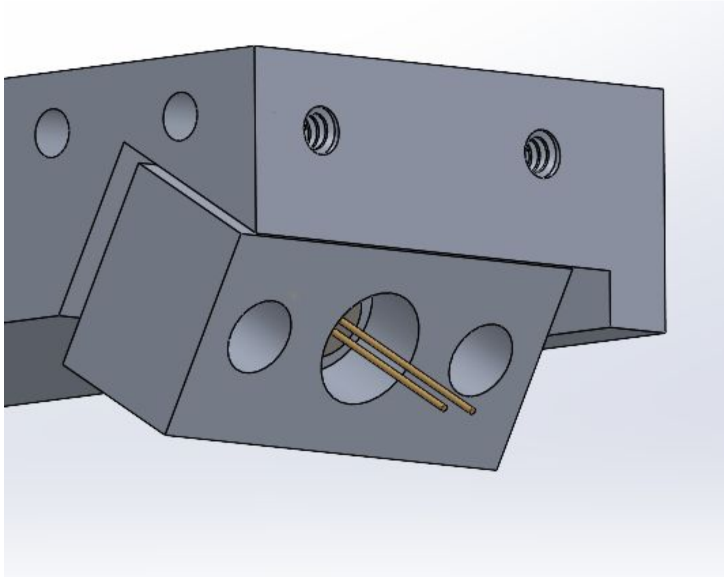
During Alignment



Optics Bench with 19.05 mm
Return Sphere Placed on focus



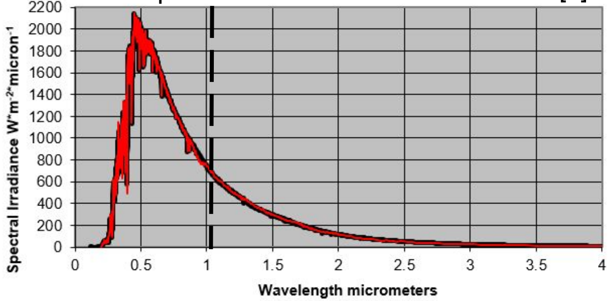
During Measurement



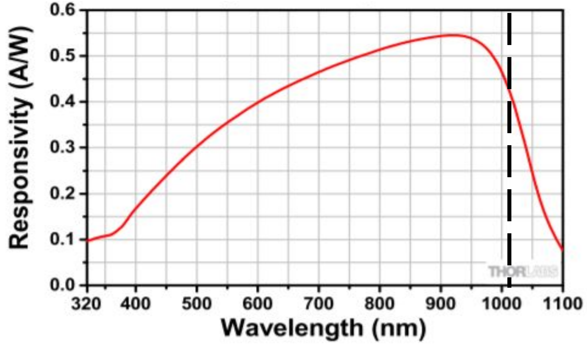
Optics Bench with Photodiode
Block aligned on focus

Optics Photodiode Parameters

Solar Spectral Irradiance Data from NREL[9]



Photodiode Spectral Responsivity from ThorLabs



(1) $P_{inc} = FOV/\theta_{sd}^2 \, \Phi \, BW \, A_{ap} F_{sd} F_{sys}$

(2) $\Delta\lambda = 0.0089\,T - 0.2174$ nm

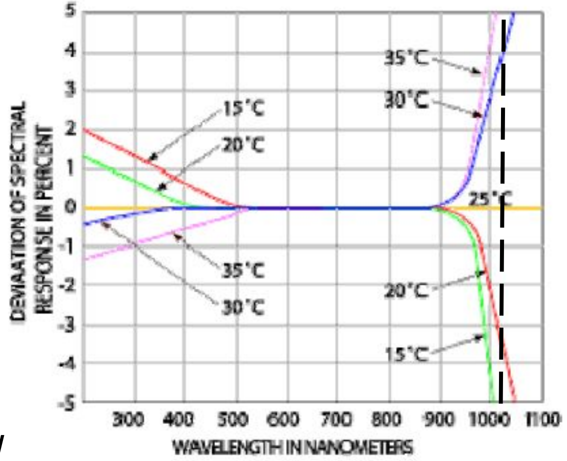
(3) $P_{inc} = -9.059 \times 10^{-8}\,T + 0.00658$ W

(4) $R_{25°C} = 0.3925$ A/W

(5) $\Delta R = 0.01 \times 0.0092 \times (\lambda + \Delta\lambda - 952.9)$

(6) $R = R_{25°C} + \Delta R = 0.0024\,T + 0.3322$ A/W

Deviation in Spectral Responsivity



Max incident power: 0.0066 W
Sunset: Max R: 0.3660 A/W Min R: 0.3653 A/W
Sunrise: Max R: 0.3456 A/W Min R: 0.3439 A/W

Electronics Relevant Requirements

1.0: Data Capture
- Communicates via photodiode with optical bench
- Samples, processes, and stores data at a rate greater than 50 Hz
- Data is collected in a 10 bit resolution
- Enough storage space for one orbital period
- Housekeeping data is stored (temperature, voltages)
- The system uses less than 7.3W

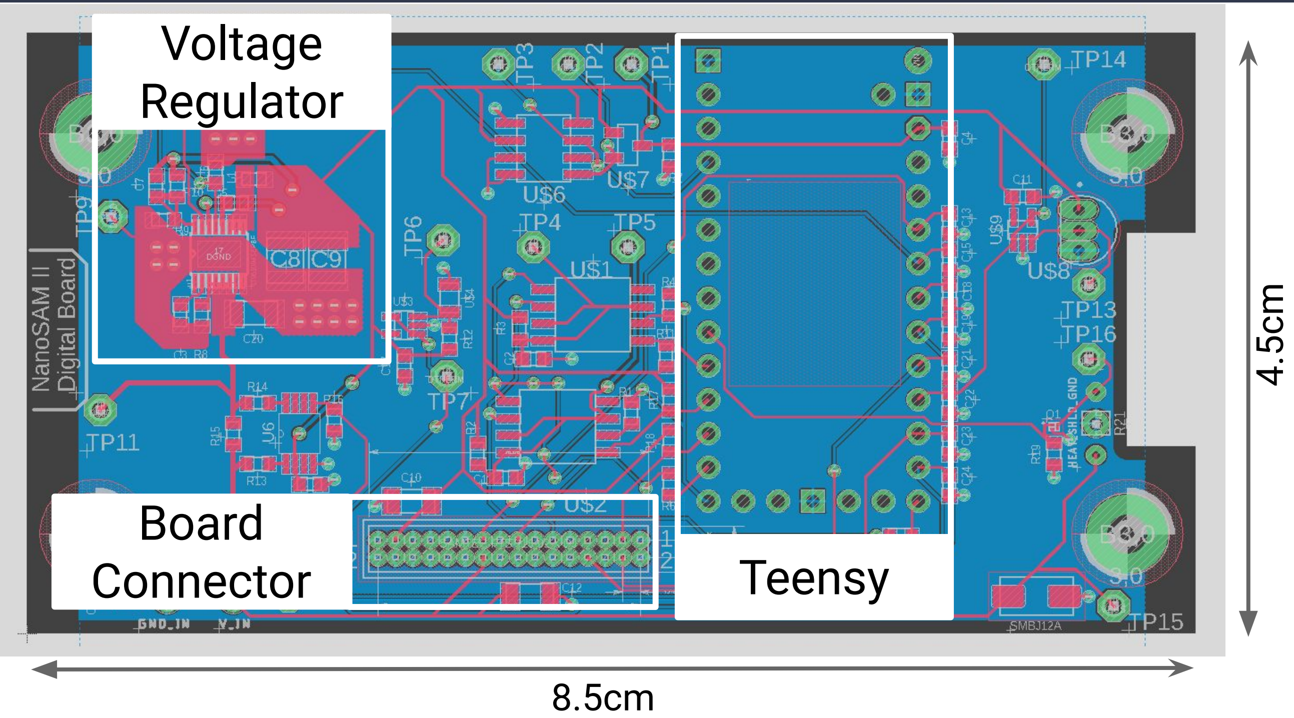
2.0: Communications
- Comms with laptop for ground testing
- Signal to noise ratio (SNR) greater than 3500

4.0: Payload Dimensions
- Payload size must be less than 0.5U
- Payload mass less than 0.615 kg

Requirements Satisfaction
(Unchanged since PDR) [6]

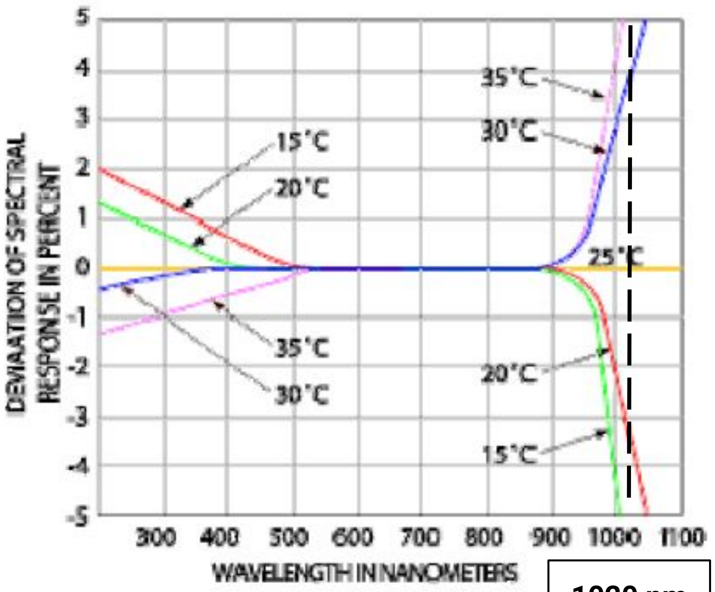
- Shielded wire photodiode attachment
- Transimpedance Amp
- 16 bit ADC
- 833 Hz sampling
- 256 Mb Flash Storage
- Thermistor Monitoring
- Analog Housekeeping
- USB I/O
- High Efficiency Vreg
- Dual-Board Design

Digital Board Layout



Routed board fits in 0.5U CubeSat footprint

Temperature Monitoring Correction

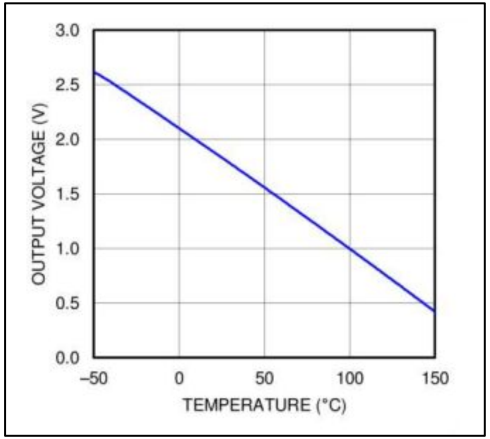


1020 nm

Texas Instruments LMT86LP

-10.9 mV/°C slope

Sampled w/ 12 bit ADC:
= 0.8mV LSB
= 0.043°C resolution



High precision analog optics bench temperature sensor to track temperature-related errors, correct these errors in software - 0.0198 V/K

Temperature Change on the Photodiode Block

Data Window	Max ΔT (K)	Time (s)
Sunset	0.28	192.6
Sunrise	0.70	192.6

- Calculated for β = 60° (orbital parameters corresponding to maximum length data window)
- Average values used for albedo, IR, and solar radiation [2]
- $0.7P_{i,max}$ used in model alongside a 3 W heater
- Black anodize exterior coating [3]
- No longer lumped system analysis (done through Solidworks + MATLAB modeling)
    - Threads and screws removed along with small holes

Software Relevant Requirements

1.0: Data Capture

- Data collection is timed to capture both sunrise and sunset through the stratosphere
- Samples, processes, and stores data at a rate of 50 Hz or greater
- Baseline irradiance data is measured for each sample window
- Housekeeping data is stored and monitored for irregularities
    - Temperature, memory usage, voltages
- Errors in data are detected and corrected

2.0: Communications

- A warning is downlinked when an anomaly in housekeeping data is detected
- Total data volume, including EDAC, does not exceed the data volume of a 9.6 kbps downlink over a 5 minute window per day.

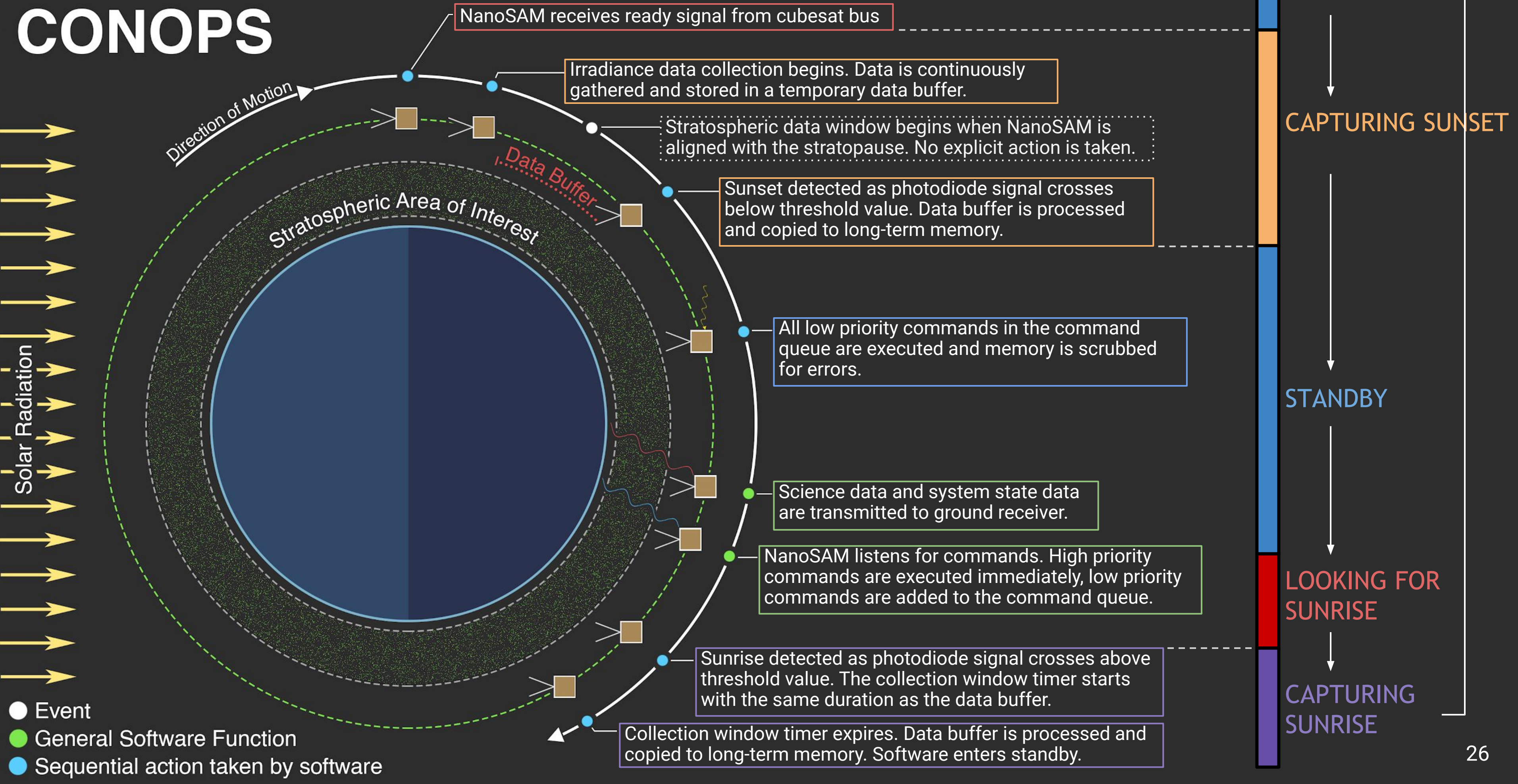
Requirements Satisfaction

- Data capture timing triggered by photodiode signal

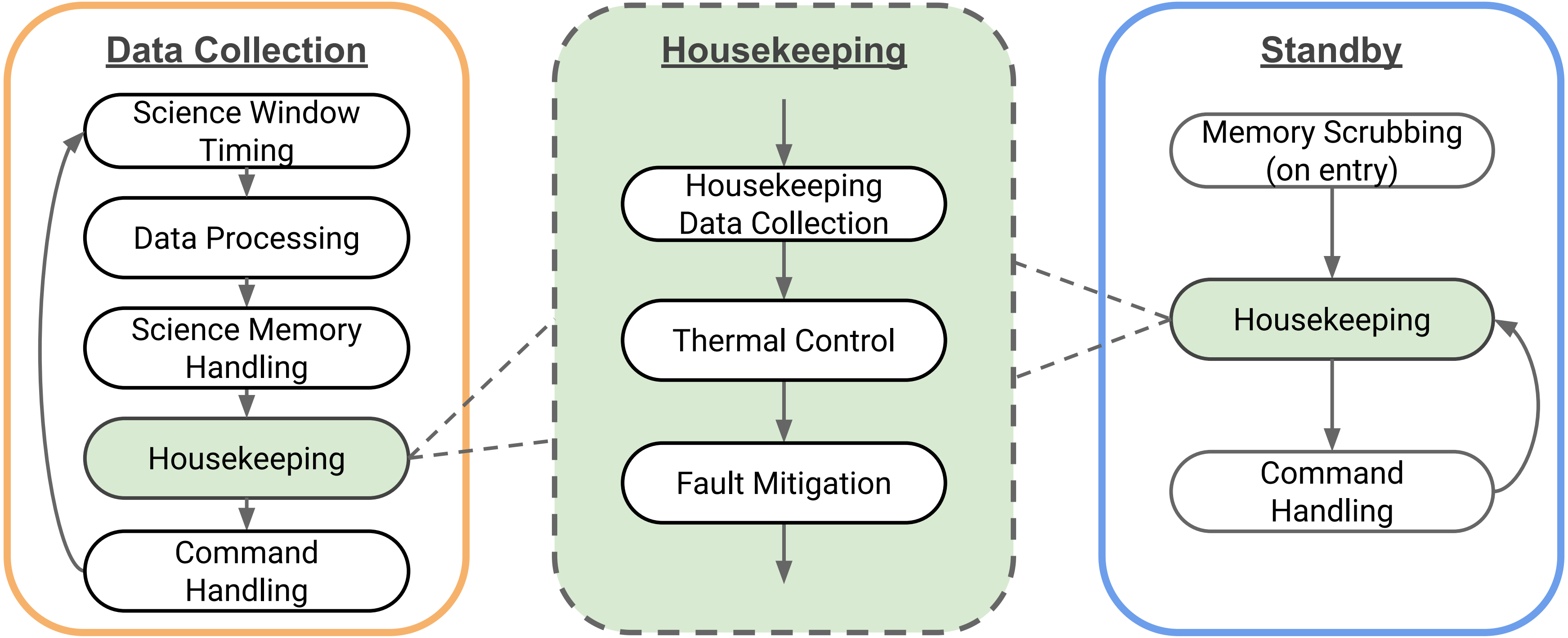
- Data stored in continuous data buffer which includes baseline data

- Hamming code EDAC to protect against SEEs

SOFTWARE CONOPS



Software Sequence



Teensy 4.0 Code and Development Status

- Teensy code written in modified Arduino language based on C++
  - Most Arduino libraries compatible with Teensy
- Program logic designed in pseudocode
- Each software module defined with functionality, inputs/outputs, and relationships to other modules

```
Timing
    pdThreshold = <minimum photodiode signal to be confident that we are pointed at the sun>
    sweepTimeout = <max time to reverse sweep>
    enum timingState
    {
```

```
Temperature Control
    TempThresholdHigh = <target temp> + <some margin>
    TempThresholdLow = <min safe temp> + <some other margin>

// This version will result in oscillating temperature but requires less switching on/off of the heater
```

```
Hamming EDAC
    segmentSize = <bit length of each segment in data blocks>

dataBlockWithEDAC_t applyHamming(dataBlock)
    // applies Hamming code EDAC to a data block and returns a new data block with embedded EDAC data

    // declare dataBlockWithEDAC
    dataBlockWithEDAC_t dataBlockWithEDAC

    doHammingStuff() // placeholder for EDAC encoding
    /* The way this is done is super cool and something I (Jackson) would love to do,
    but needs a bit more research to make it scalable to arbitrary block sizes */
    // We can also just use an existing library

    // return data with EDAC code embedded
    return dataBlockWithEDAC

errorReport_t detectErrors(dataBlockWithEDAC)
    // takes a data block, checks for errors, returns an error report

    // declare errorReport
    errorReport_t errorReport

    // scan for errors and report size of error between 0 and 2
    errorReport.errorSize = runReverseHammingCodeAndTellHowBigTheErrorIs(dataBlockWithEDAC) // obviously

    if (errorSize == 1) // we can only correct single bit errors with Hamming codes
        errorReport.errorLocation = findTheError(dataBlockWithEDAC) // another placeholder
```

Project Risks

Dan Wagner

Risk Matrix (Pre-Mitigation)

	Negligible Impact	Low Impact	Moderate Impact	Extreme Impact	Catastrophic Impact
Almost Certain			Unable to get return sphere	Photodiode Temp Changes	Cannot perform alignment
High Probability			Short inability to downlink	Structure fails vibration test	Components not manufacturable
Moderate Probability			Main loop below 50Hz		
Low Probability					ADC Failure
Negligible Probability					

Risk Mitigation (Structures & Optics)

Risk	Mitigation Strategy	Outcome
Components cannot be manufactured	Reviewed structure with Prof. Rhode to ensure manufacturability	Likelihood reduced
Structure fails vibration requirement	Variety of boundary conditions considered in SOLIDWORKS vibration simulations	Likelihood reduced
Cannot perform alignment	Reach out to other local companies to use their alignment facilities	Severity greatly reduced, Using Meadowlark alignment facility
Unable to procure return sphere	Use ball bearings and update alignment procedure for convex return instead of concave return	Likelihood greatly reduced

Risk Mitigation (Electronics & Software)

Risk	Mitigation Strategy	Outcome
Primary ADC Failure	Backup 12 bit ADC built into Teensy microcontroller meets SNR requirement	Severity greatly reduced, 0 fault tolerant → 1 fault tolerant
Photodiode responsivity changes with temperature	Optical bench thermal isolation and optics temperature sensor with 0.043°C resolution	Severity and likelihood reduced
Radiation Errors in Memory	Memory scrubbing, real time error detection and correction (EDAC), program memory rollback	Reduced severity
Payload unable to downlink for more orbits than planned	Implement command to only store data from sunset events, as these likely will have higher fidelity	Reduced severity, Payload will store only the most useful data until it reestablishes downlink

Risk Matrix (Pre-Mitigation)

	Negligible Impact	Low Impact	Moderate Impact	Extreme Impact	Catastrophic Impact
Almost Certain			Unable to get return sphere	Photodiode Temp Changes	No alignment facility access
High Probability			Short inability to downlink	Structure fails vibration test	Components not manufacturable
Moderate Probability			Main loop below 50Hz		
Low Probability					ADC Failure
Negligible Probability					

Risk Matrix (Post-Mitigation)

	Negligible Impact	Low Impact	Moderate Impact	Extreme Impact	Catastrophic Impact
Almost Certain					
High Probability		Short inability to downlink			
Moderate Probability			Photodiode Temp Changes		
Low Probability	Single ADC Failure	Main loop below 50Hz		Structure fails vibration test	
Negligible Probability			Unable to get return sphere	Components not manufacturable	No alignment facility access

Verification & Validation

Matt Bridges

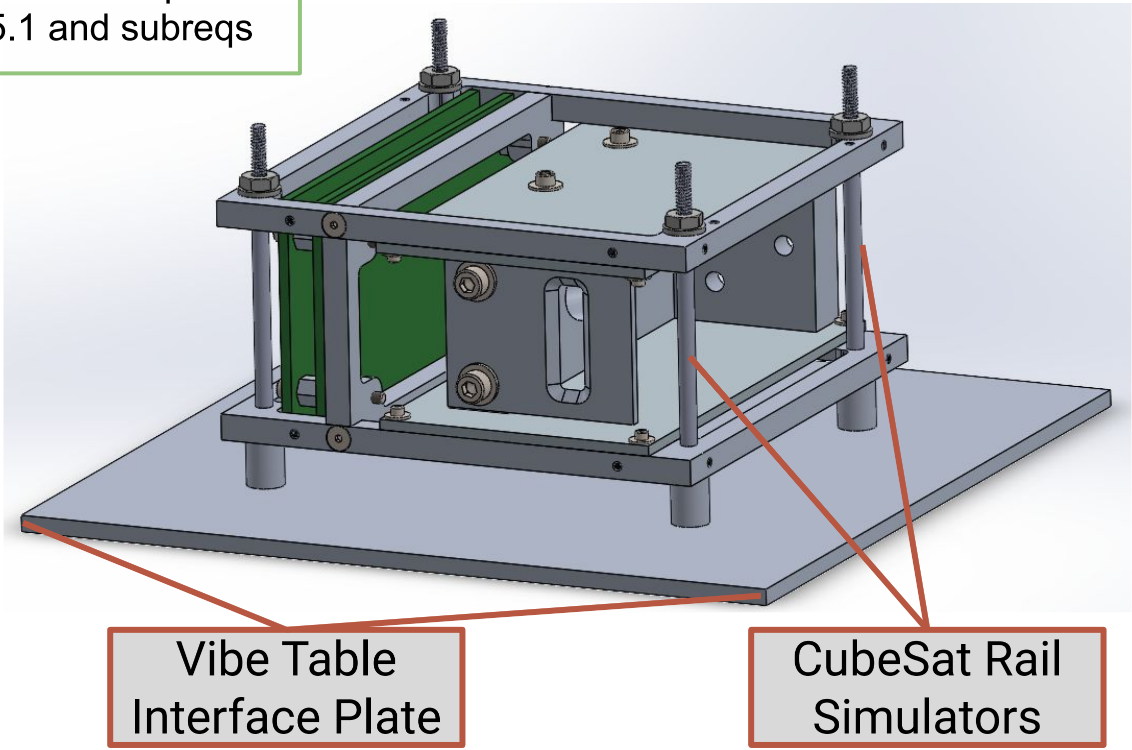
Requirements Coverage

Test Scope	Verification Procedure Name	Requirements Covered	Verification Type
Component Level	Electronics system test	1.5	Test
	Memory Error Testing	1.3, 2.2	Analysis
	System State Monitoring	1.4, 1.4.1, 1.4.2, 1.4.3	Test
	Collection Window Timing	1.2, 1.1.4	Analysis
	Downlink Data Transfer	2.3	Analysis
Subsystem Level	Data Collection Test	1.1 - 1.1.4, 1.4.1 - 1.4.3, 2.0, 2.1	Test
	Alignment	3.1 - 3.2	Test
	Optics Measurements	3.2, 3.2.1, 3.2.2	Analysis
	Solar Tracking test	3.3	Test
System Level	Solar Attenuation	1, 2, 3	Test
	Regulated light test	1.3 - 1.5, 2.0, 2.1, 3.1	Test
	Structure Measurements	4.1, 4.2	Inspection
	Vibration Test	5.1, 5.1.1, 5.1.2	Test
	Thermal Test	5.2, 5.2.1, 5.2.2	Test
	Vacuum Test	5.3	Test

Structure: Vibration Test

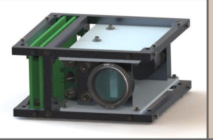
Subsystem-Level Test

Verifies reqs:
5.1 and subreqs



- The structure's lowest natural frequency can be found through a vibration table scan
  - Range of frequencies: 20-2000 Hz [10]
- Will be run with just the structure first, prior to whole system test
  - Ensure no frequencies excite structure or disrupt other subsystem functionality

Structure CPE



Vibrational Modes Simulation & Testing

Optics: Alignment Analysis

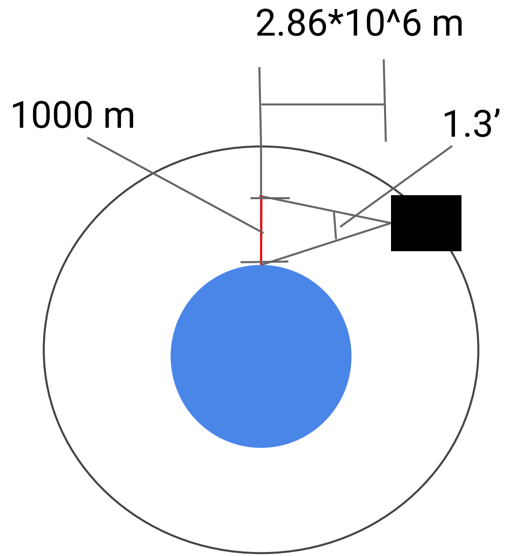
Subsystem-Level Test

- Pinhole Measurement
  - Due to small size, measured with telescopic gauge
- Using pinhole diameter, calculate field of view
  - Result should be ~ 1.3 arcminutes
- Calculate the vertical resolution/field of view
  - Result should be ~ 1km

$$FOV = 57.3 * \frac{pinhole\ diameter}{OAP\ focal\ length}\ (rad)$$

$$Vertical\ Resolution = 2.86 * 10^6 * tan(FOV)$$

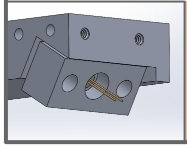
Verifies reqs: 3.2 and subreqs



Interferometer Measurements:

- Use interferometer to measure the Modulation Transfer Function (MTF) of the optical system during alignment

Optics CPE

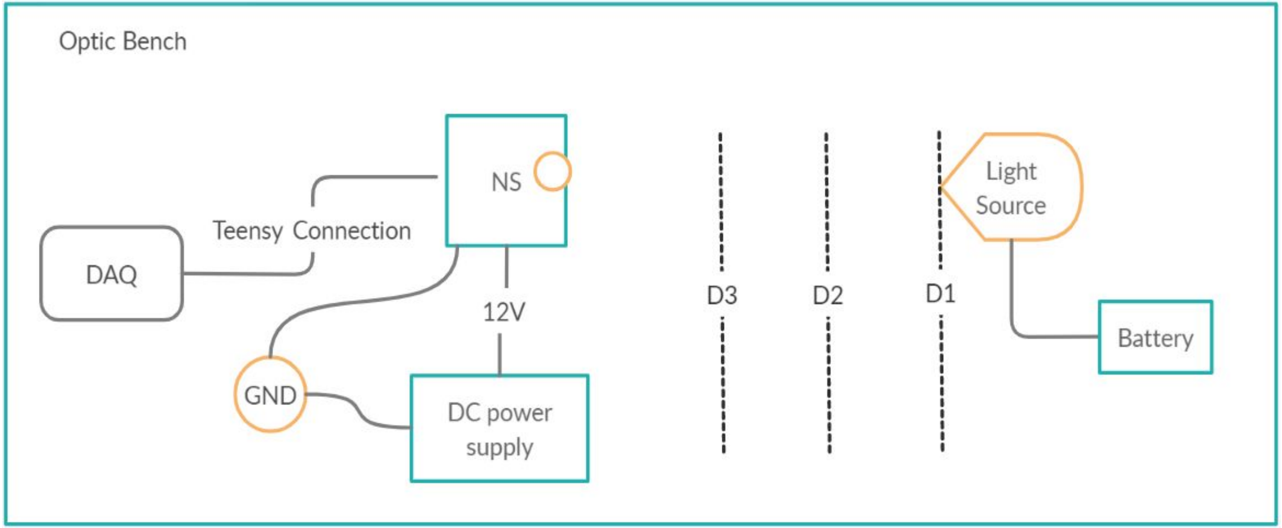


Match SAM-II Instrument Legacy Performance

Electronics: Regulated Light Test

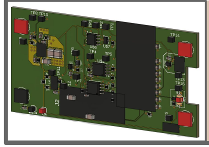
System-Level Test

- Integrated system test using light source with known luminosity and frequency distribution
- Characterize signal to noise ratio through data analysis
  - ‘snr’ function, Matlab
  - Collecting data through range of incident flux
  - Compare to flight conditions
- Check for photodiode saturation
  - Looking for plateau in photon count



Verifies reqs:
1.3-1.5, 2.0, 2.1, 3.1

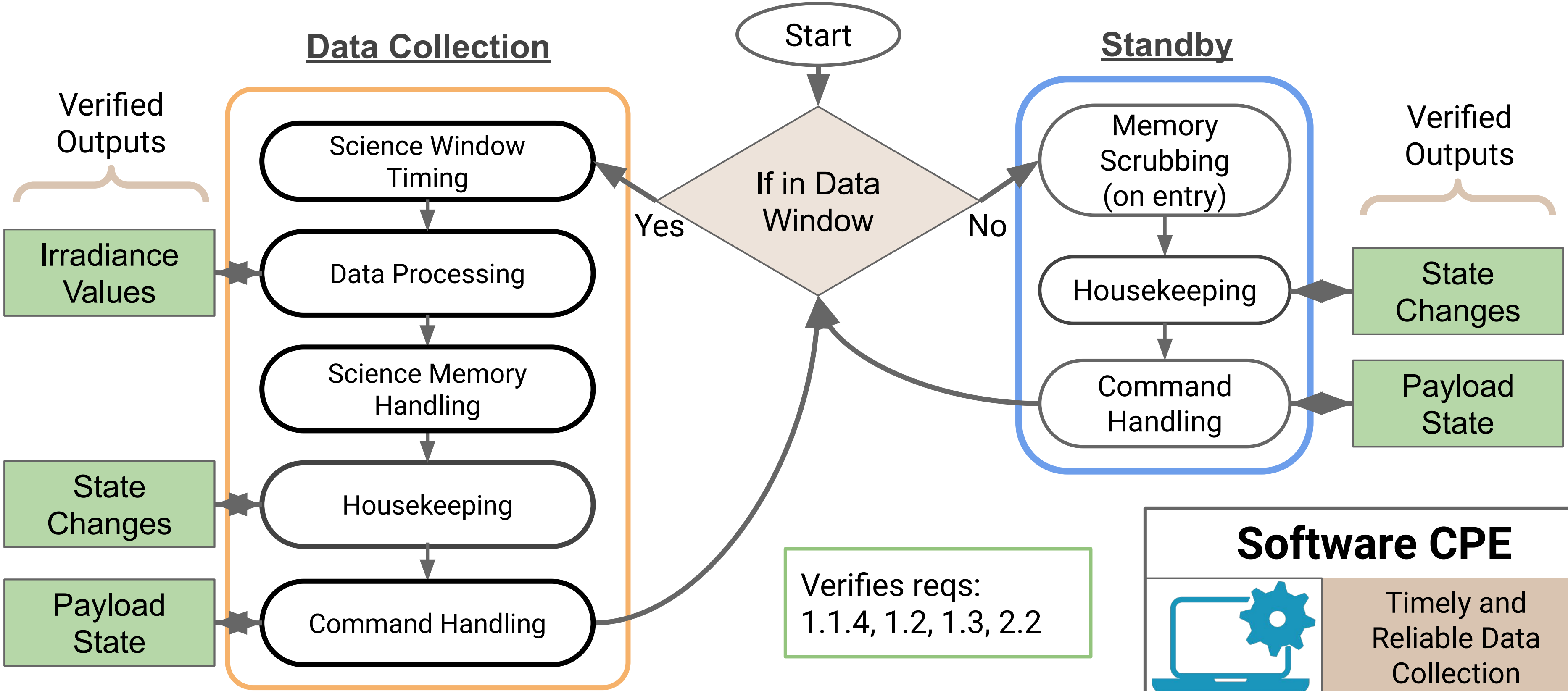
Electronics CPE



Low-Noise Signal Processing

Software: Main Loop Simulation

Subsystem-Level Test



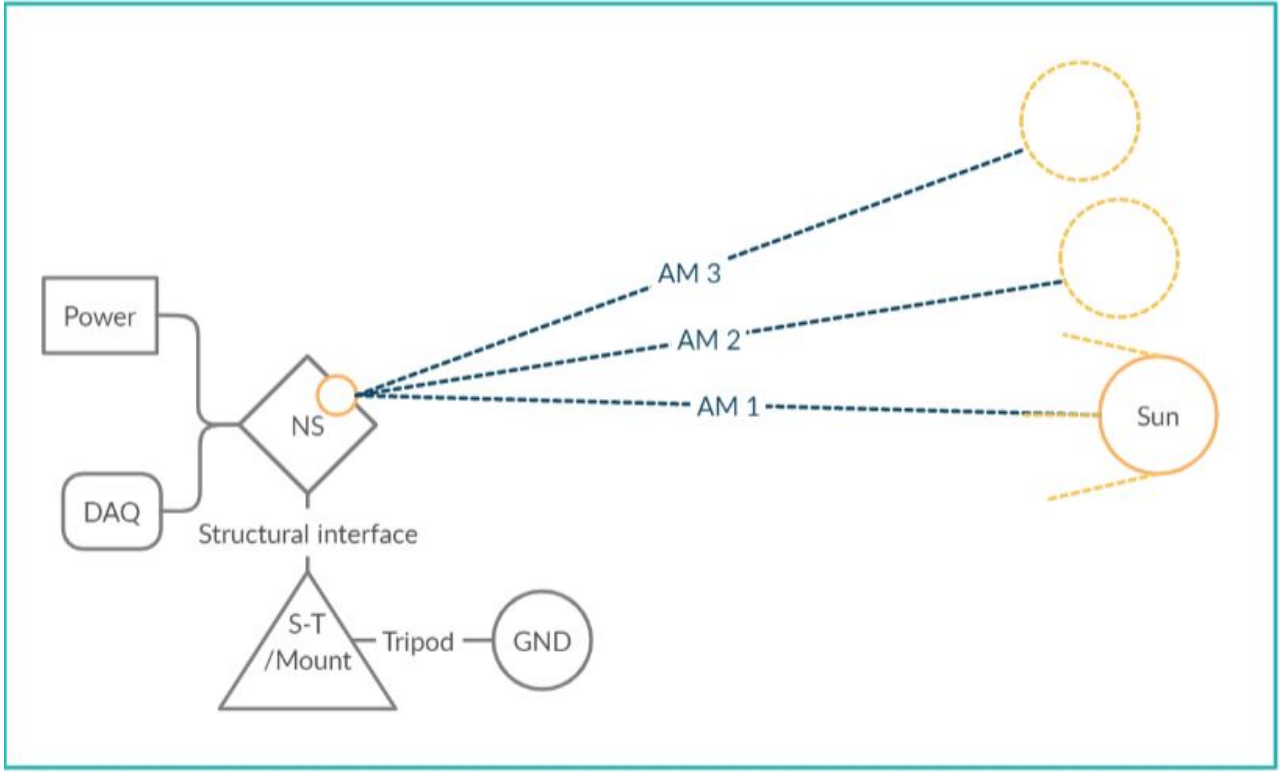
Verifies reqs:
1.1.4, 1.2, 1.3, 2.2

Software CPE

Timely and Reliable Data Collection

Solar Attenuation Test

System-Level Test



Objectives:

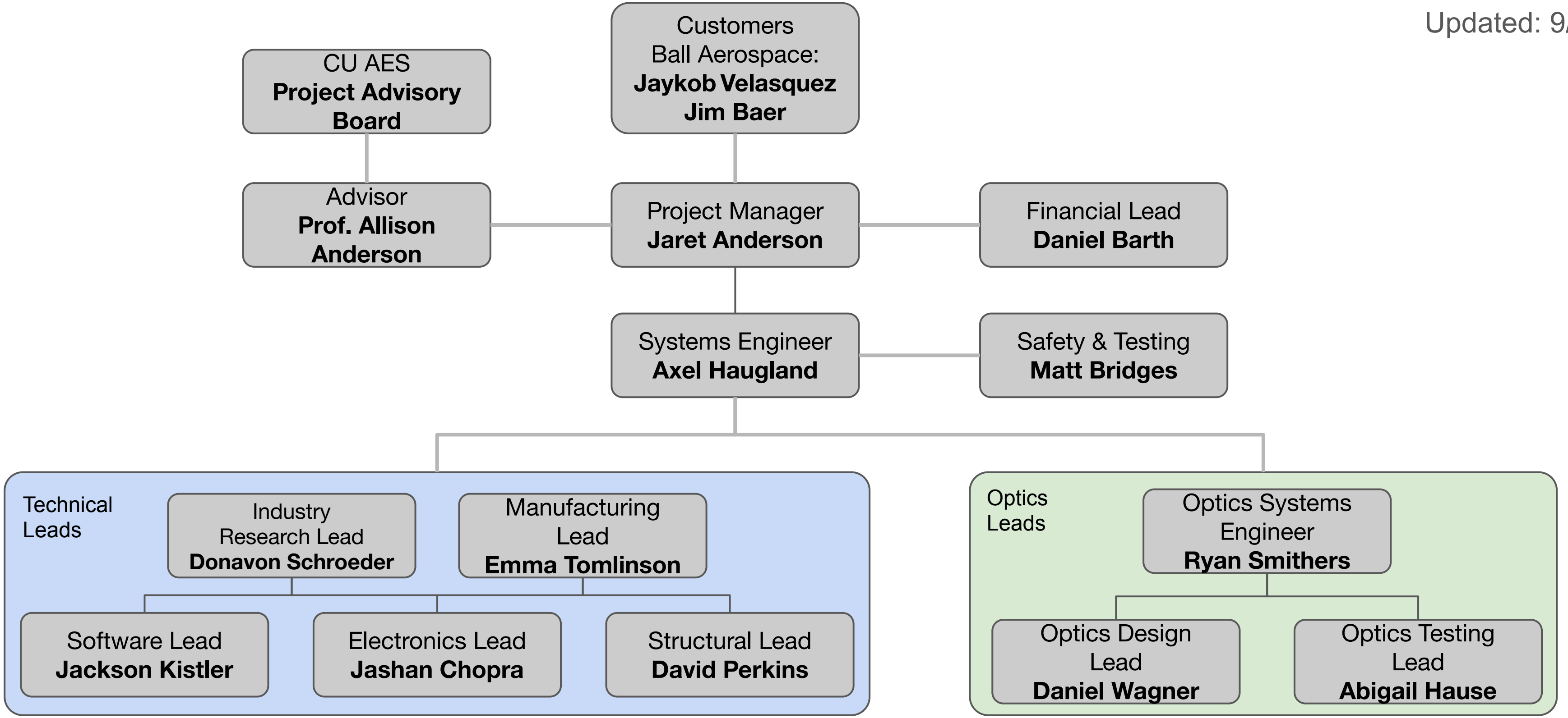
- Develop routine functionality for the NanoSam system
- Obtain measurements at various air-mass (AM) conditions for Langley plot analysis
- AM conditions, ranging from 1 to 3
  - AM = sec(zenith angle)
  - Zenith angle found by NOAA Solar Position Calculator
- Overlapped verification of reqs in level 1.0, 2.0, and 3.0

Project Planning

Jaret Anderson

Organization Chart

Updated: 9/16/20



Work Breakdown Structure

Structures
- Structure Design
- Thermal Simulation
- Vibrational Simulation
- Order Parts
- Manufacture Structure
- Structure Integration
- Vibration Testing

Optics Design
- Alignment Tooling Design
- Machining Error Analysis
- Order Parts
- NS1 Hardware Alignment
- MTF Determination
- Optimize Aperture Size
- NS2 Hardware Alignment

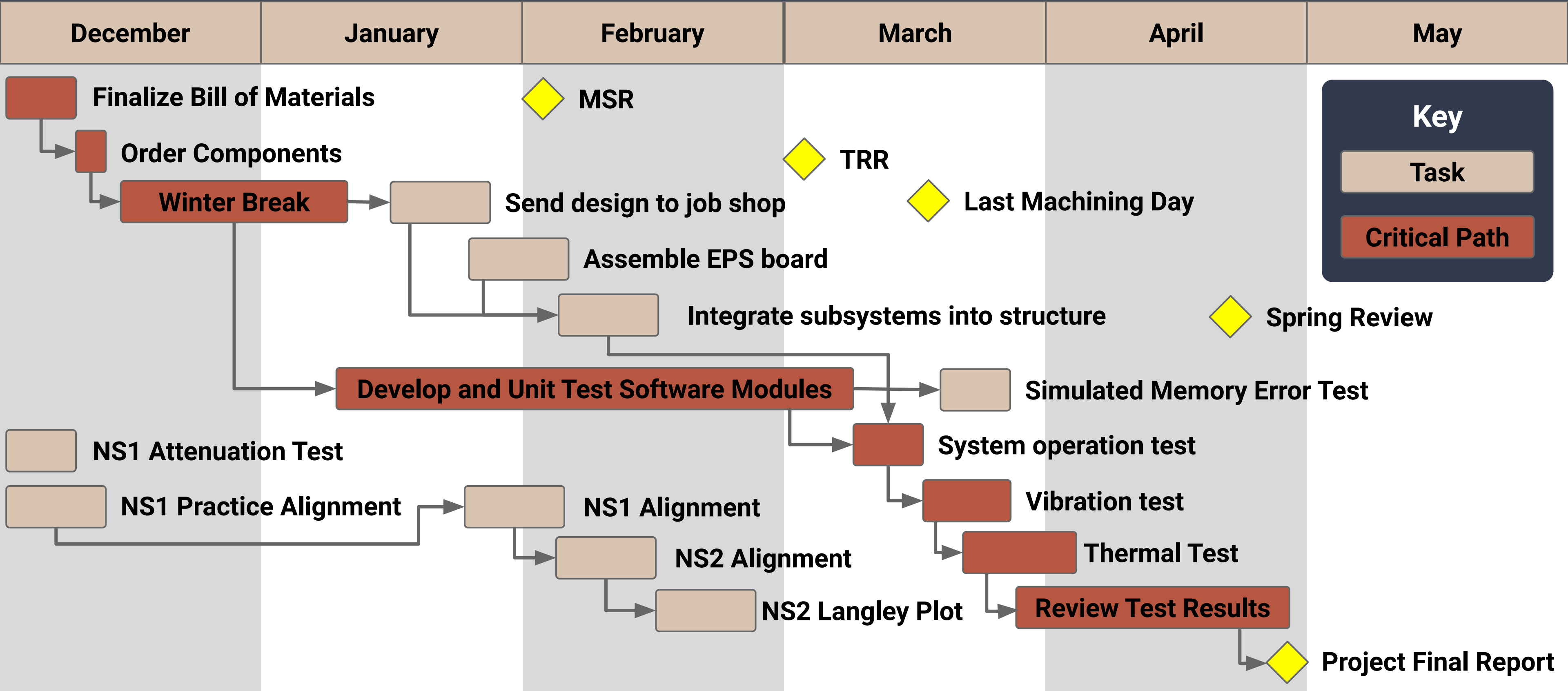
Optics Testing
- Solar Tracking Test (NS1)
- Attenuation Test (NS1)
- Langley Plot (NS1)
- Above Tests w/ NS2 Hardware

Software
- Module Architecture
- Module I/O
- Dev Priority Selection
- Module Pseudocode
- Module Development
- Unit Testing
- Integration Testing

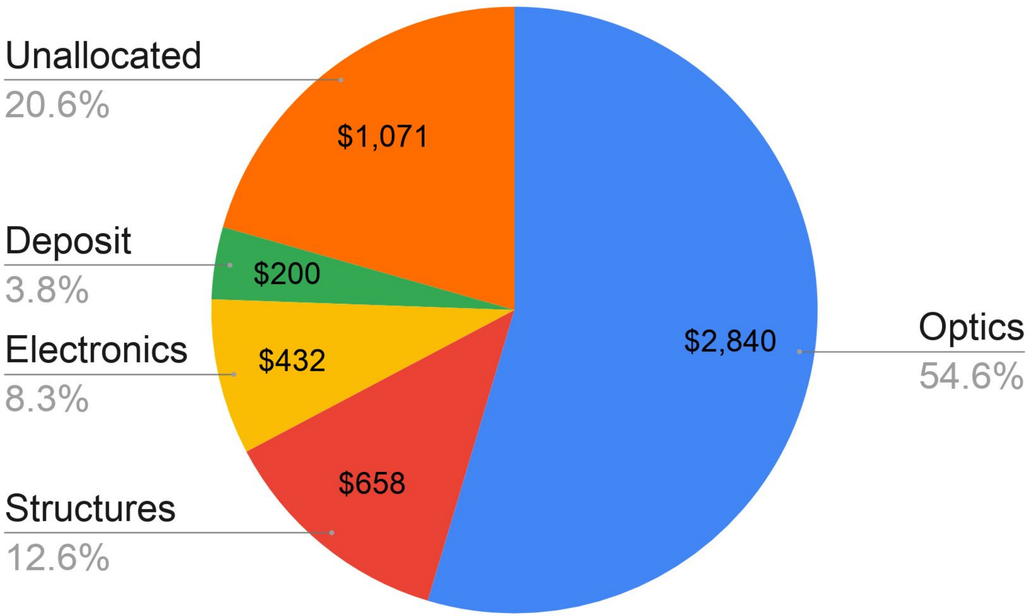
Integrated Testing
- System Operation
- Attenuation Test (NS2)
- Regulated Light Test
- Thermal Test
- Vibration Test

Key
- Complete
- In Progress
- Future Work

Work Plan


December
January
February
March
April
May
Finalize Bill of Materials
MSR
Order Components
TRR
Winter Break
Send design to job shop
Last Machining Day
Assemble EPS board
Integrate subsystems into structure
Spring Review
Develop and Unit Test Software Modules
Simulated Memory Error Test
NS1 Attenuation Test
System operation test
NS1 Practice Alignment
NS1 Alignment
Vibration test
NS2 Alignment
Thermal Test
NS2 Langley Plot
Review Test Results
Project Final Report
Key
Task
Critical Path

Cost Plan

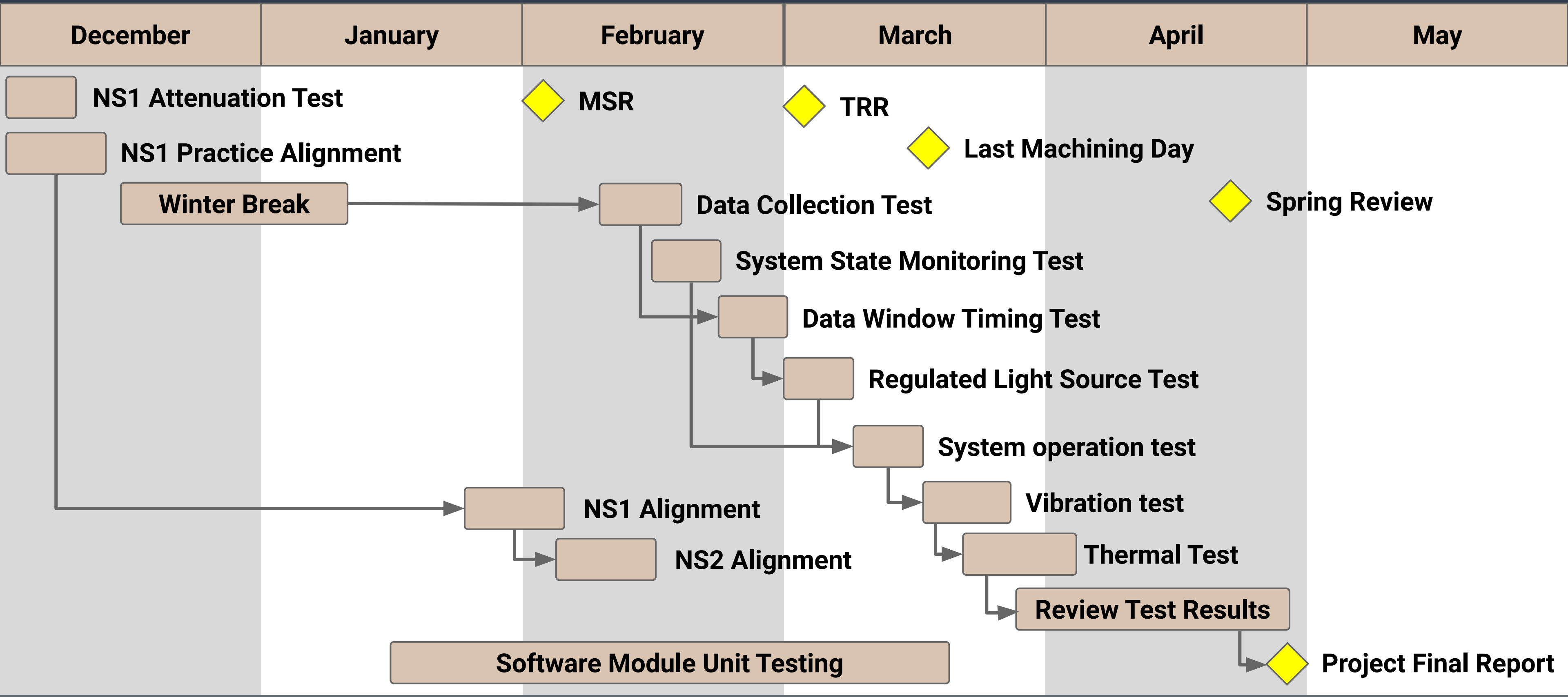


- Total Budget of $5000
- Expected Cost: $1965
- 2x margin applied to designated funds
- Budget for optics primarily from the cost of alignment tooling and O/A mirror (~$1500 w/ margin)
- Electronics cost plan does not include parts that could be reused
- $200 Pilot deposit for access to on-campus tools and facilities has no margin (no margin applied)
- Unallocated funds most likely to be used if required for access to testing facilities

Test Plan

Test Scope	Verification Procedure Name	Equipment	Verification Type
Component Level	Electronics system test	Power supply, DMM, scope	Test
	Memory Error Testing	Software module, unit test function	Analysis
	System State Monitoring	Power supply, electronics, and software	Test
	Collection Window Timing	Software module, unit test function	Analysis
	Downlink Data Transfer	Software module, unit test function, stubbed incoming data	Analysis
Subsystem Level	Data Collection Test	Power supply, payload, test computer	Test
	Alignment	Alignment tooling, optics bench, return sphere, interferometer	Test
	Optics Measurements	Ruler, optics and structure, solar tracker	Analysis
	Solar Tracking test	Solar Tracker	Test
System Level	Solar Attenuation	Solar Tracker & mount, integrated system, laptop, power supply	Test
	Regulated light test	Known light source, integrated system, laptop, power supply	Test
	Structure Measurements	Ruler, payload, scale, calipers	Inspection
	Vibration Test	Vibration table, vibration test stand, structure, stand-in components	Test
	Thermal Test	Oven, integrated payload, pass-through connector, laptop, power supply	Test

Test Flow



December
January
February
March
April
May
NS1 Attenuation Test
MSR
TRR
NS1 Practice Alignment
Last Machining Day
Winter Break
Data Collection Test
Spring Review
System State Monitoring Test
Data Window Timing Test
Regulated Light Source Test
System operation test
NS1 Alignment
Vibration test
NS2 Alignment
Thermal Test
Review Test Results
Software Module Unit Testing
Project Final Report

Acknowledgements

Our Customers:

Jim Baer & Jaykob Velasquez
Ball Aerospace

CU Aerospace Department:

Dr. Allison Anderson
The PAB
… and an amazing cohort of professors that answer our endless questions

Our Peer Evaluators:

Lara Buri & Colin Claytor
Team WASP
… and all of our personal friends who should send us a bill for their time doing engineering review

Our Local Professionals:

Meadowlark Optics Inc
Blue Canyon Technologies
John Ferguson

Questions

References

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Backup Slides

Table of Contents

Backup Slides: Risk

Electronics Risks

Risk	Mitigation
Voltage regulator noise	Low noise components, voltage reference for ADC, recommended routing patterns
Pin overvoltages	TVS diode on heating resistor, zener diode on ADC input, voltage regulators
ADC failure	Backup 12 bit ADC on Teensy meets SNR requirements
ESD component destruction	Test plan recommendations, ESD safety in test procedures
Signal integrity	Signal-ground connector layout, low frequency signals, off-board wire shielding, robust SPI communication design

Electronics Risks

Risk	Mitigation
ESD damage or component issues go undetected	Abundant test points to check all input/outputs to each IC
Photodiode saturation	Reverse bias voltage applied on pin >3.3V
Photodiode responsivity changes	Software correction via high sensitivity optical temp sensor IC
ADC Dynamic Range	Feedback resistor sized for maximum expected output current with margin of error
Radiation triggers Teensy 4.0 latch up	External watchdog monitoring circuit and backup watchdog implementation in software (using microprocessor built in)

Optics Risks

Risk	Mitigation
No access to ball alignment facility	Approach other interferometer owners to ask for access Alignment tooling design (maybe)
MTF and Alignment Precision	Complete Zemax tolerance model
Center Wavelength of Filter change due to Temperature	Thermally isolate the bandpass filter
Vertical Resolution	Size pinhole to correspond to 1 km vertical resolution
Lack of Return Sphere for Alignment	Use ball bearings and update alignment procedure for convex return instead of concave return

Structures Risks

Risk	Mitigation
Components cannot be manufactured or cannot be assembled	Discussions with Matt Rhode to ensure manufacturability
Structure fails vibrational requirements or is damaged during testing	Numerous boundary conditions considered in SOLIDWORKS, full suite of simulations conducted
Structure fails thermal requirements	Thermal isolation of optic and implementation of heater-temperature feedback loop
Interfacing with Optics subteam	Frequent reviews with our customer with industry optics experience to maximize optic performance
Interfacing with EPS subteam	Reviews with Jashan to ensure electronics would fit and could be easily accessed if needed.

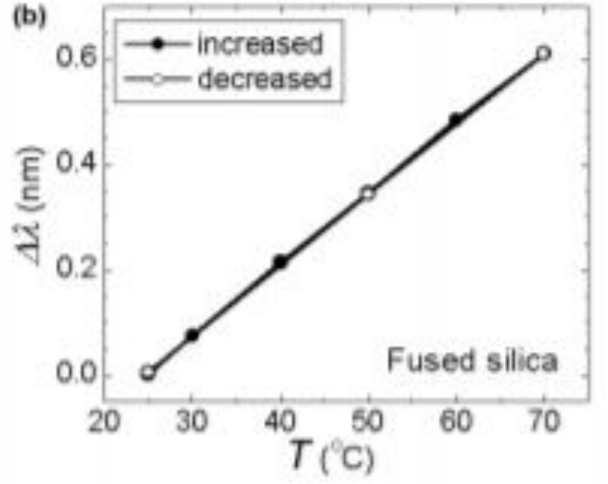
Software Risks

Risk	Mitigation
Overhead infringes on 50Hz sample rate	Spread operations across multiple timing segments
CMOS latchup	Multiple external watchdogs to trigger reset
Radiation errors in memory	Memory scrubbing, real time EDAC, program rollback
Signal interference	Hamming codes and redundant SPI and USB communication schemes
Prolonged downlink interval	Adjustable sample rate to conserve memory

Backup Slides: Optics

Optics: Filter CWL Changes Due to Temperature

Fused Silica Filter CWL change at 1550 nm [11]

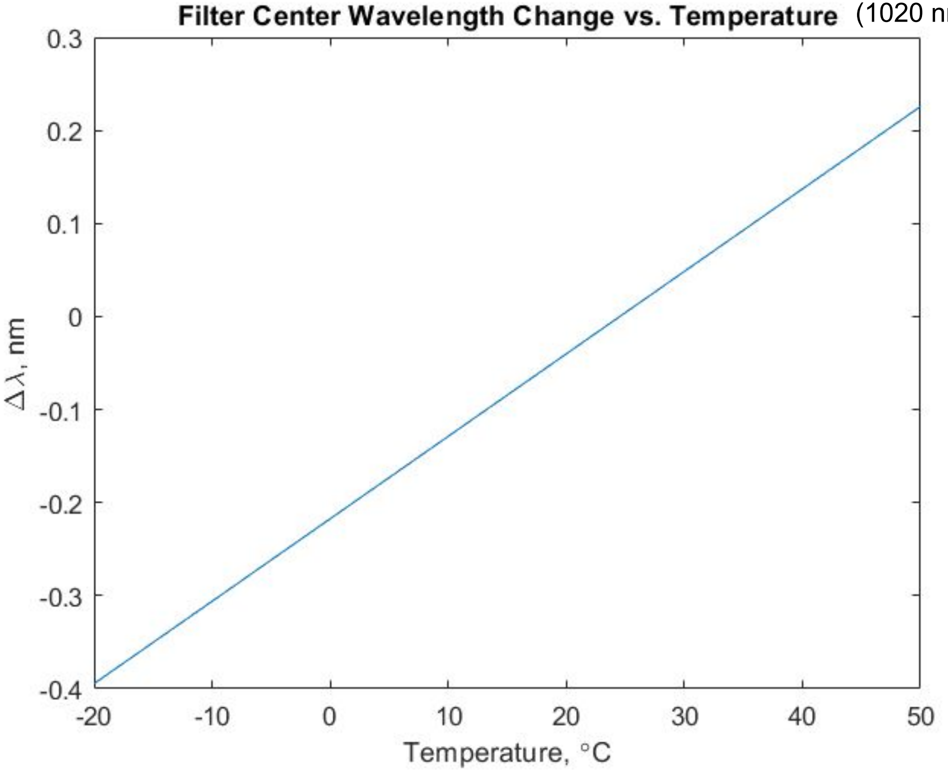


$\Delta\lambda_{1020} = 1020/1550*\Delta\lambda_{1550}$

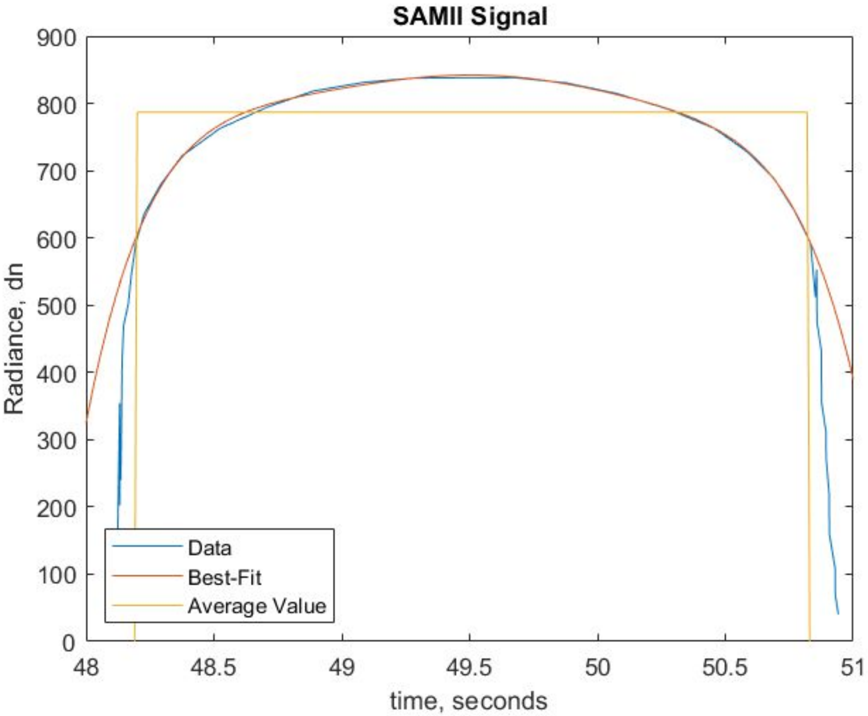
Values extrapolated over T = -20℃ to 50℃

$\Delta\lambda_{1020} = 0.0089\,T - 0.2174$ nm

(1020 nm)

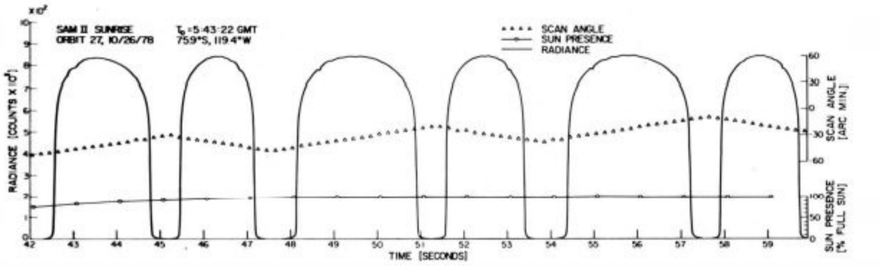


Optics: Uniform Solar Disk Assumption Correction Factor



- Solar disk size not uniform, uniform assumption does not account for max value of incident power, correction factor required
- Obtained by fitting SAMII signal curve and finding integral over data window to find average signal value
- F_{sd} = Radiance max/Radiance average = $P_{inc,max}/P_{inc,avg}$

SAM II Signal [12]

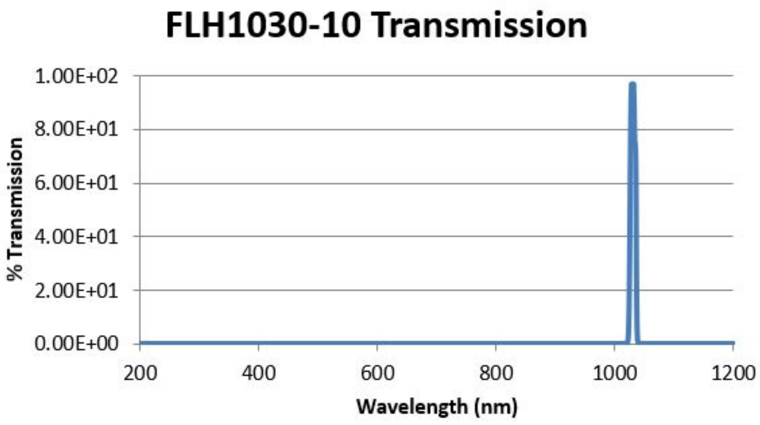


Optics: System Transmission Factor

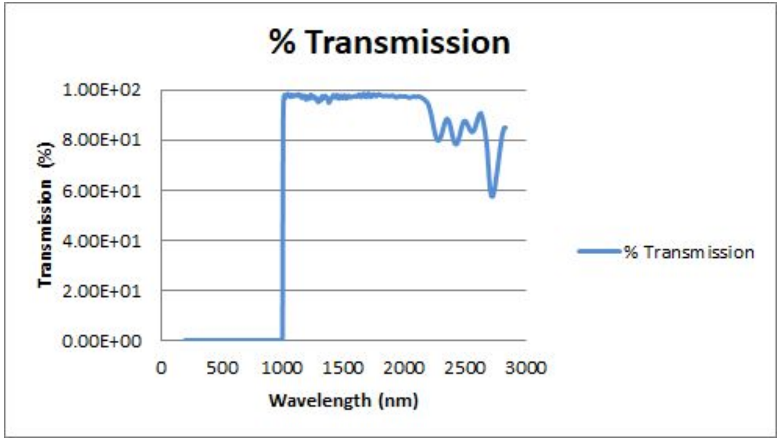
$F_{sys} = F_{bandpass} F_{longpass} F_{OAP}$

Filter transmission factors obtained from manufacturer (ThorLabs)

Bandpass:

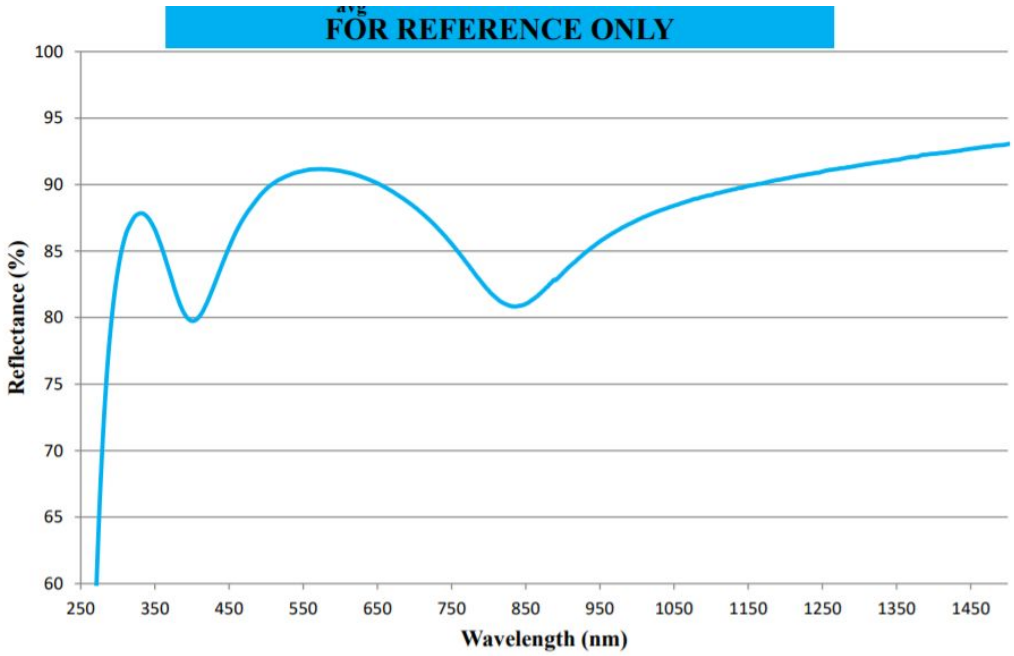


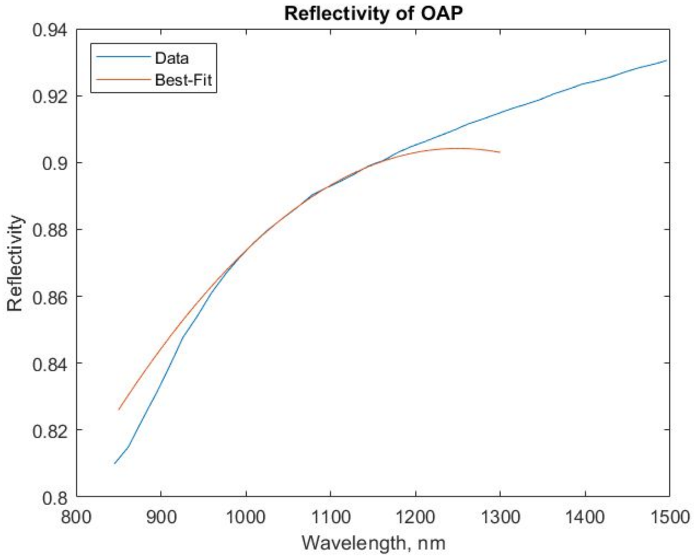
Transmission for FELH1000 Longwave pass filter



Optics: Mirror Reflectivity/Transmission Factor

OAP Reflectivity From Edmund Optics





Estimated using quadratic equation:

$F_{OAP} = -4.8878*10^{-7}(\lambda+\Delta\lambda)^2 + 0.0012(\lambda+\Delta\lambda)+0.1405$

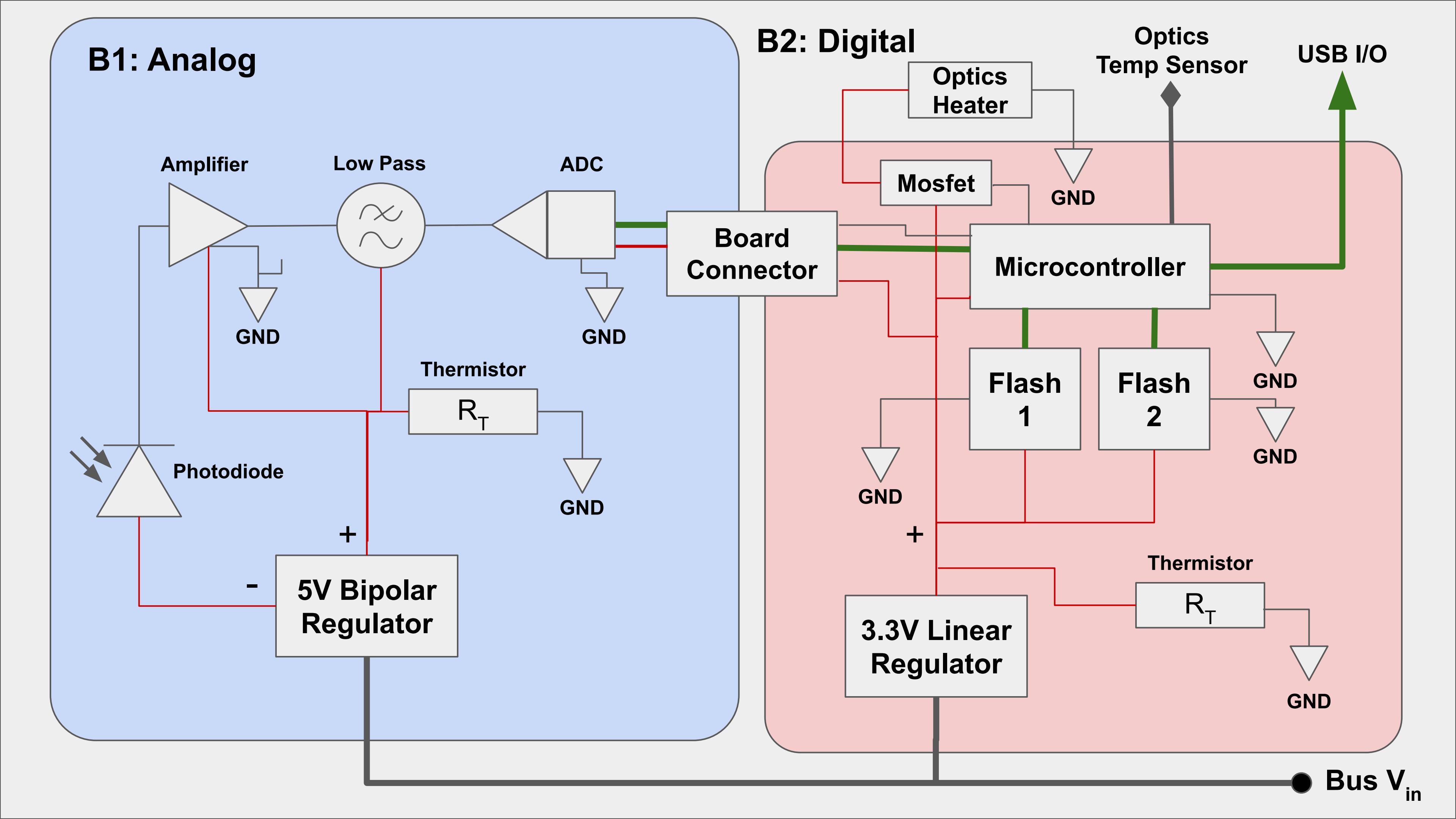
Backup Slides: Electronics

Electronics: Key Values

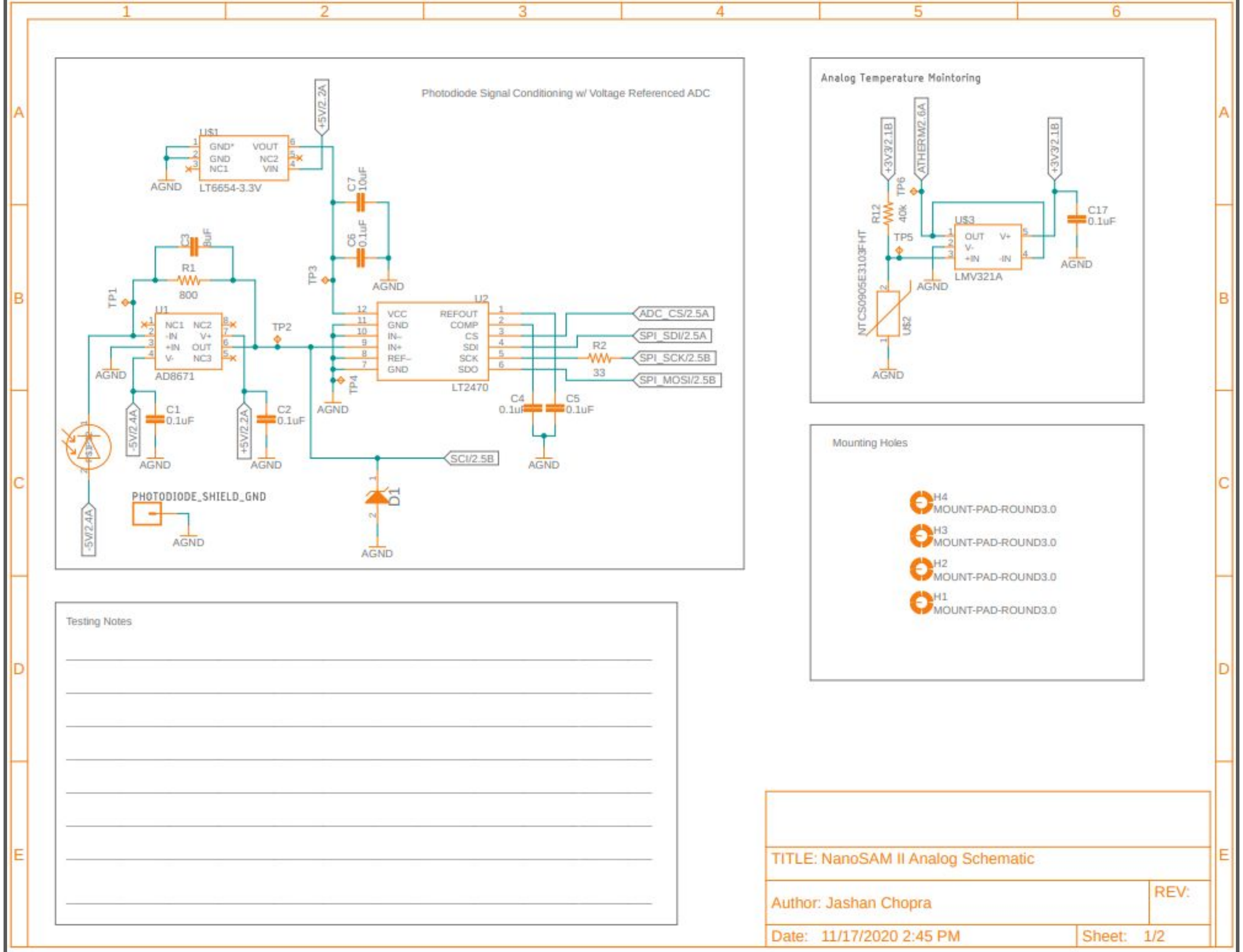
Analog Front End Characteristics	Value	Units	Condition
Photodiode Current	0.004095	A	Expected Max
ADC Voltage	3.3	V	Expected
ADC # Bits	16	bits	Datasheet
Least Significant Bit (LSB)	0.00005035400391	V	Expected
Feedback Resistor	765.5677656	Ohm	Expected
Digital Supply Voltage	3.3	V	Expected
Analog Supply Voltage	5	V	Expected
Signal Frequency	1.04E+02	Hz	Expected
Feedback Capacitor	8.00E-06	F	Expected

Optical Characteristcs	Value	Units	Condition
Incident Power	0.0091	W	Maximum
Responsivity (Datasheet)	0.45	A / W	298 K
Responsivity (Expected)	0.45	A / W	273 K
90% ADC Range	3.135	V	

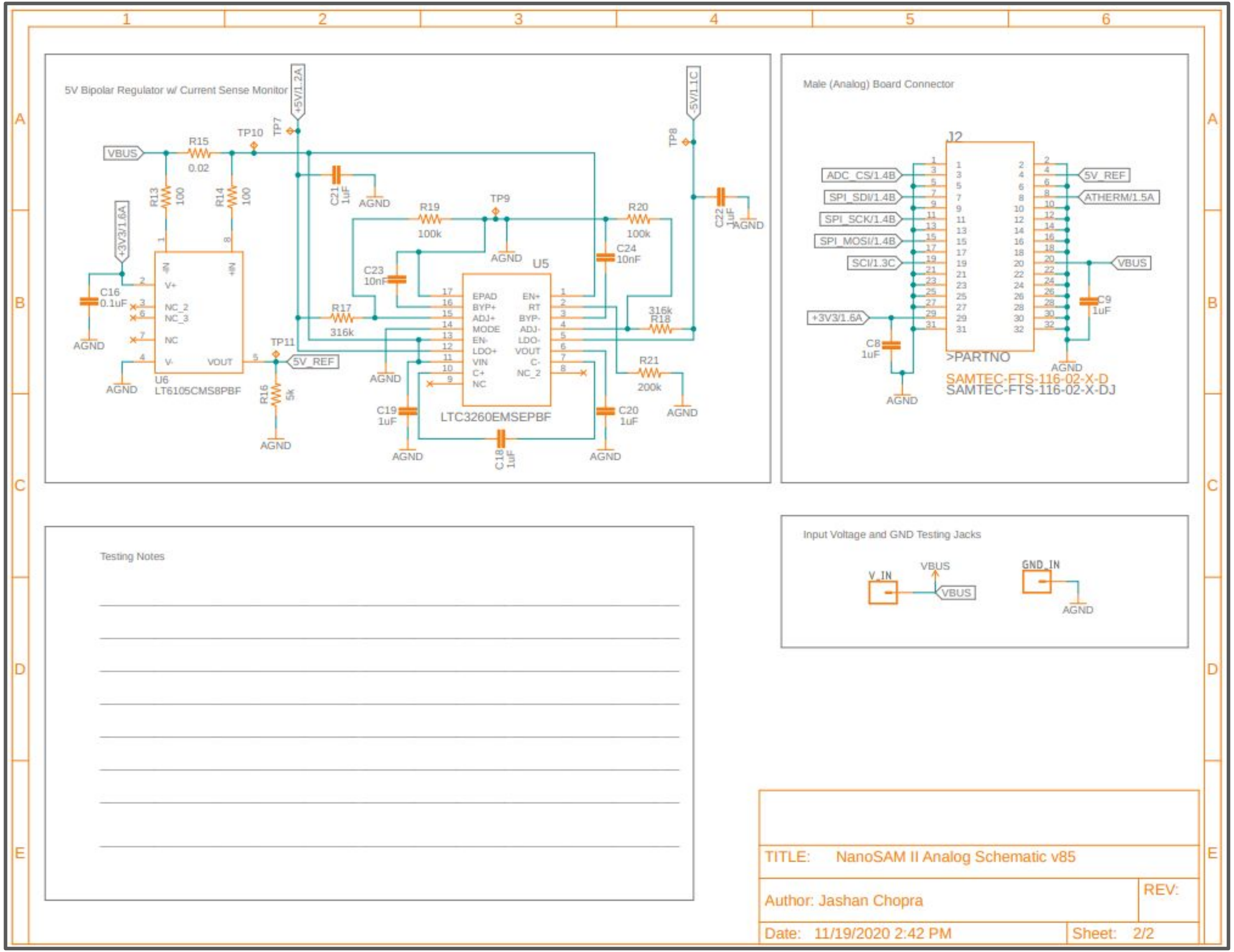
Storage Requirements	Value	Units	Condition
ADC Data Collection Rate	833	samples / s	Datasheet
Science Collection Period	240	s	Via orbital calculation
Science Data Storage	95961600	bits	Expected Max
Housekeeping Analog Pins	8	inputs	Maximum
Housekeeping Collection Rate	10	samples / s	Up to Software
Orbital Period	5676.808417	s	Via orbital calculation
Microcontroller ADC Bits	12	bits	Datasheet
Housekeeping Data Storage	5449736.08	bits	Expected Max
Total Bits Required	101411336.1	bits	Expected Max
Total Bits Required	101.4113361	Mb	Expected Max
External Flash Storage	256	Mb	Datasheet
Teensy Flash Storage	15.872	Mb	Datasheet
Storage Used %	39.61380316	%	Expected Max


B1: Analog
Amplifier
Low Pass
ADC
GND
GND
Thermistor
R_T
GND
Photodiode
+
-
5V Bipolar Regulator
B2: Digital
Optics Heater
Optics Temp Sensor
USB I/O
Mosfet
GND
Board Connector
Microcontroller
GND
Flash 1
Flash 2
GND
GND
+
Thermistor
R_T
3.3V Linear Regulator
GND
Bus V_{in}

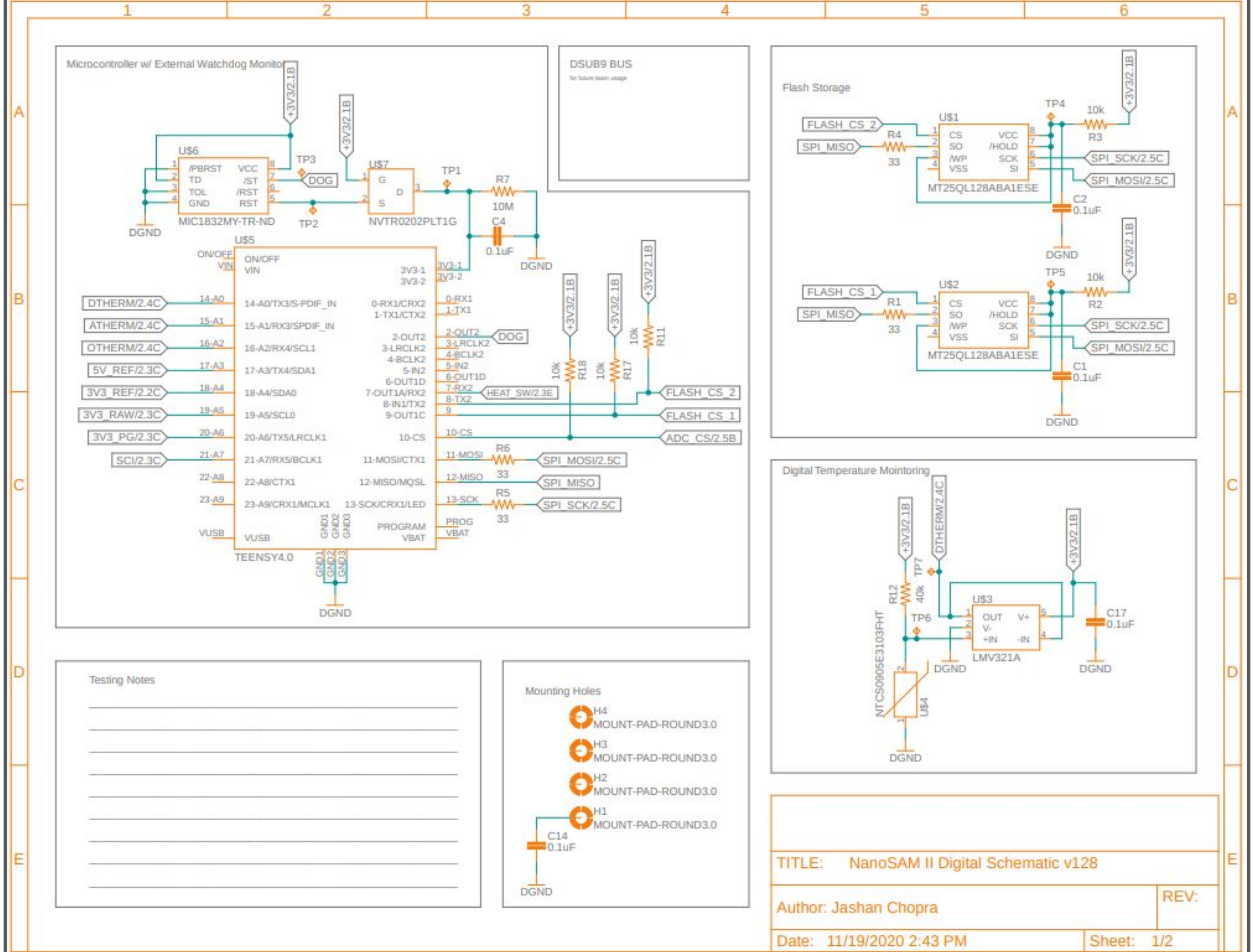
Analog Board (1/2)



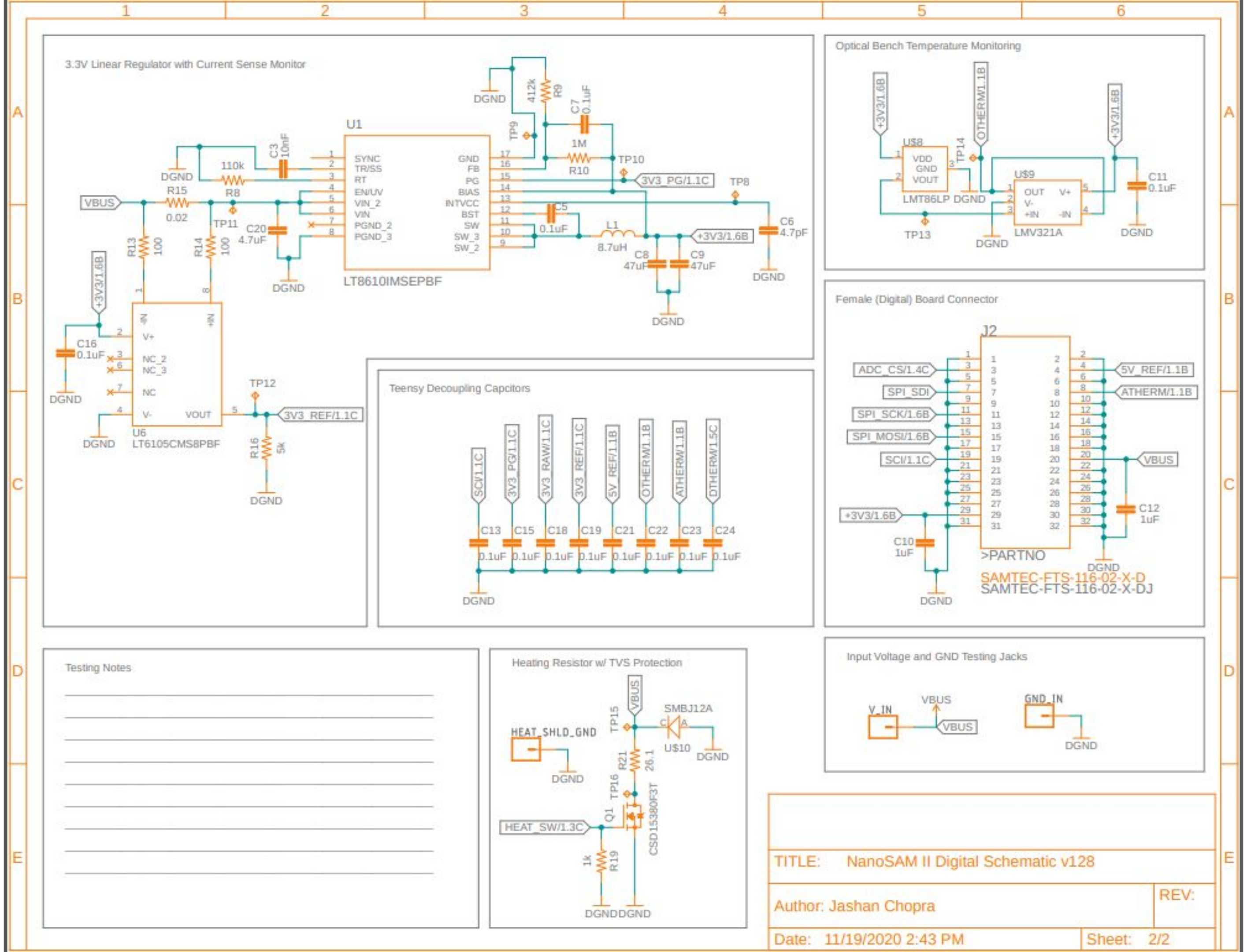
Analog Board (2/2)



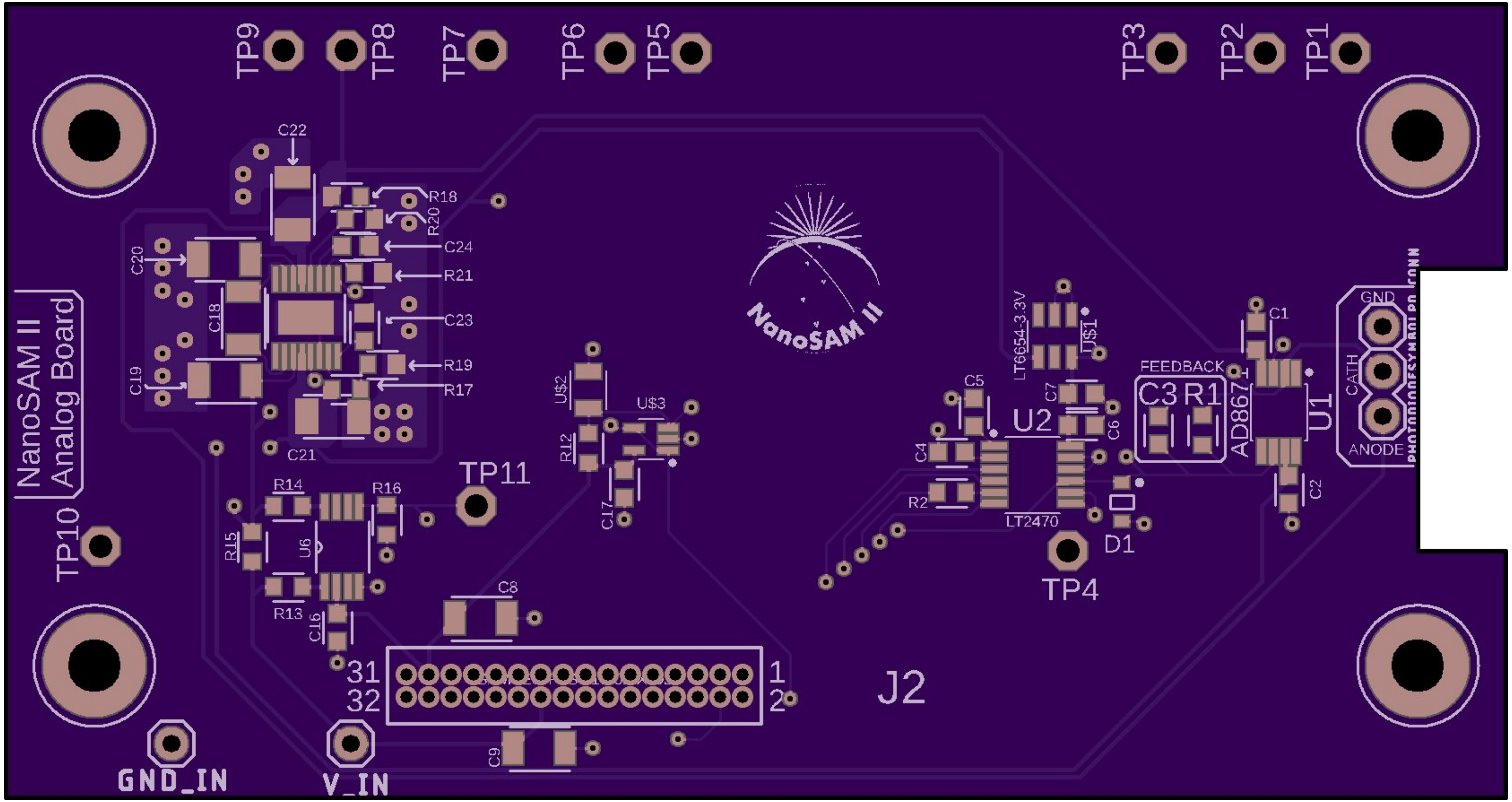
Digital Board (1/2)



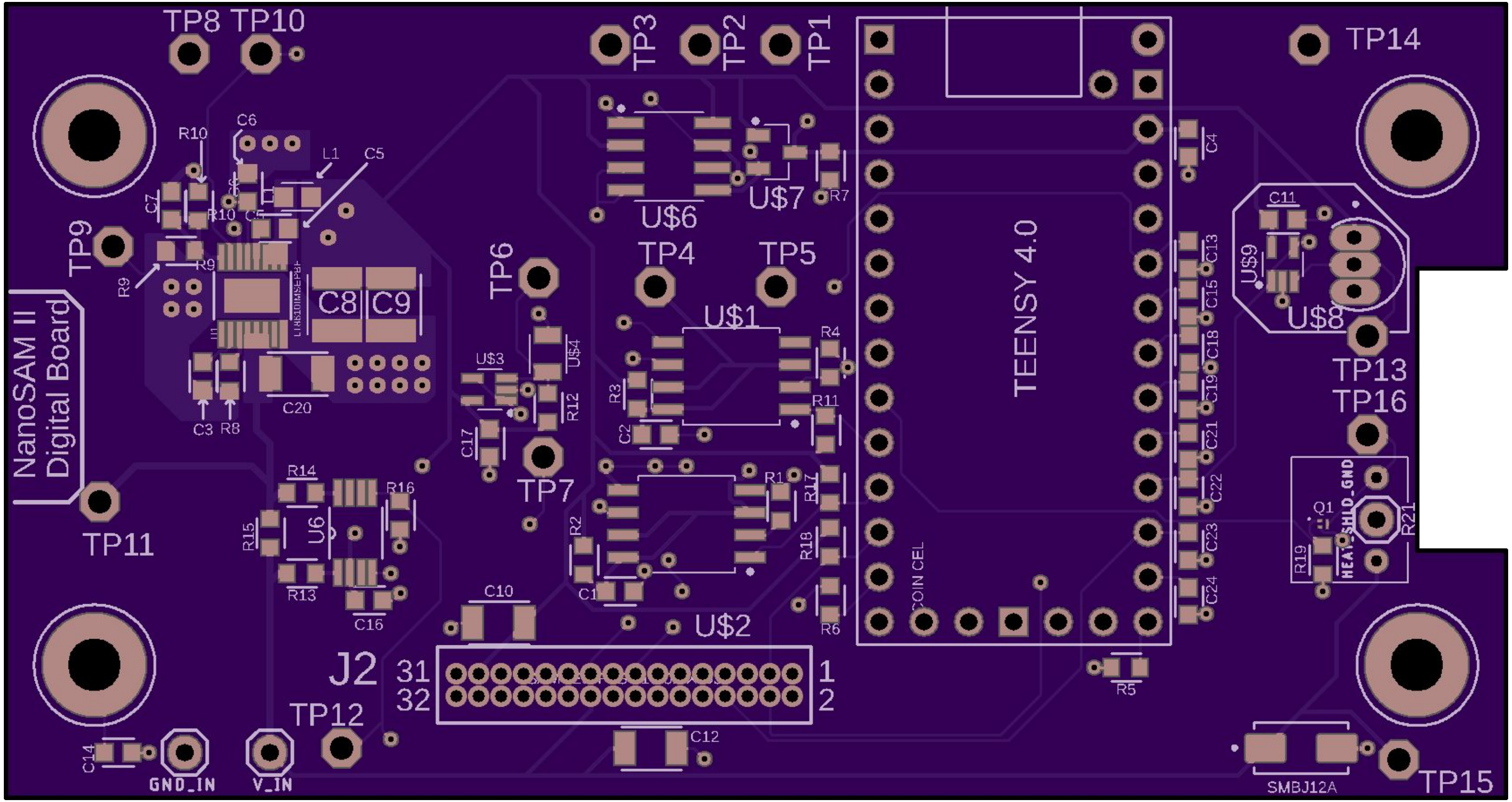
Digital Board (2/2)



OSHPark CAM Job Render [Analog]



OSHPark CAM Job Render [Digital]



Electronics: Extended Bill of Materials

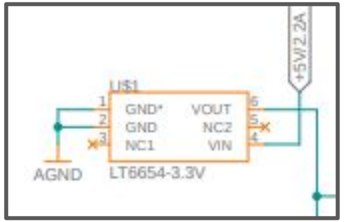
Part	Value	Device	Package	Size (mm^2)	DK Part #	Cost	Temperature Rating
U$2	TEENSY4.0	TEENSY4.0	TEENSY4.0	814.1	1568-DEV-16997-ND	24.38	-40°C ~ 85°C
U$3	AD8671	AD8671	SO8	31	AD8671ARMZ-ND	2.89	-40°C ~ 125°C
U$4	LT6105	LT6105	MSOP8	4.7925	LT6105HDCB#TRMPBFTR-ND	3.46	-40°C ~ 125°C
U$5	LTC2470	LTC2470	MSOP12	10.5	LTC2470IMS#TRPBFTR-ND	5.01	-40°C ~ 85°C
U$12	LT8610A	LT8610A	MSOP16	19.79	LT8610AEMSE#TRPBFTR-ND	9.5	-40°C ~ 125°C
U$16	MT25QL128ABA1ESE	MT25QL128ABA1ESE	SO-08M	48	557-1982-2-ND	2.29	-40°C ~ 85°C
U$17	MT25QL128ABA1ESE	MT25QL128ABA1ESE	SO-08M	48	557-1982-2-ND	2.29	-40°C ~ 85°C
U$19	THERMISTOR	THERMISTOR	M0805	2.58064	BC3395CT-ND	1.08	-40°C ~ 150°C
U$26	LTC2470	LTC2470	MSOP12	10.5	LTC2470IMS#TRPBFTR-ND	5.01	-40°C ~ 85°C
U$30	LT6105	LT6105	MSOP8	4.7925	LT6105HDCB#TRMPBFTR-ND	3.46	-40°C ~ 125°C
U$33	LT6654-3.3	LT6654-3.3	SOT23-6L	8.12	LT6654BMPS6-5#TRMPBFTR-ND	9.76	-55°C ~ 125°C
U1	LTC3260EMSEPBF	LTC3260EMSEPBF	MSOP-16_MSE	16	LTC3260EMSE#PBF	8.47	-40°C ~ 125°C
U2	LMV324	LMV324	SO14	9.15	LMV324QPW-ND	0.9	-40°C ~ 125°C

Total Size (mm^2)	Total Cost ($)	# Components	Clearence (mm^2)	Traces (mm^2)	Board Cost
5060.264744	517	129	14.5125	655.32	65

Temperature Effects on Components

Device	Temperature Effects (over -20C to 50C)
Transimpedance Amplifier	Output voltage high and low remain within our necessary bounds, supply current delta around 0.5mA, and slight increase in input offset voltage with temperature, overall negligible.
ADC	Gain error and offset error change by ~6-10 LSB, unavoidable but quite small. Calibrating for median temperature will help. Negligible change in conversion time.
Voltage Reference	~0.1mV change maximum, will not affect a significant amount of LSB.
5V Bipolar Regulator	~100mV change maximum, could introduce AD8671 op-amp noise, but we use decoupling capacitors. Does not veer outside of required operating range.
3.3V Linear Regulator	~5mV change in voltage output, not enough to affect digital component operation
Current Sense Monitors	0.01% gain error change, no concern

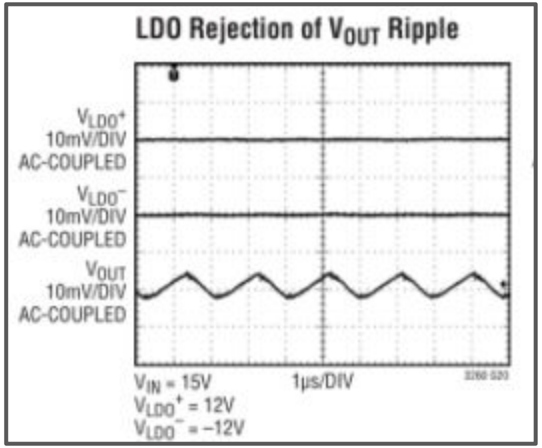
Reference voltage for ADC



Electronics: Voltage Regulator Output Noise

5V Bipolar Regulator		
Output Voltage Noise	100e-6 V	2 bins noise

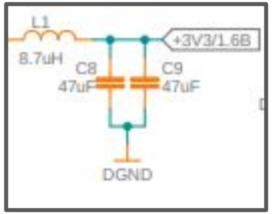
\+ Decoupling capacitors on transimpedance amplifier Vcc



3.3V Linear Regulator

Table 1. Output Voltage Ripple vs Output Capacitance for LT8610AB when V_{IN} = 12V, V_{OUT} = 3.3V, and L = 4.7μH

OUTPUT CAPACITANCE	OUTPUT RIPPLE
47μF	40mV
47μF ×2	20mV
47μF ×4	10mV



Electronics: Recommended Voltage Regulator Routing

Analog Voltage Regulator

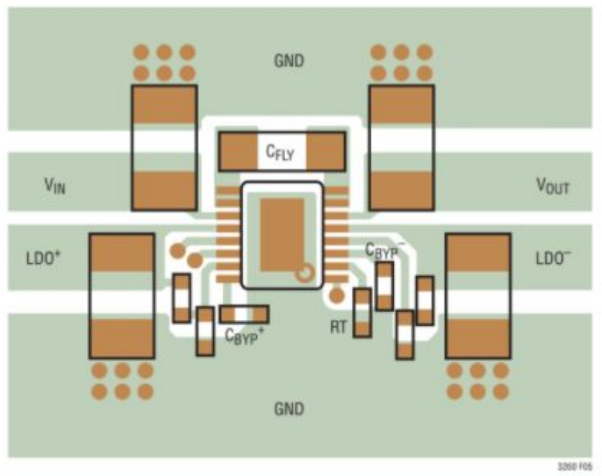


Figure 5. Recommended Layout

Digital Voltage Regulator

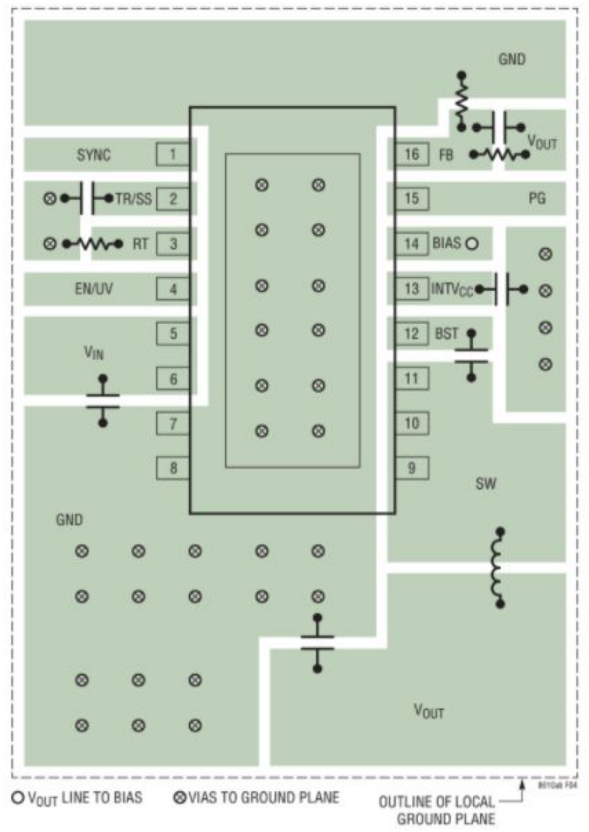


Figure 4. Recommended PCB Layout for the LT8610A/LT8610AB

Electronics: Microcontroller Overvoltage

Risks

No pin should receive over 3.3V (with a 0.3V tolerance). Otherwise the Teensy will be destroyed.

Solution

3.3V Voltage Regulator controls Vcc input

3.3V Zener Diode Regulates backup ADC Trace

Primary ADC Output limited by 3.3V

Other pin inputs limited by 3.3V, controlled by 3.3V voltage regulator

Electronics: Signal Conditioning or ADC Failure

Risks

Op-amp voltage input out of range

VCC and GND pins reversed

Exceed common mode input range

Solution

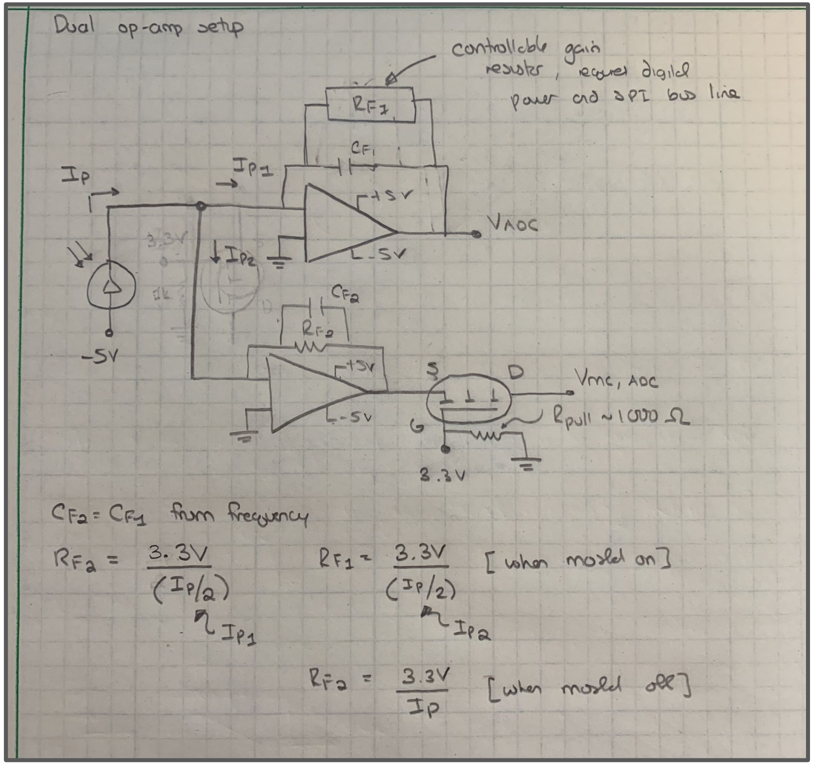
Voltage Regulator controls op-amp voltages

Robust test procedures and external I/O labels

Photodiode oversaturation protected by bias voltage

Note: A second transimpedance amplifier increases complexity and adds another failure point, see backup slide for more details. We will use a MOSFET controlled backup trace from the first transimpedance amplifier that goes directly to a microcontroller analog input for ADC redundancy!

Electronics: Signal Conditioning Backup



Add second transimpedance amplifier and a programmable gain resistor.

Adds complexity and failure point in the SPI connection of the controllable gain resistor, and another MOSFET.

Thus, will not be used - however, thought was given to a secondary design.

Electronics: ESD Handling

Part Element	Part Type	ESD Susceptibility (Volts)	Failure Mechanism	Failure Indicator
MOS Structures	CMOS	250-3000	Dielectric Breakdown	Short Circuit
Semiconductor Junctions	MOSFET, Schottky Diodes	100-200, 300-2500	Thermal Breakdown	Short Circuit
Film Resistors	Thin & Thick	300-3000	Dielectric Breakdown	Resistance Shift

MOSFET, ICs, and power regulator inventory and handling

Board manufacturing
Board testing
Board integration

Structure handling post integration

ESD wristbands, ESD jacket

ESD wristbands, ESD jacket, ESD mat performed in standard ESD certified lab, extreme certification not required

ESD jacket or grounded structure

https://nepp.nasa.gov/DocUploads/9220611A-6EAA-426D-A60A74EF7A16E40E/ESDWhitePaper.pdf
https://lmse.larc.nasa.gov/admin/public_docs/LPR_8739-21C_Final.pdf

Electronics: Board to Board Signal Integrity

Risk Mitigation Strategies

Power rating up to 398 VDC, 3.4A per pin

Signal-Ground-Signal-Ground routing

Coupling capacitors (0.1uF) on primary signal

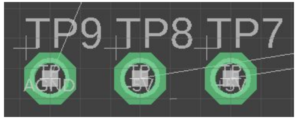
Routed Signals

Bus voltage line (DC)
Primary ADC signal (833 Hz)
Backup ADC signal (DC)
Thermistor (DC)
Regulator current (DC)
Regulator voltage (DC)

With low frequency and DC signals, not worried about signal loses due to crosstalk, propagation delay, return loss, insertion loss, or rise time degradation.

http://suddendocs.samtec.com/literature/samtec_si_handbook.pdf

Electronics: Test Points



Test Point	Description	Expected Value	Checks?
1	Pre Feedback Resistor	Depends on light source	Photodiode working
2	Post Transimpedance Amplifier	Depends on light source	Transimpedance amp working
3	ADC Vcc	3.3V	Voltage reference working
4	ADC Ref-	GND	ADC reference good
5	Analog Thermistor Voltage Divider Output	Depends on temperature	Thermistor good
6	Analog Thermistor Voltage Buffer Output	Should be the same as T5	Voltage follower good
7	5V Regulator Positive Output	+5V	Bipolar regulator good
8	5V Regulator Negative Output	-5V	Bipolar regulator good
9	5V Regulator EPAD Ground	GND	Bipolar regulator good
10	Voltage Bus Input	System Vin	Voltage source good
11	Current Sense Output	Backsolve for Vin	Current sense monitor good

DIGITAL BOARD TEST POINTS

Test Point	Description	Expected Value	Checks?
1	Microcontroller Vin	3.3V	Microcontroller getting required power, also checks MOSFET not busted
2	Watchdog RST Signal	3.3V	If watchdog triggers, RST goes high
3	Watchdog /ST Signal	3.3V, 50ns width square	Microcontroller outputs watchdog signal
4	Flash 1 Vin (U$1)	3.3V	Flash 1 power
5	Flash 2 Vin (U$2)	3.3V	Flash 2 power
6	Digital Thermistor Voltage Divider Output	Depends on temperature	Thermistor good
7	Digital Thermistor Voltage Buffer Output	Should be the same as T6	Voltage follower good
8	3.3V Regulator Output	3.3V	Linear regulator good
9	3.3V Regulator GND	GND	Linear regulator good
10	3.3V PG Pin	High (~3.3V)	Linear regulator good
11	Voltage Bus Input	System Vin	Voltage source good
12	Current Sense Output	Backsolve for Vin	Current sense monitor good
13	Optical Bench Thermistor	Depends on temperature	Thermistor good
14	Optical Thermistor Voltage Buffer Output	Same as T13	Voltage follower good
15	Resistor Heater Vin	~System Vin (minus TVS diode drop)	Use to check heating resistor voltage drop
16	Resistor Heater GND	~GND (+MOSFET Drop)	Use to check heating resistor voltage drop

Electronics: TVS Diode

For resistor heater

Max voltage applied before TVS activates

Max possible voltage across DUT w/ TVS in place

Part Number (Uni)	Part Number (Bi)	Marking		Reverse Stand off Voltage V_R (Volts)	Breakdown Voltage V_{BR} (Volts) @ I_T		Test Current I_T (mA)	Maximum Clamping Voltage V_C @ I_{PP} (V)	Maximum Peak Pulse Current I_{pp} (A)	Maximum Reverse Leakage I_R @ V_R (μA)	Maximum Temperature coefficient of V_{BR} (%/C)	Agency Approval
		UNI	BI		MIN	MAX						
SMBJ12A	SMBJ12CA	LE	BE	12.0	13.30	14.70	1	19.9	30.2	1	0.075	X

Voltage where TVS begins to conduct and protects the DUT

Maximum current TVS can withstand

TVS Diode prevents voltage spikes across this resistor heater which could result in surpassing the power limit and destroying the heating resistor!

Electronics: Photodiode Saturation

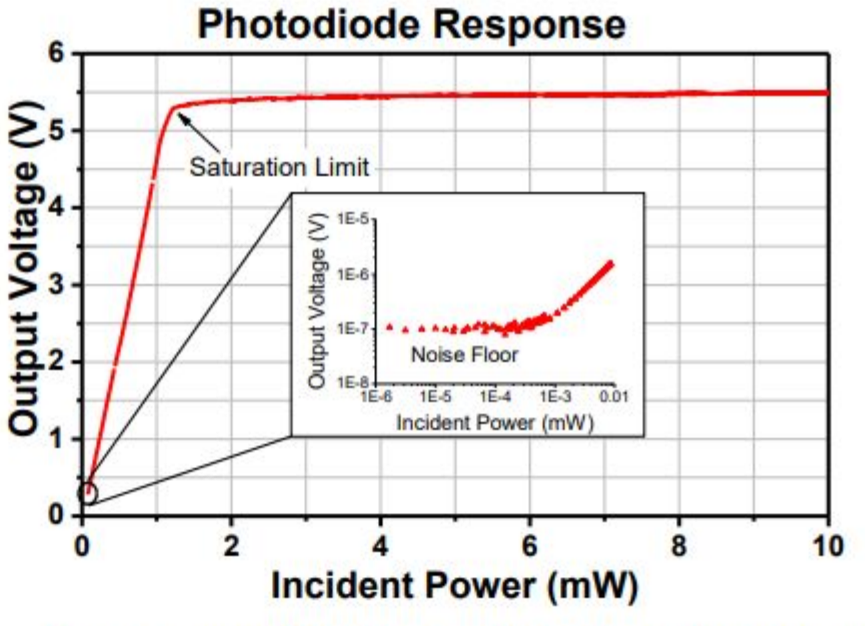
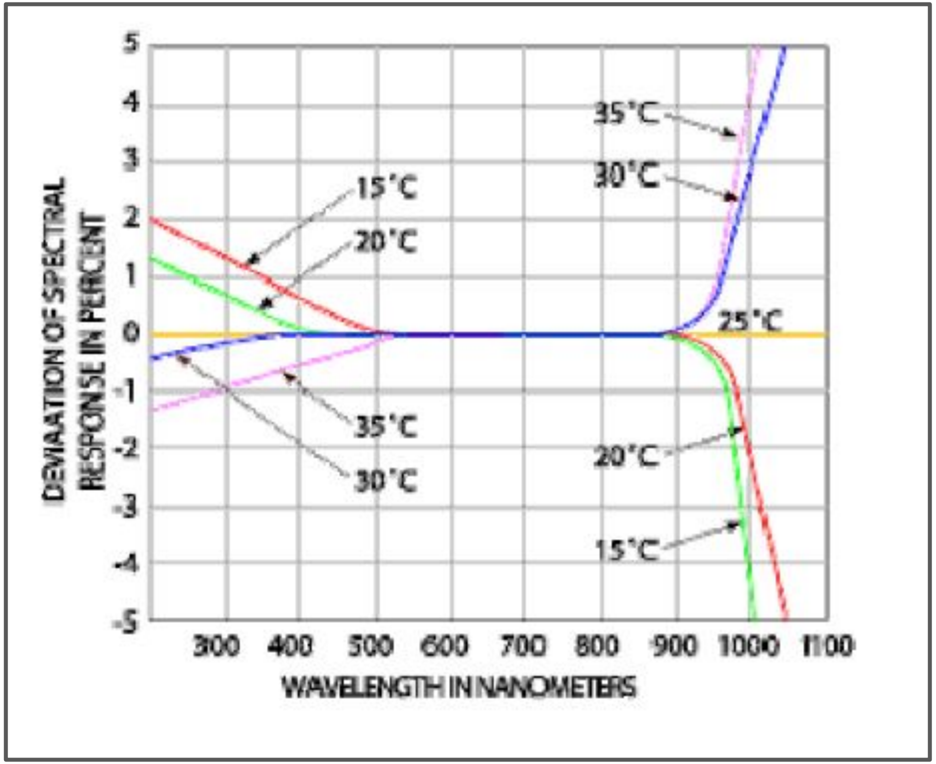


Figure 2: Measured response of a FDS100 silicon photodiode showing the noise floor and saturation limit for a 5 V bias from a DC power supply and 10 kΩ load resistor.

The photodiode output will saturate when the output voltage approaches the reverse bias voltage on the photodiode.

Our reverse bias voltage should be greater than the maximum output voltage, which is 3.3V.

Electronics: Photodiode Temperature Effects



~3% deviation for 5K change, leads to 0.0027 A/W per K change in responsivity. This is equivalent to a 0.0198 V/K response in our output voltage (with 5121 ohm feedback resistor).

This is 393 bins / K (0.6% error in voltage read out per kelvin).

We will size the feedback resistor for the estimated responsivity at the expected temperature of the photodiode during the data collection window.

Error from temperature change will be measured by a thermistor and fixed in software, because it is a linear error.

“Optical Detectors”, Wang, Wei-Chih, National Tsing Hua University.

7.5 Accuracy Characteristics

These limits do not include DC load regulation. These stated accuracy limits are with reference to the values in Table 3.

PARAMETER	CONDITIONS	MIN (1)	TYP (2)	MAX (1)	UNIT
Temperature accuracy (3)	40°C to 150°C; V_{DD} = 2.2 V to 5.5 V	–2.7	±0.4	2.7	°C
	0°C to 40°C; V_{DD} = 2.4 V to 5.5 V	–2.7	±0.7	2.7	°C
	0°C to 70°C; V_{DD} = 3.0 V to 5.5 V		±0.3		°C
	–50°C to 0°C; V_{DD} = 3.0 V to 5.5 V	–2.7	±0.7	2.7	°C
	–50°C to 0°C; V_{DD} = 3.6 V to 5.5 V		±0.25		°C

7.6 Electrical Characteristics

Unless otherwise noted, these specifications apply for $+V_{DD}$ = 2.2 V to 5.5 V. MIN and MAX limits apply for $T_A = T_J = T_{MIN}$ to T_{MAX} , unless otherwise noted; typical values apply for $T_A = T_J$ = 25°C.

PARAMETER	TEST CONDITIONS	MIN (1)	TYP (2)	MAX (1)	UNIT
Average sensor gain (output transfer function slope)	–30°C and 90°C used to calculate average sensor gain		–10.9		mV/°C

Table 3. LMT86 Transfer Table

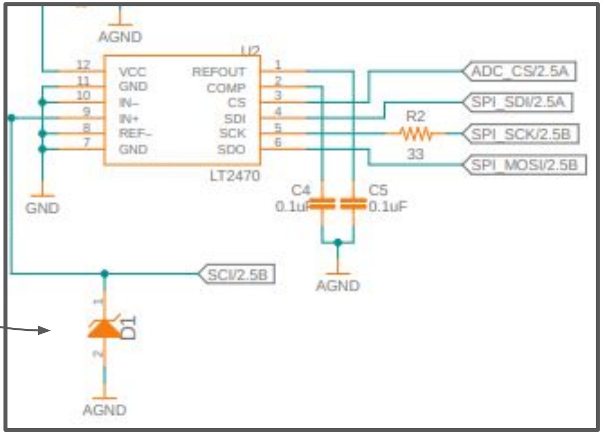
TEMP (°C)	V_{OUT} (mV)	TEMP (°C)	V_{OUT} (mV)	TEMP (°C)	V_{OUT} (mV)	TEMP (°C)	V_{OUT} (mV)	TEMP (°C)	V_{OUT} (mV)
-50	2616	-10	2207	30	1777	70	1335	110	883
-49	2607	-9	2197	31	1766	71	1324	111	872
-48	2598	-8	2186	32	1756	72	1313	112	860
-47	2589	-7	2175	33	1745	73	1301	113	849
-46	2580	-6	2164	34	1734	74	1290	114	837
-45	2571	-5	2154	35	1723	75	1279	115	826
-44	2562	-4	2143	36	1712	76	1268	116	814
-43	2553	-3	2132	37	1701	77	1257	117	803
-42	2543	-2	2122	38	1690	78	1245	118	791
-41	2533	-1	2111	39	1679	79	1234	119	780
-40	2522	0	2100	40	1668	80	1223	120	769
-39	2512	1	2089	41	1657	81	1212	121	757
-38	2501	2	2079	42	1646	82	1201	122	745
-37	2491	3	2068	43	1635	83	1189	123	734

Electronics: Optics Bench Temperature Software Correction

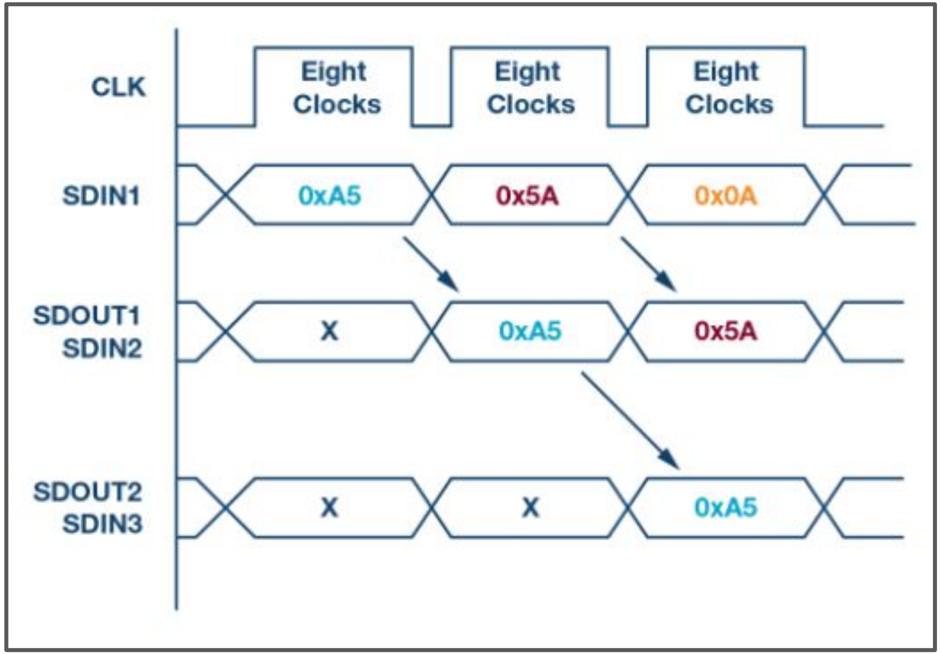
Electronics: ADC Saturation

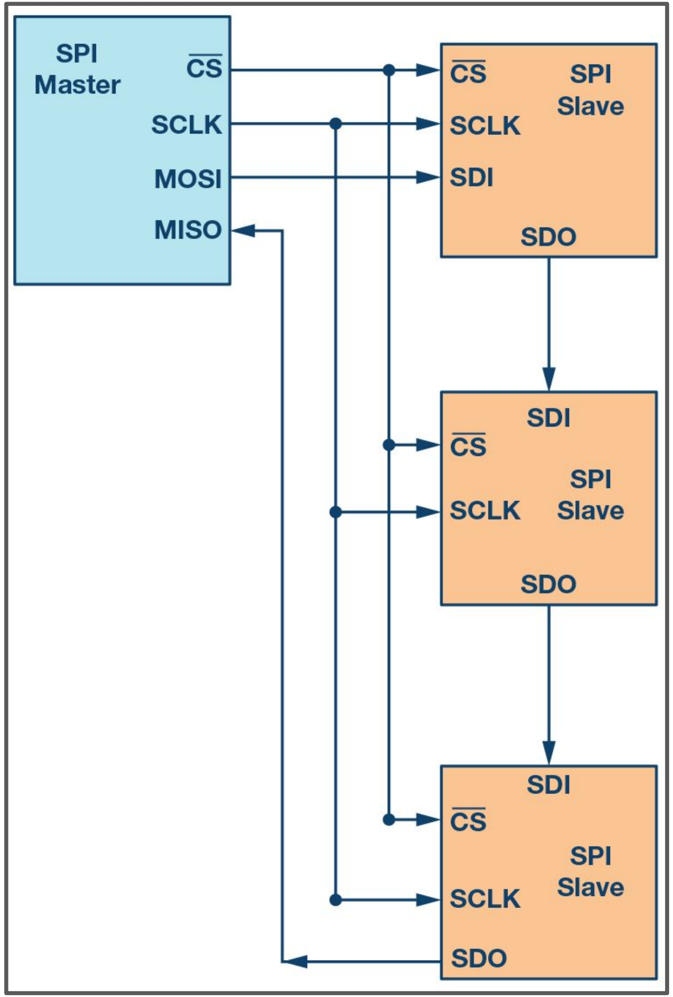
Maximum temperature (during data collection):	30 deg C
Responsivity at maximum temperature:	0.405 A/W
Maximum incident power:	0.006 W
Maximum output current:	0.00247 A
Feedback resistor for 3.3V	1268 Ohms

We also use a 3.3V zener diode on the ADC input to prevent overvoltage. The ADC COMP can only accept 3V to 3.6V (at 3.3V Vcc).



Electronics: SPI Bus Connections





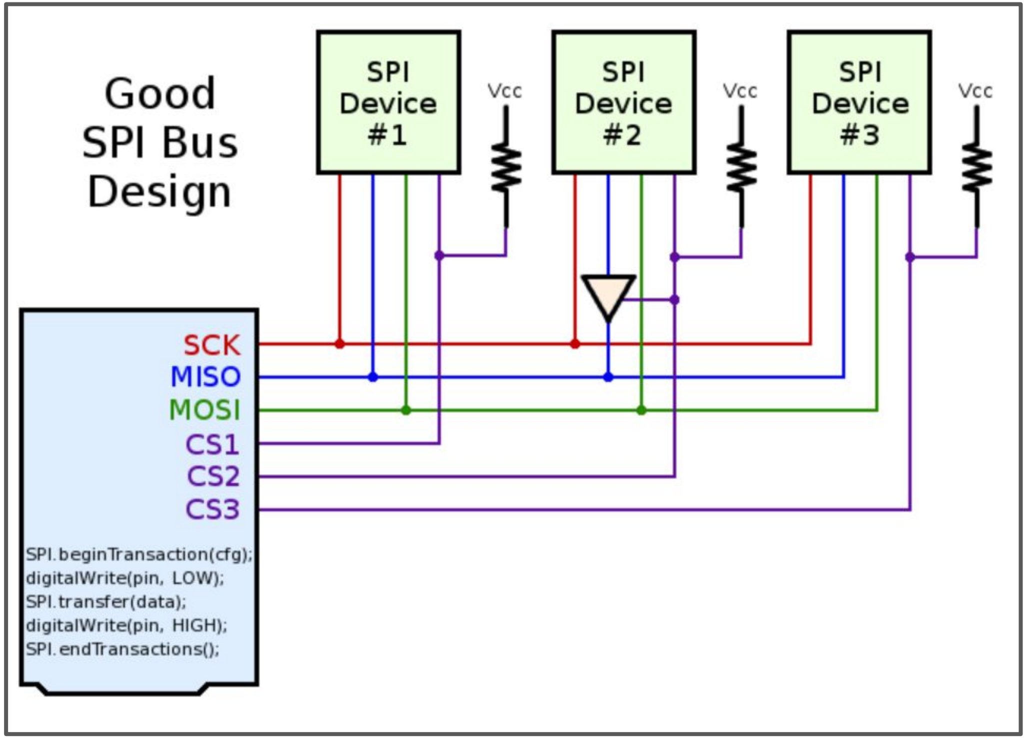
https://www.analog.com/en/analog-dialogue/articles/introduction-to-spi-interface.html

Electronics: SPI Bus Pull Up Resistors

Pull up resistors on the chip select pins ensure that the CS pin is high, thus the MISO/MOSI lines will disengage.

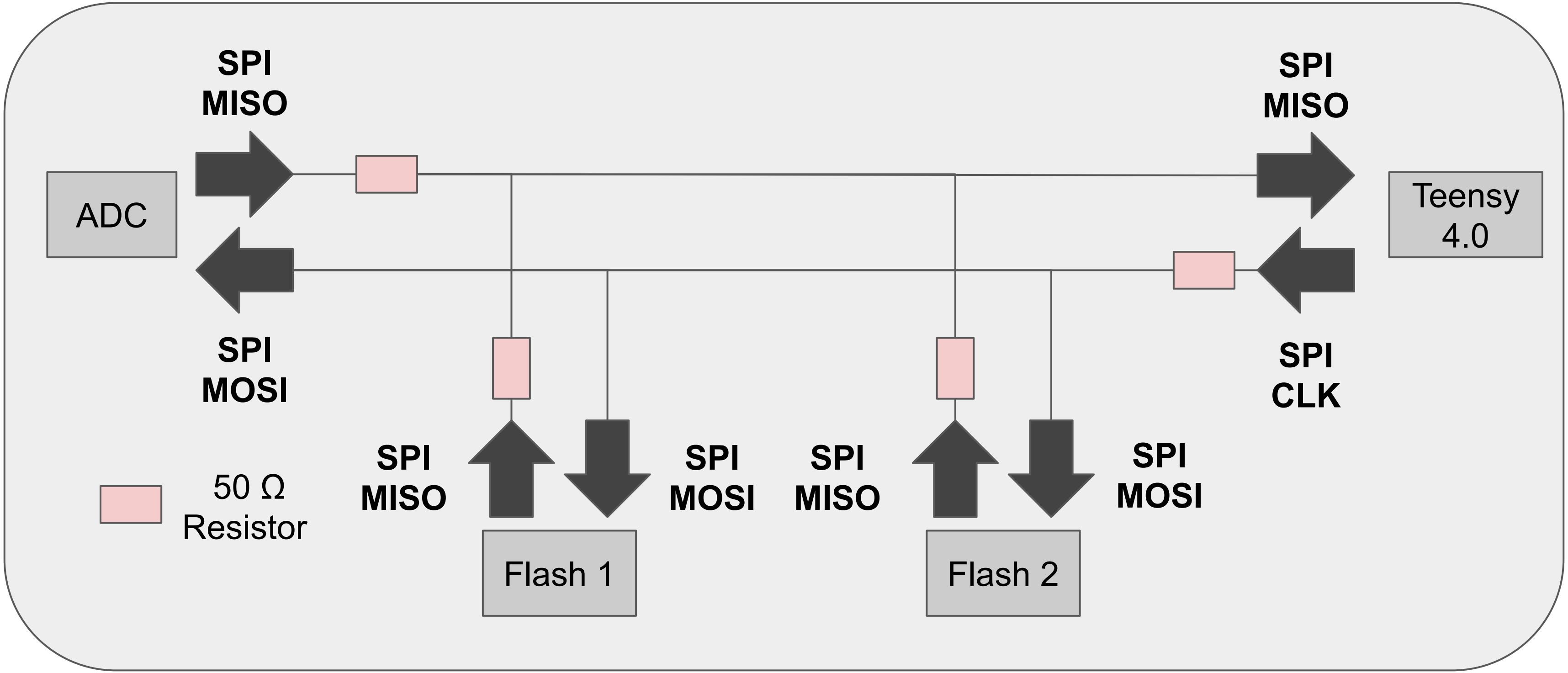
This makes sure a line is only transmitting when absolutely driven low by the microcontroller, reducing potential cross talk.

This can also be corrected in software, but it provides an extra layer of redundancy at little cost.



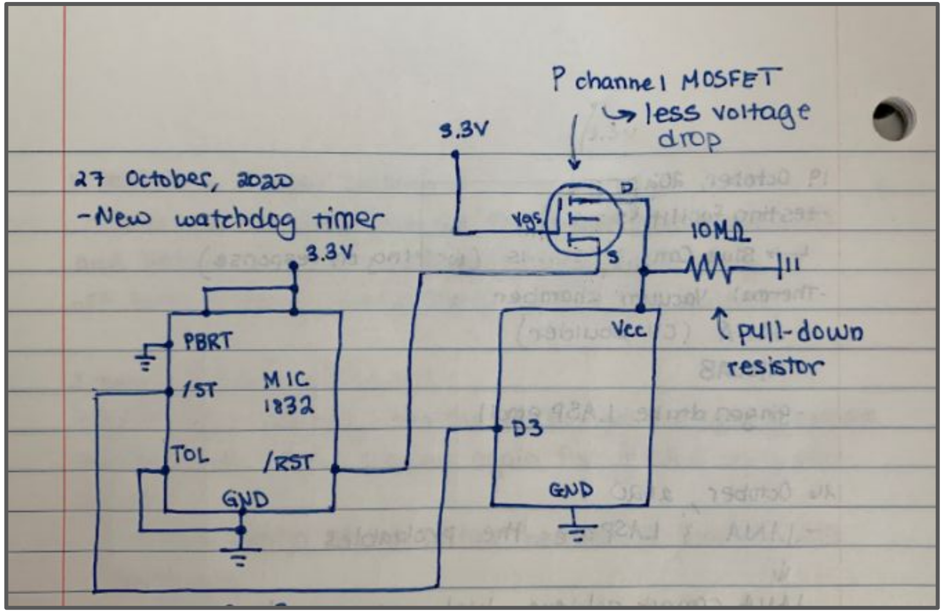
https://www.pjrc.com/better-spi-bus-design-in-3-steps/
https://hackaday.com/2016/07/01/what-could-go-wrong-spi/

Electronics: SPI Bus Reflection Reduction



https://www.diodes.com/assets/App-Note-Files/AB023.pdf
http://www.the-signal-and-power-integrity-institute.com/files/Andrew_Norte_Source_Termination_Resistor_Location_2.pdf

Electronics: Watchdog Timer Circuit



TD pin set to VCC to make watchdog timer 1.2 seconds.

Digital output on microcontroller sends 50ns pulse every 0.5 seconds to /ST pin.

RST pin asserts to switch off the MOSFET if timer trips, which breaks the microcontroller power input for 250ms

Pull down resistor used to make sure no capacitance build up on MOSFET.

Electronics: Watchdog Backup Considerations

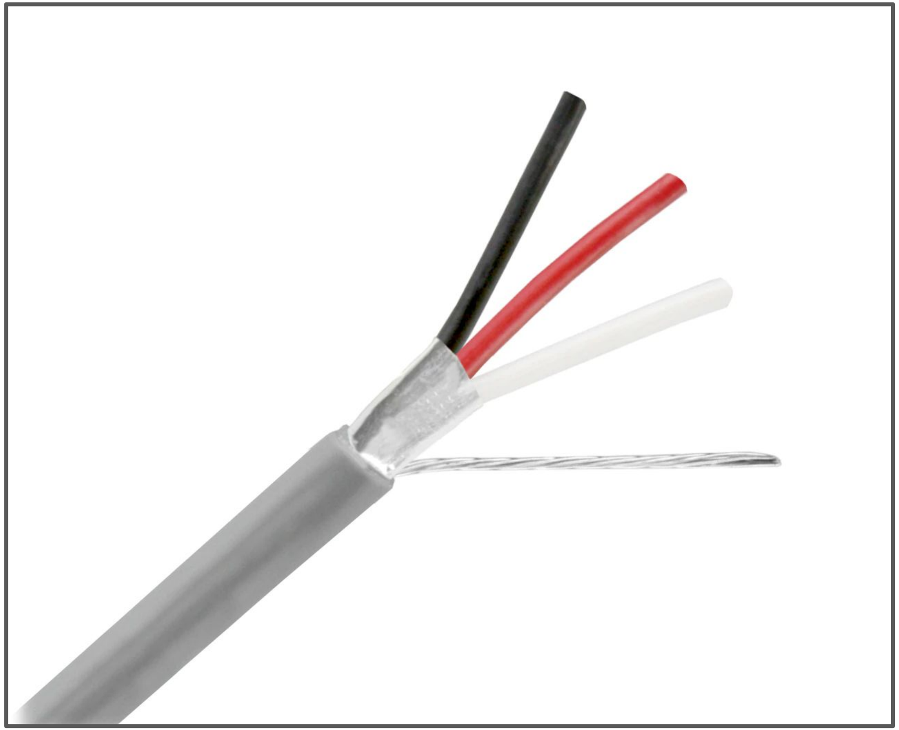
The Teensy 4.0 uses a IMXRT1060 microprocessor which has three internal watchdogs and an external watchdog monitor (EWM).

Thus, a watchdog can easily be implemented in the software. With two or more watchdogs, we drastically improve our redundancy.

This involves editing microprocessor memory blocks, which is pretty involved. Luckily, some genius EE folks over at the Teensy forum provided me with information and sample code for each of the four IMXRT1060 watchdogs.

https://forum.pjrc.com/threads/64075-Questions-on-Watchdog-IC-Interface-to-reset-Teensy-4-0?p=257442#post257442
https://github.com/tonton81/WDT_T4

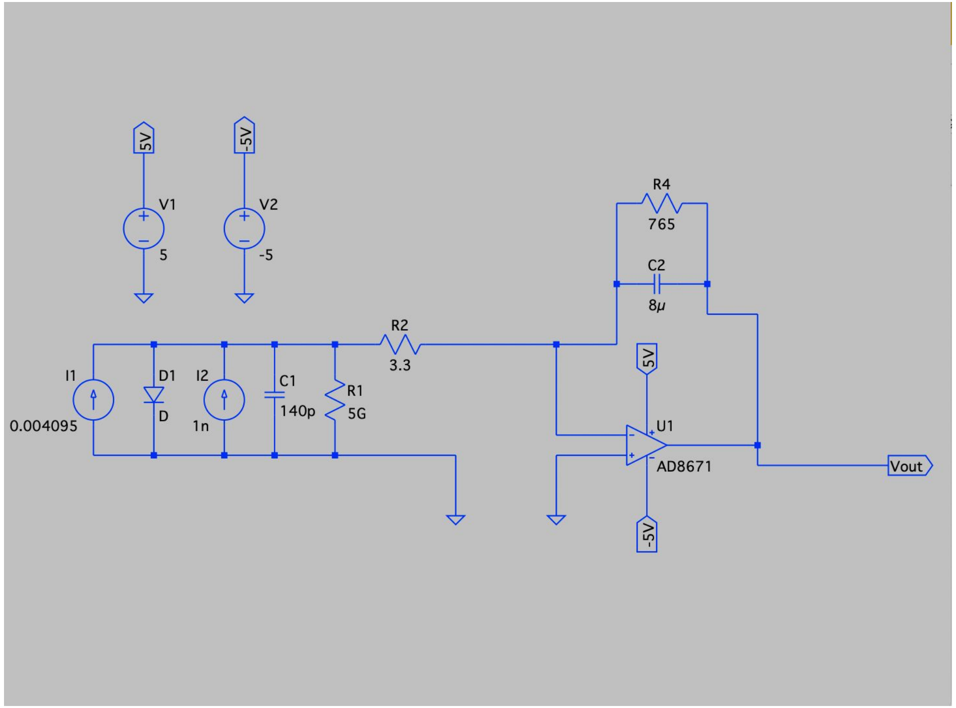
Electronics: Resistor Heating PWM Switching High Frequency



High frequency signals switching the current through the heating resistor can produce antenna like noise effects, so shielding the off-board wires is a must.

An alternate solution is to place the MOSFET on the optical bench, to have the low frequency voltage line being the one sent through off-board wires. This increases manufacturing complexity and will only be used as a backup.

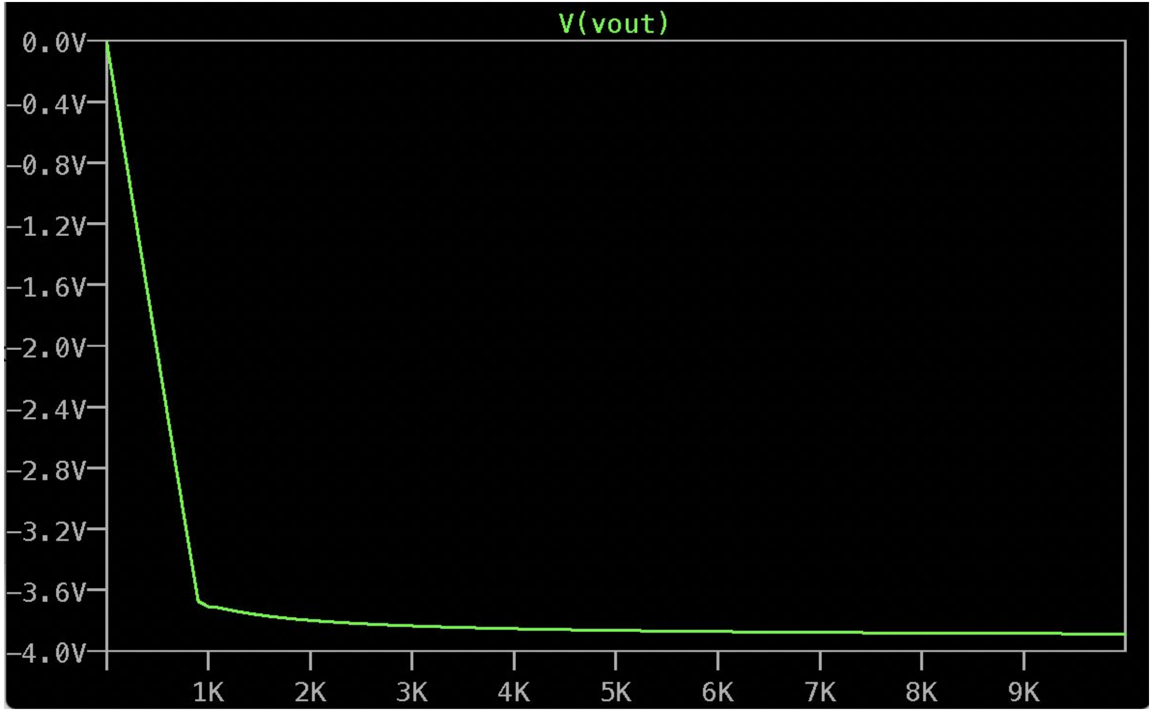
Electronics - LTspice Schematic



Output Voltage = -3.13 V

Voltage across Feedback Resistor = 3.13 V

Electronics - Ltspice - Output Voltage vs Feedback Resistance



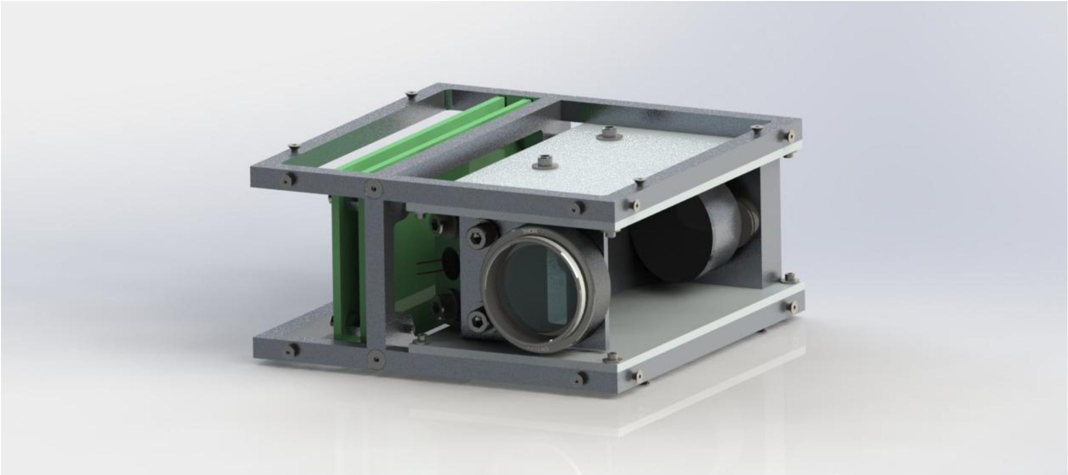
As feedback resistance is increased to about 900 Ohms, the output voltage reaches a limit of about -3.9V

MinXSS Board Heat Dissipation

- Miniature X-Ray Solar Spectrometer (MinXSS) – A Science-Oriented, University 3U CubeSat
  - Similar power requirements - relied on conduction to dissipate heat into the cubesat bus and radiate into space
- https://arxiv.org/pdf/1508.05354.pdf

Backup Slides: Structures

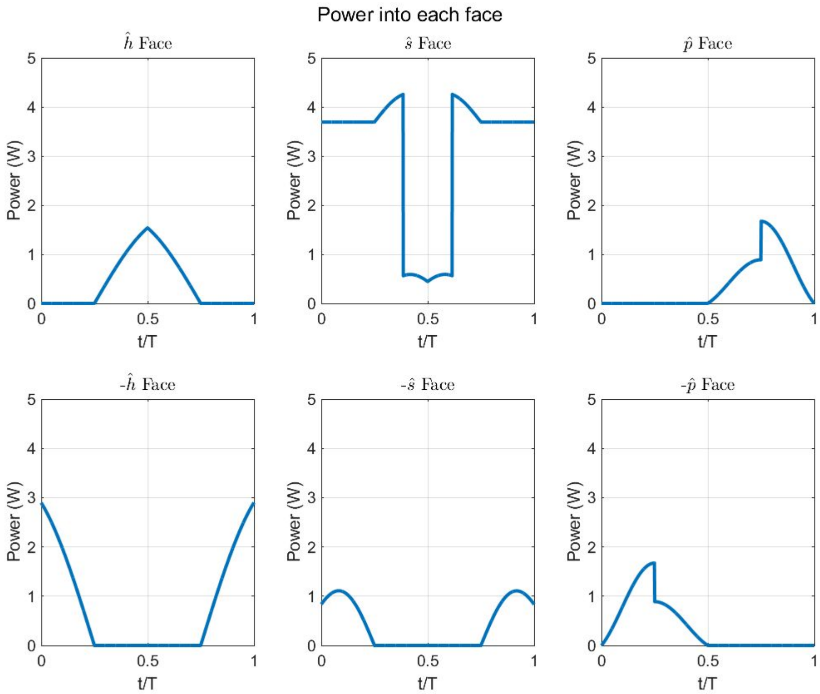
Thermal Isolation of the Optics Bench



- Introduction of structural fiberglass on either side of the optics bench (S-Glass)

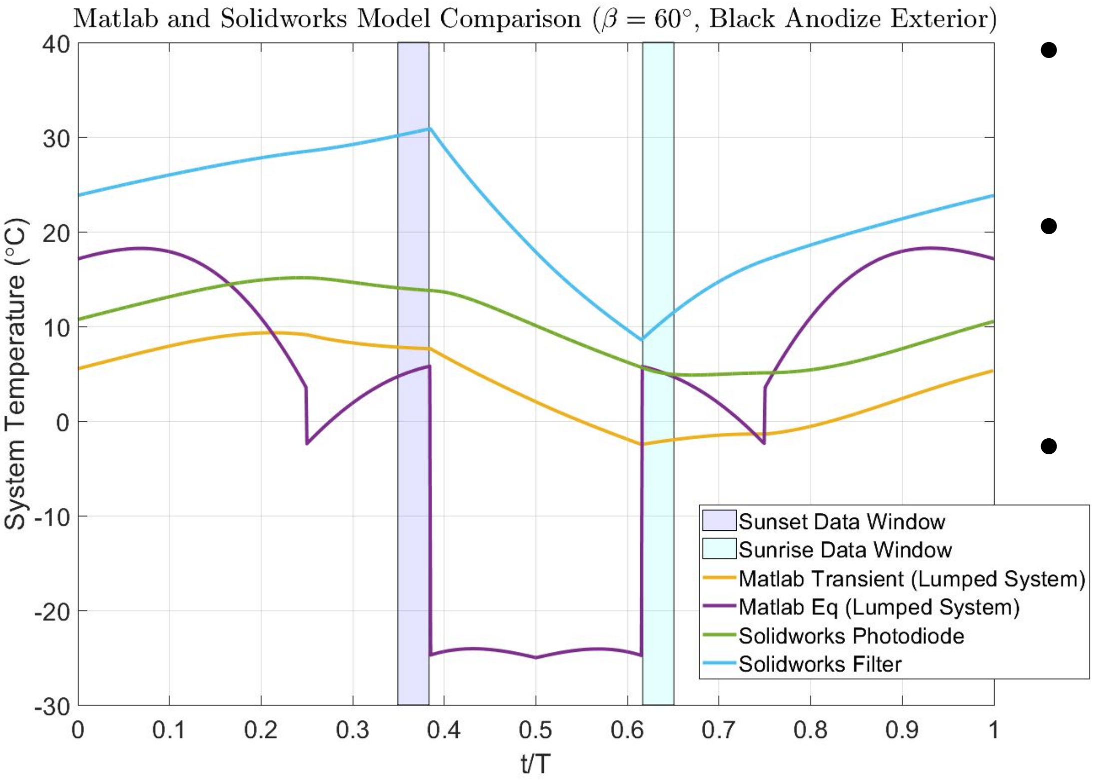
S-Glass Properties	
Density	2.49 g/cc
Thermal Conductivity	1.28 W/m-K
Specific Heat	738 J/kg-K

Temperature Change on the Photodiode Block



- Input into SolidWorks in order to account radiation from the Earth
  - Neither SolidWorks or ANSYS has this ability built in
- Still uses **area** factor analysis
- Modeled as surface sources alongside the heater and the EPS board power dissipation

Temperature Change on the Photodiode Block



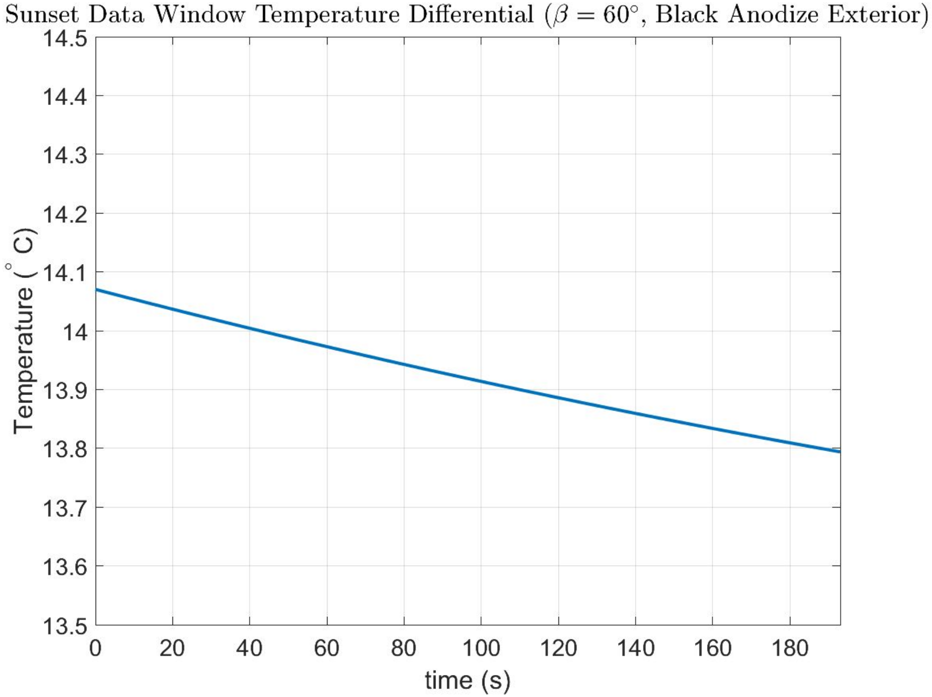
- Trend in Solidworks matches MATLAB transient model
  - Expected since MATLAB power data was used to generate results
- Expected higher temperature of photodiode block due to thermal isolation and internal heater
  - Smoother inflection and critical points
- Filter temperature variation is large due to being connected to the external surface
  - No thermal isolation to environment
  - Less energy required to change temperature due to small mass

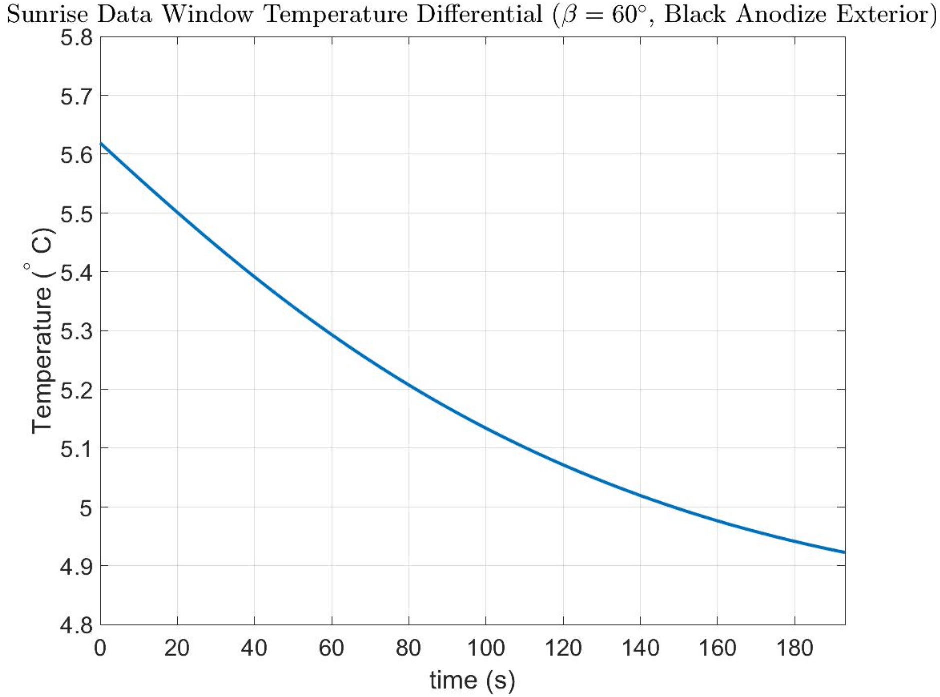
Temperature Change on the Photodiode Block

Data Window	Max ΔT (K)	Time (s)
Sunset	0.28	192.6
Sunrise	0.70	192.6

- Calculated for **β** = 60° (close to maximum data window)
- Average values used for albedo, IR, and solar radiation
- $0.7P_{i,max}$ used in model alongside a 3 W heater
- Black anodize exterior coating
- No longer lumped system analysis (done through Solidworks + MatLab modeling)
    - Threads and screws removed along with small holes

Temperature Change on the Photodiode Block



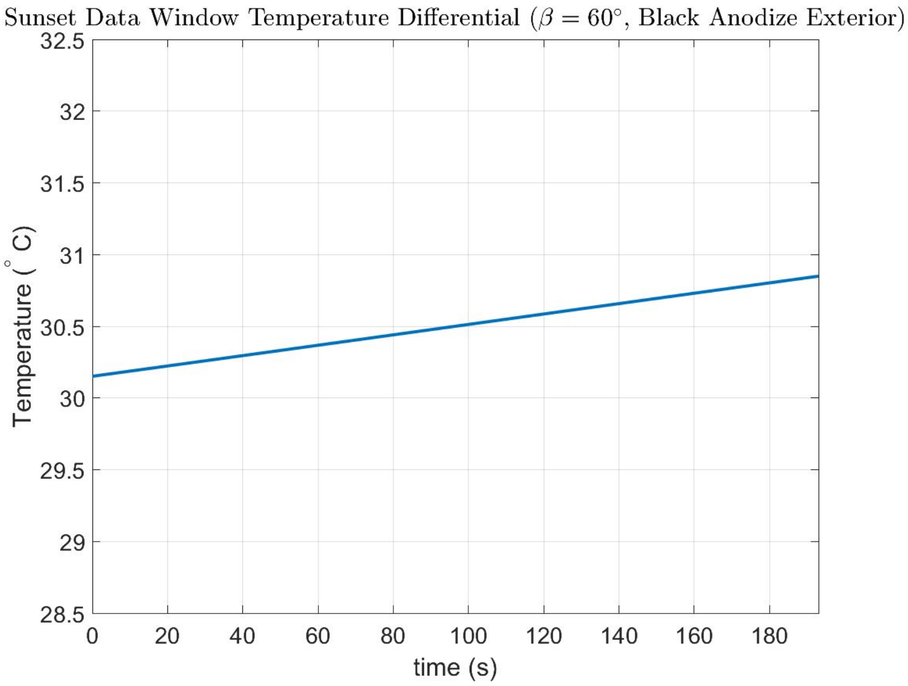


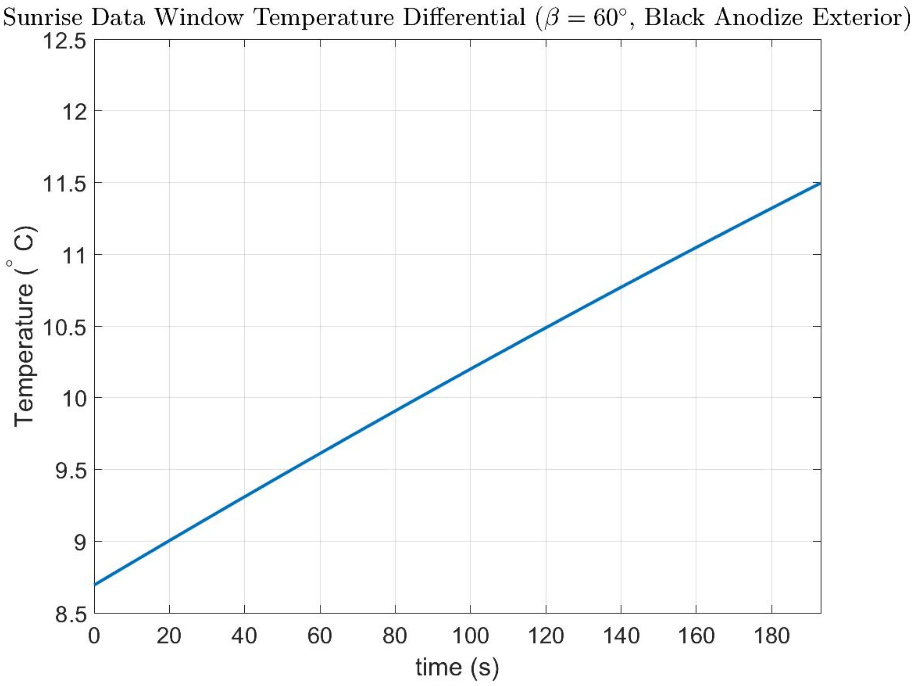
Temperature Change of Filter

Data Window	Max ΔT (K)	Time (s)
Sunset	0.70	192.6
Sunrise	2.80	192.6

- Larger temperature changes as expected for external surfaces
- Smaller temperature change during sunset window
  - loss of energy from albedo decreases the slope of curve during sunset
  - Sudden increase in energy from sun sharply increases the slope of the curve during sunrise

Temperature Change of Filter

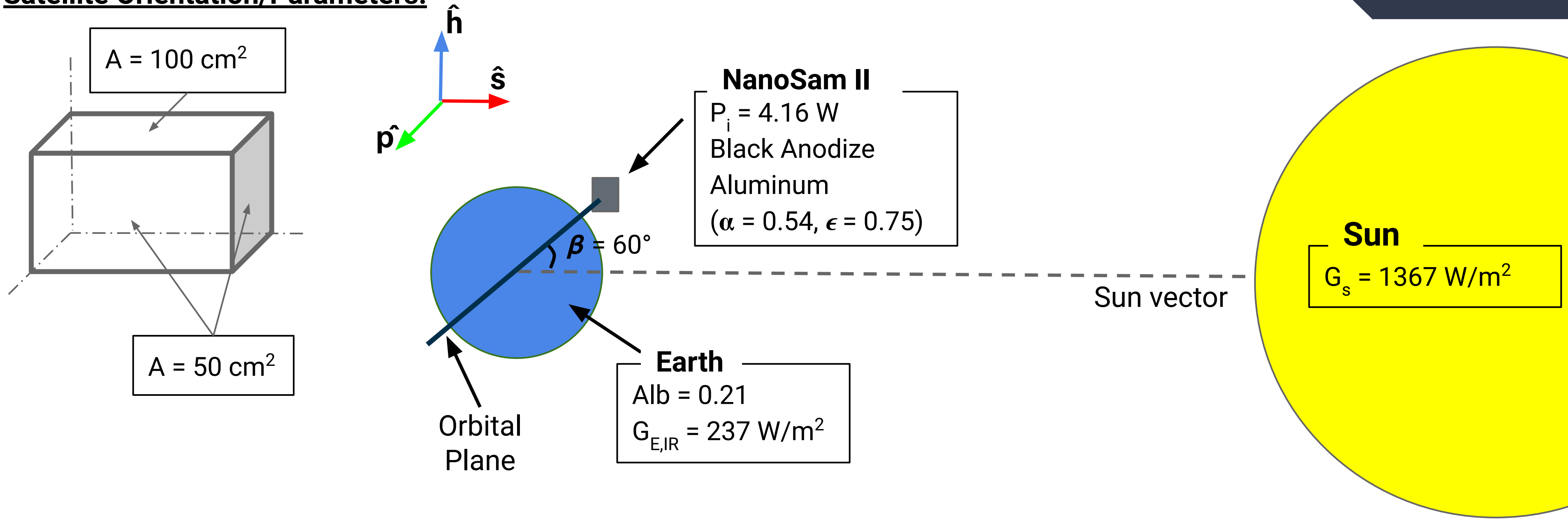




Thermal Model Diagram

Sources : [3] [4]

Satellite Orientation/Parameters:



Thermal Model Details

Key Assumptions:

- Bodies other than the Earth/Sun don't produce significant incident radiation
- Kirchoff's law ($\epsilon_\lambda(T) = \alpha_\lambda(T)$)
- Satellite surfaces are gray, diffuse, surfaces
- Radiation to deep space (0 K)

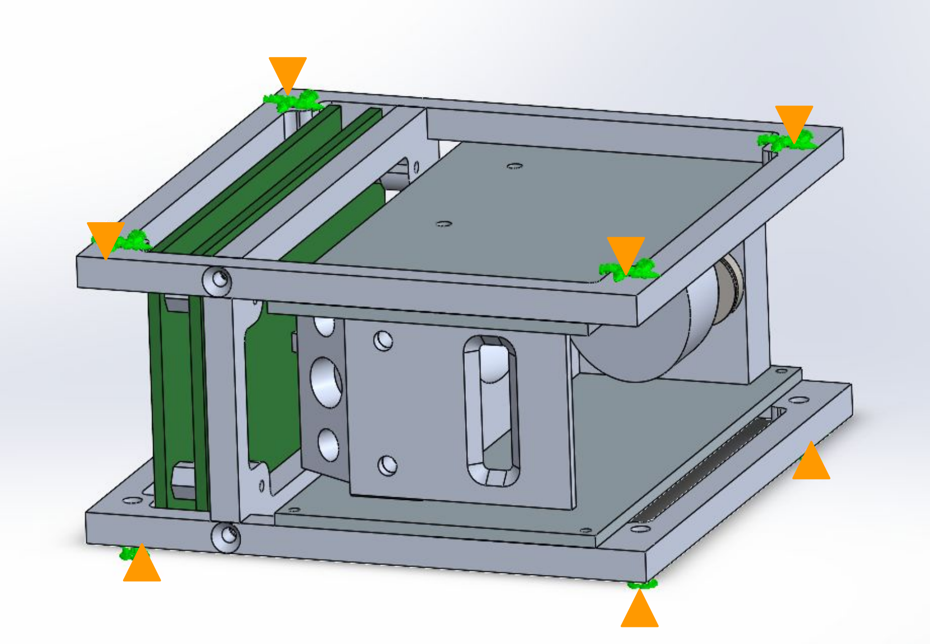
Key Equations:

$$T_{sys,eq} = \left[\frac{\dot{Q}_{in,sun} + \dot{Q}_{in,A} + \dot{Q}_{in,IR} + P_i}{2\sigma\epsilon(2A_s + A_p)}\right]^{(1/4)}$$

$$\dot{Q}_{tot} = \dot{Q}_{in,A} + \dot{Q}_{in,IR} + \dot{Q}_{in,sun} + P_i - \dot{Q}_{out}$$

$$T_i = \frac{\dot{Q}_{tot}\Delta t}{mc_p} + T_{i-1}$$

Vibrational Study – Vibe Test Simulation



Commercial CubeSat Interface Mount - PC104 Specs [8]

Key:

▶ Fixed

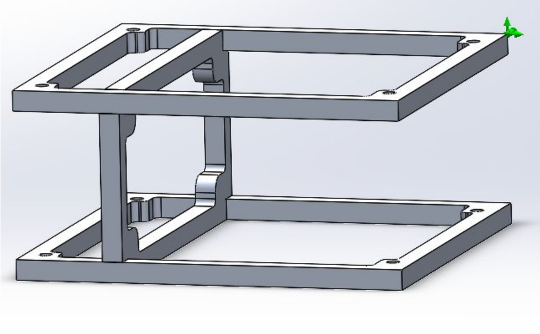
Lowest Frequency: 1197 Hz

No resonant frequencies below 100Hz requirement

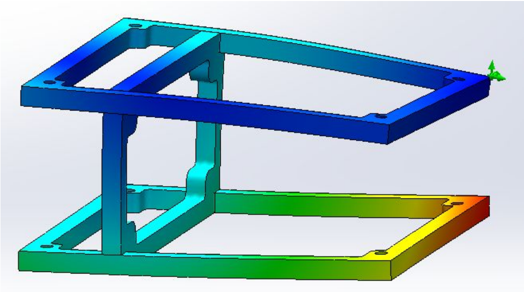
Structural Study - Simplified (Only Ribs)

Only the rib components are analyzed here, with a single fixed corner in Solidworks

Mode Number	Frequency (Hz)
1	189
2	330
3	505
4	558
5	786



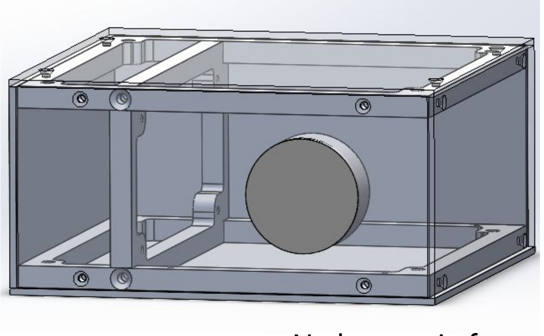
Mode 1



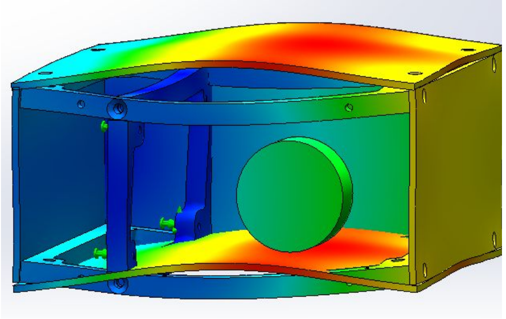
- No harmonic frequencies below 100Hz
- Modes are driven by the ribs vibrating apart at low frequency
    - Adding material between these ribs should stiffen these modes (i.e. raise frequency)

Structural Study - Simplified (Ribs and Walls)

Mode Number	Frequency (Hz)
1	483
2	634
3	636
4	717
5	748
6	834
7	926



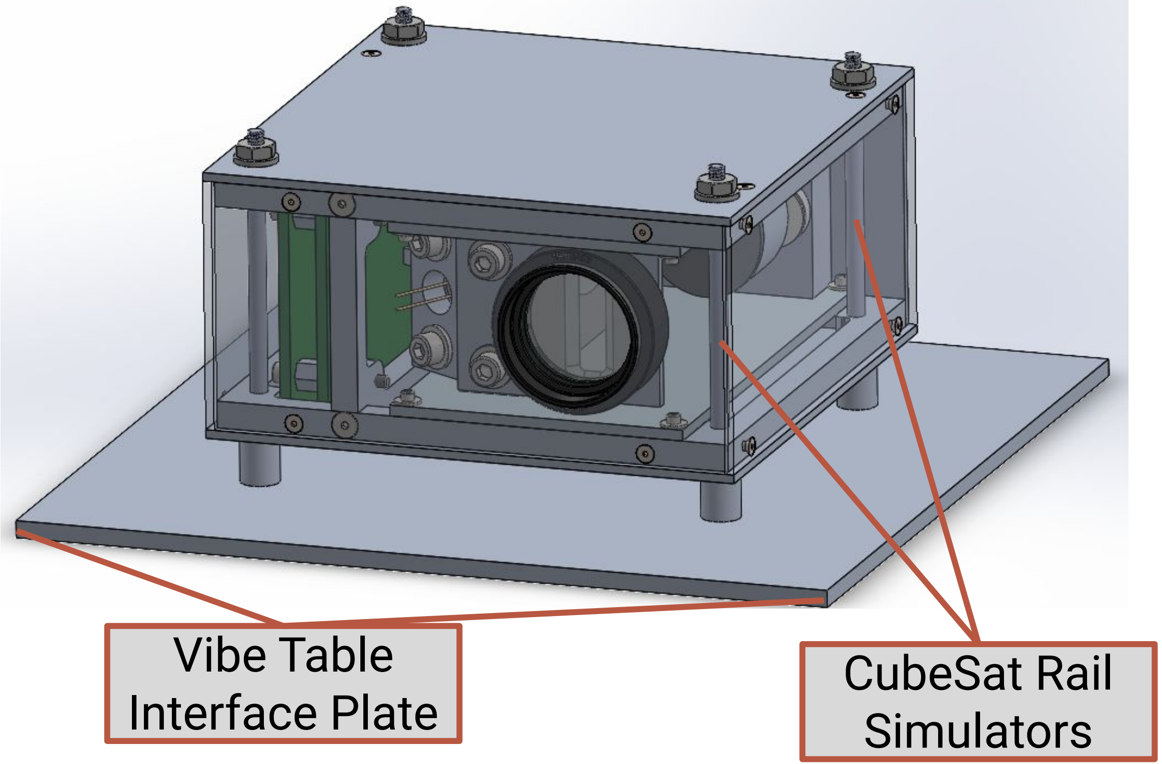
Mode 1



- No harmonic frequencies below 100Hz
- Modes are driven primarily by vibrations in the ribs coupled with vibrations in the walls
  - Adding more material (i.e. the optical bench) will further stiffen the connections between ribs, damping these modes
- Global penetration allowed
  - Increasing number of screws to rigidly attach walls along ribs would make a bonded contact make more sense

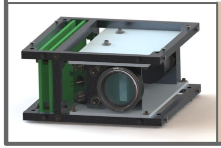
Structure: Vibration Test

System-Level Test



- Whole System Test
- Includes walls and sensitive optical components
  - Walls required to protect optical components
  - Requires that the optical components are fixed (staked)

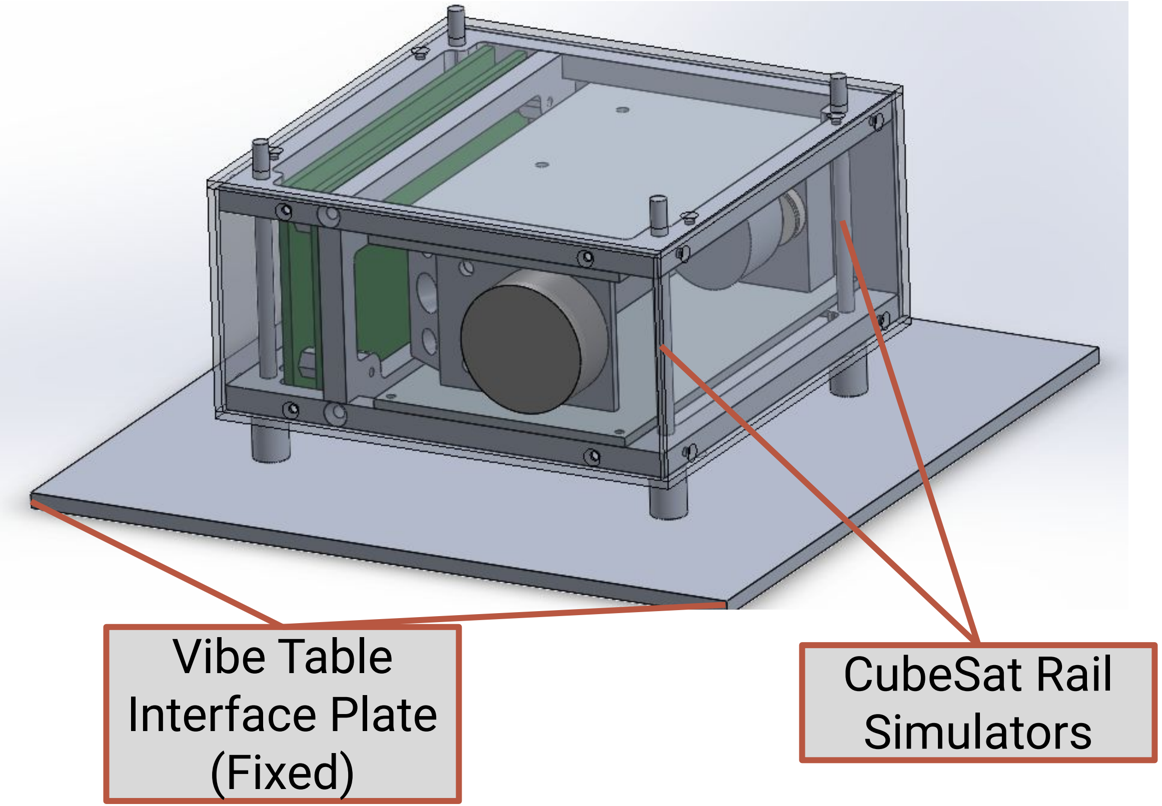
Structure CPE



Vibrational Modes Simulation & Testing

Structure: Vibration Test (FEM)

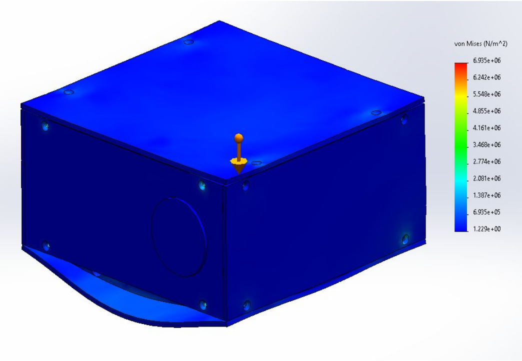
System-Level Test

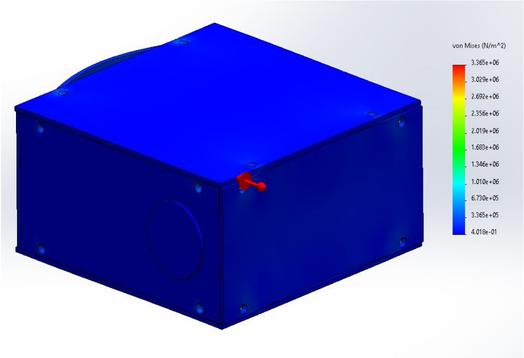


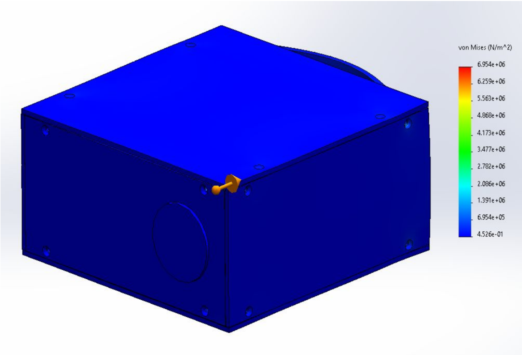
- **Lowest Frequency: 1190 Hz**
  - Bonded Contacts may not fully capture the ways the walls are free to move, inform these modes from the simplified ribs/walls model

Structural Study - G Loading (Per Axis)

Requirement from (QB50-SYS-2.1.1): 13 g, all XYZ directions for Qualification







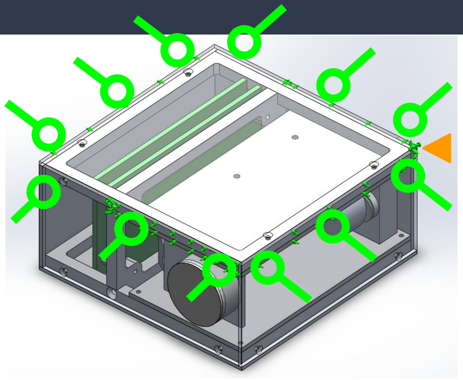
Y axis max stress: **6.94 MPa**
X axis max stress: **3.37 MPa**
Z axis max stress: **6.95 MPa**

Material Stress Limits (Tensile, Yield):

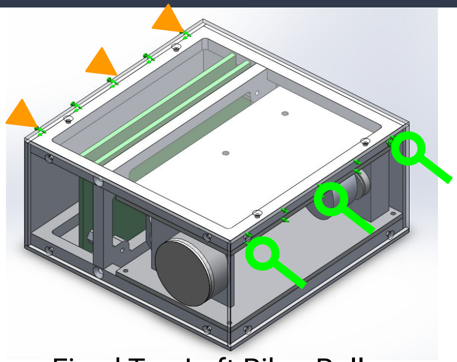
- Al 6061-T6: 276 MPa
- 18-8 Stainless Steel: 215 MPa
- S-Glass Fiber: >4500 MPa (Ultimate)

Numbers gathered from Matweb

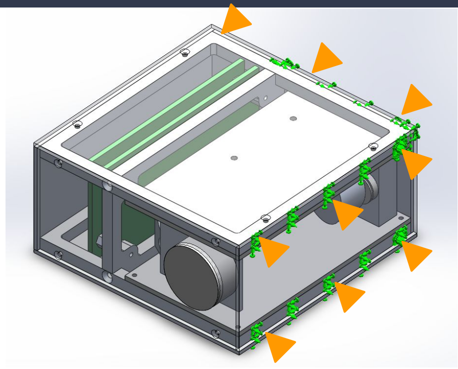
Vibrational Study – Boundary Conditions



Fixed Corner + Roller Top Rib



Fixed Top Left Rib + Roller Top Right Rib

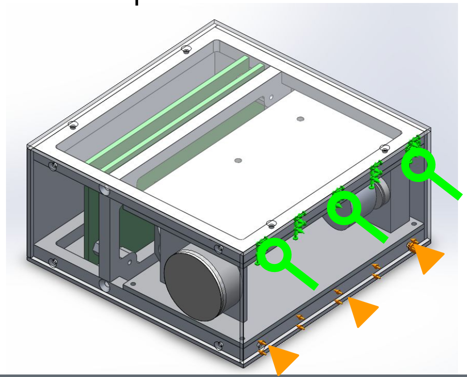


Fixed Top and Bottom Rib

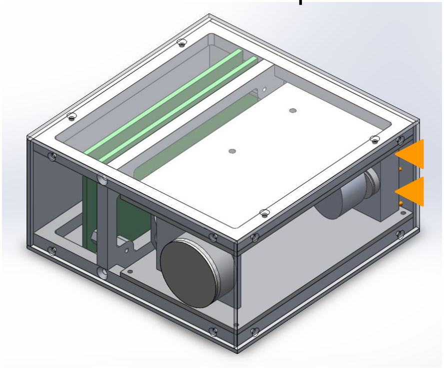
Key:

- Fixed
- Roller

Fixed Top Rib + Roller Bottom Rib



Fixed Back Plate of Optics Bench



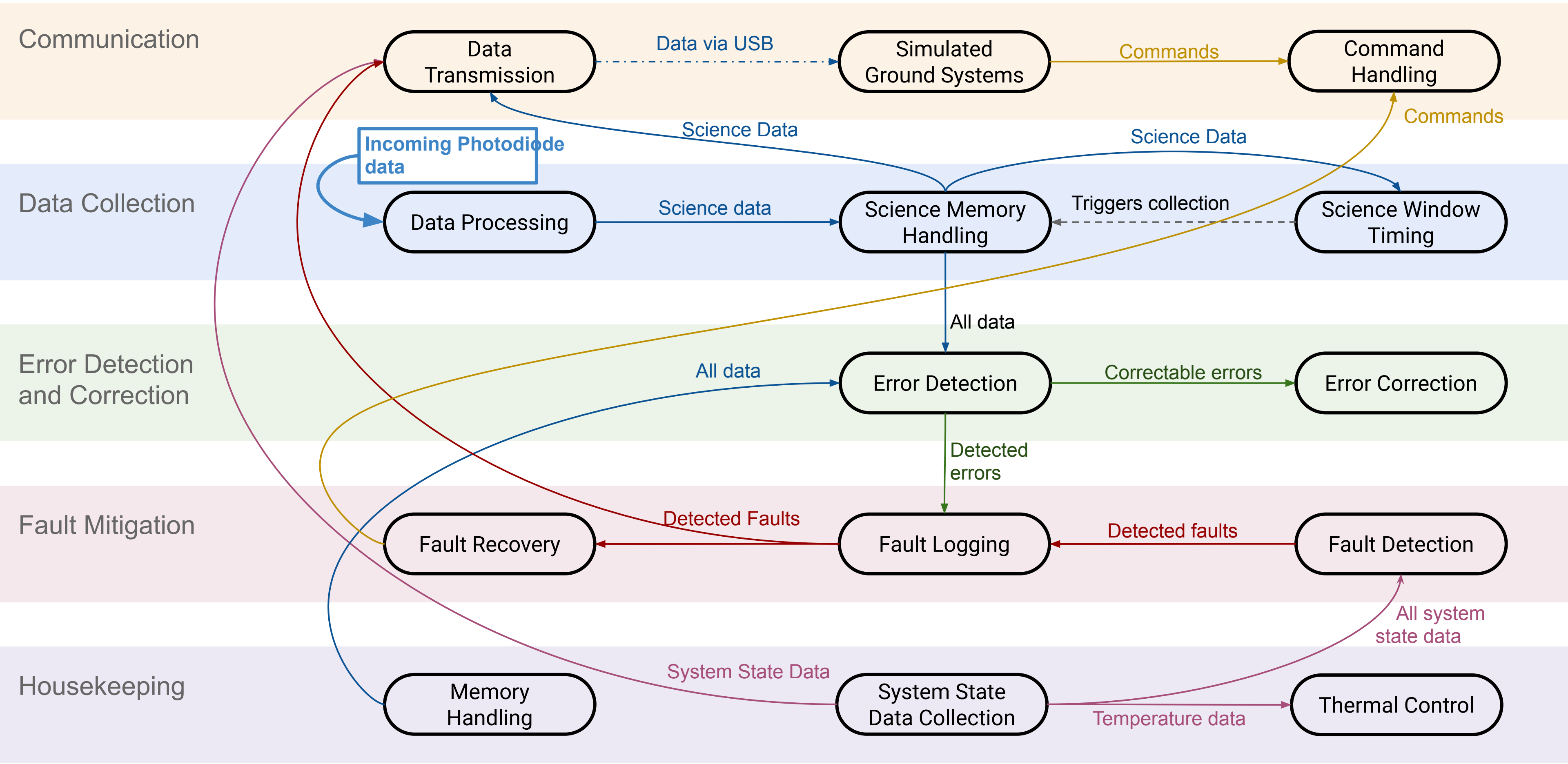
Vibrational Study – Results

Boundary Condition	Lowest Frequency
Roller Top Rib with Fixed Corner	645 Hz
Fixed Top Rib and Bottom Rib	658 Hz
Fixed Top Rib and Roller Bottom Rib	638 Hz
Fixed Top Rib and Roller Top Rib	642 Hz
Fixed Back of Optics Bench	507 Hz

No resonant frequencies below 100Hz requirement

Subject to slight changes due to Cubesat mounting hardware added to model, trend expected to hold

Backup Slides: Software



Communication
Data Transmission
Data via USB
Simulated Ground Systems
Commands
Command Handling
Commands
Science Data
Science Data
Incoming Photodiode data
Data Collection
Data Processing
Science data
Science Memory Handling
Triggers collection
Science Window Timing
All data
Error Detection and Correction
All data
Error Detection
Correctable errors
Error Correction
Detected errors
Fault Mitigation
Detected Faults
Fault Recovery
Fault Logging
Detected faults
Fault Detection
All system state data
Housekeeping
System State Data
Memory Handling
System State Data Collection
Temperature data
Thermal Control

Error Detection and Correction

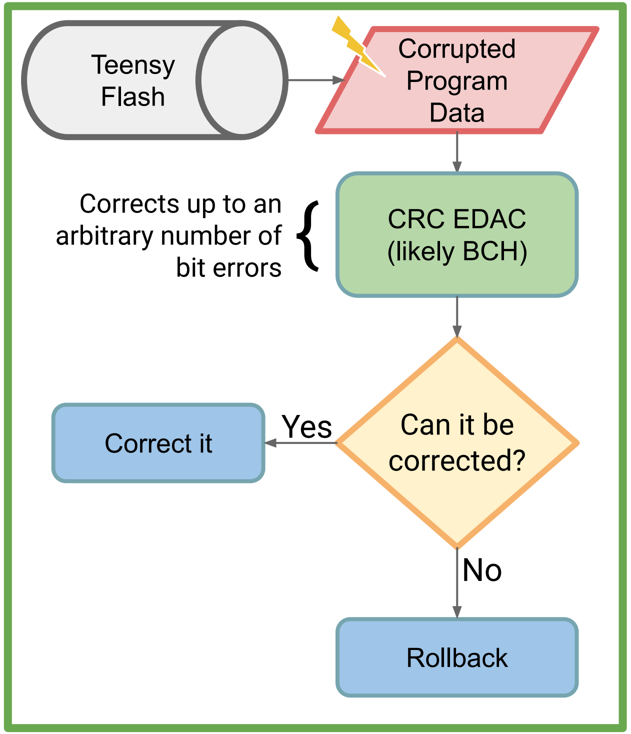
Single Event Errors

Single Event Upset Rate:
10^{-4} errors/bit-day [6]
(10^{-5} errors/bit-day typical)

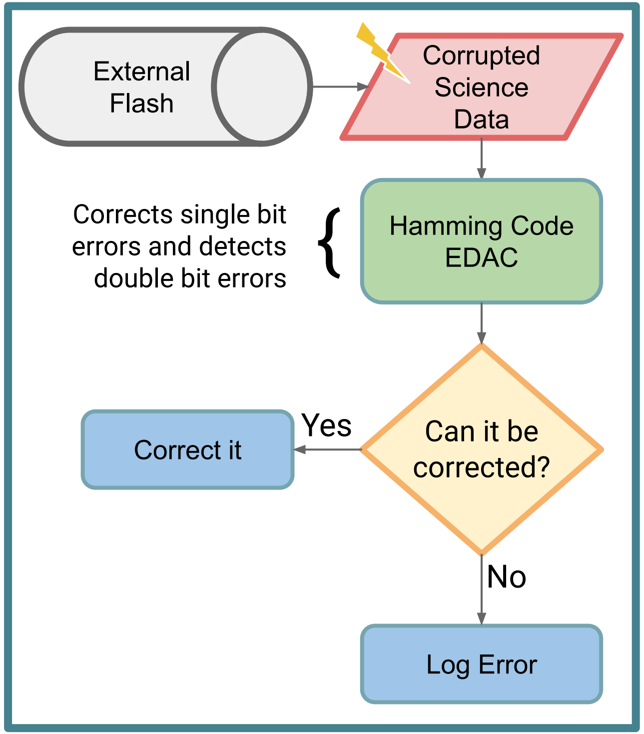
Teensy Flash:
1.6 errors/day
Each Data Window:
0.1 errors/day

Multiple Bit Errors in Teensy Flash:
0.05 errors/day (3%)
=
18 errors/year

Program Data



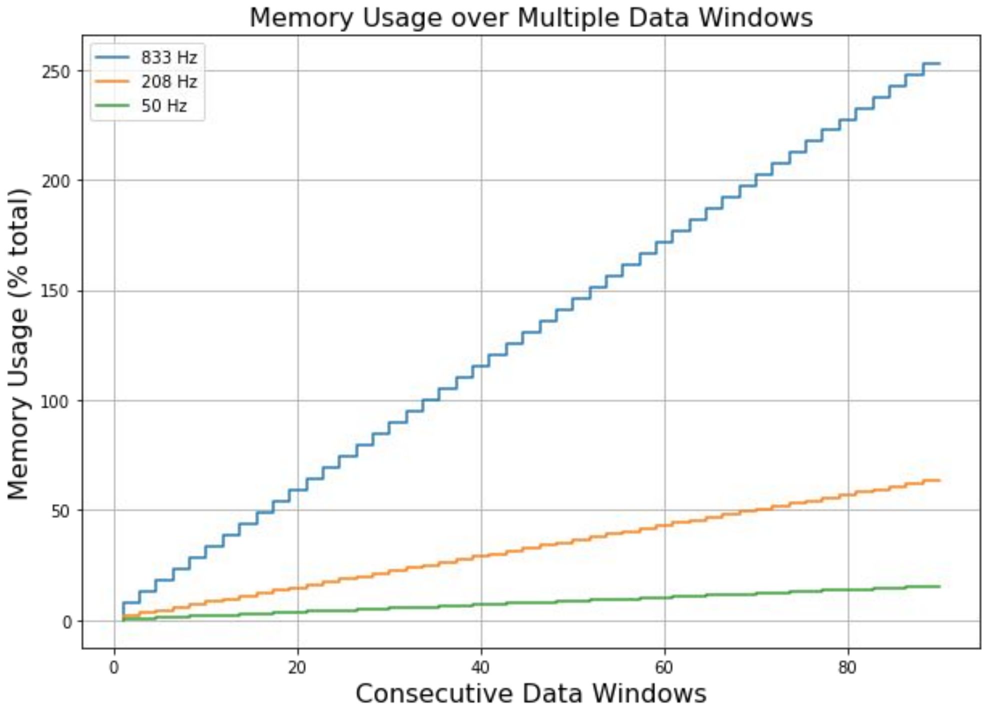
Science Data



Downlink Memory Usage

Data Parameters:
16 bit ADC output + 16 bit metadata
(72,64) Hamming code
240 second maximum window duration
30-31 windows per day

Sample Rate	Consecutive Windows To Fill Memory
833Hz	36 (1.2 days)
208Hz	143 (4.7 days)
50Hz	593 (19.4 days)



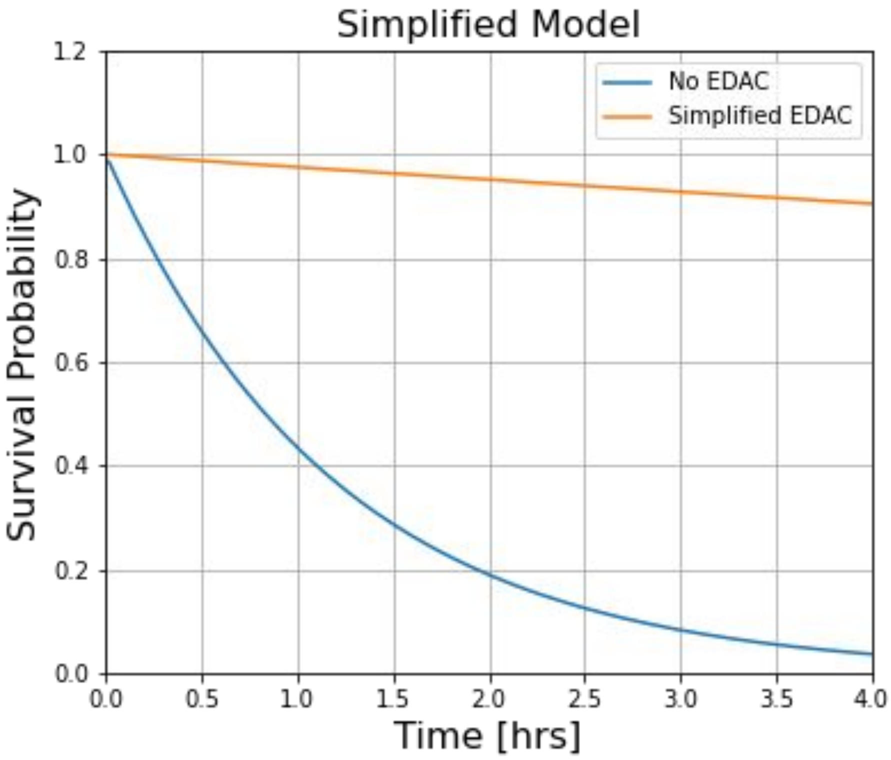
EDAC Simulation

Model Details:
15.872 Mb total program memory
Assumes 10 errors / Mbyte / day
Assumes 2% of errors are multiple bit errors
Assumes EDAC modules use 10% of program memory
Memory is scrubbed with a (72,64) SEC-DED EDAC scheme
Dual redundant cross-checking EDAC modules

Scrubbing Interval	Reliability for a Period of One Day			
	Software EDAC		Hardware EDAC	
	u = 5.52×10^{-19}	u = 5.52×10^{-18}	u = 5.52×10^{-19}	u = 5.52×10^{-18}
10 minutes	0.935506	0.513345	0.999999	0.999904
20 minutes	0.935504	0.513274	0.999998	0.999808
30 minutes	0.935503	0.513202	0.999997	0.999712
40 minutes	0.935502	0.513130	0.999996	0.999617
1 day	0.935319	0.503198	0.999862	0.986297

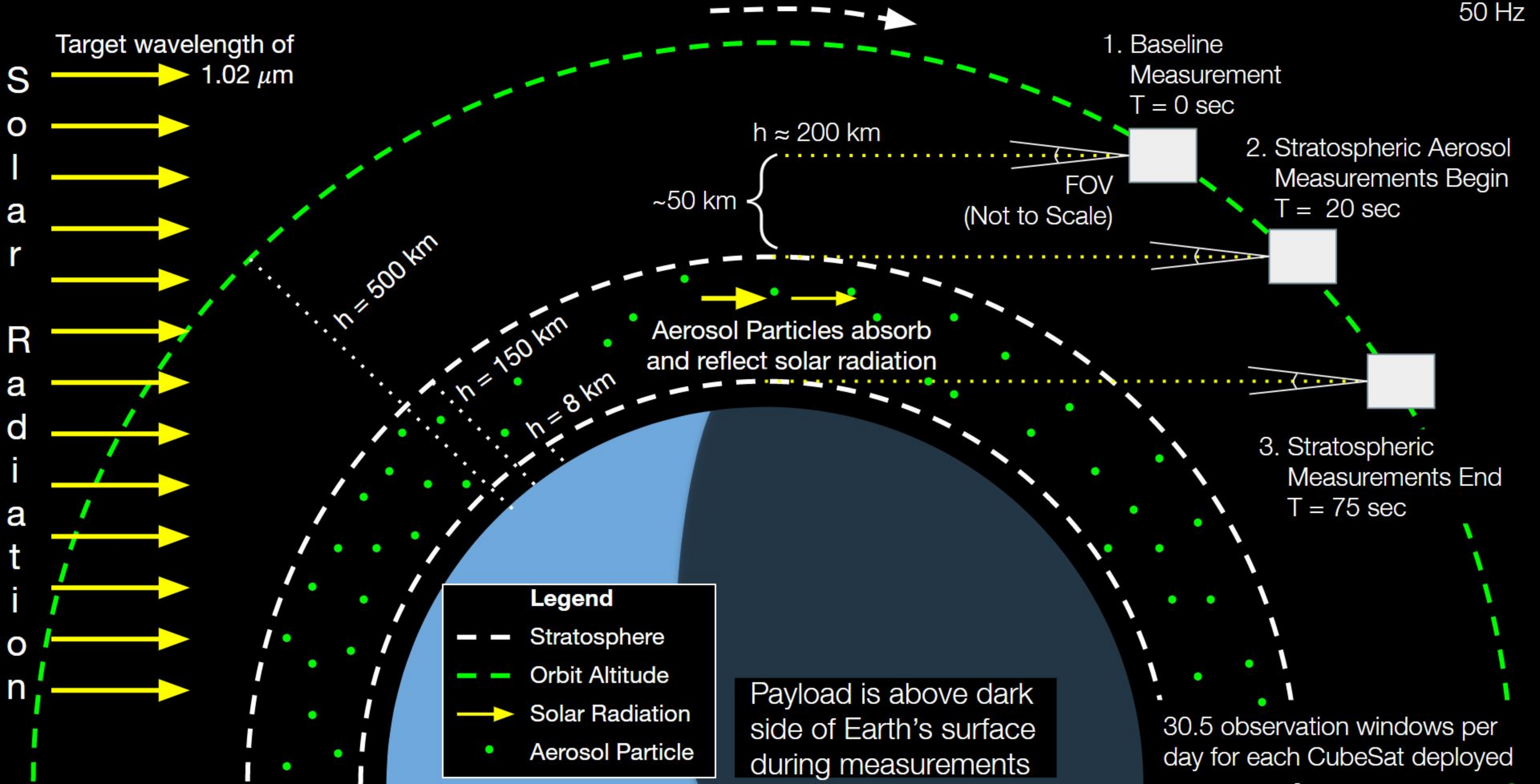
Data From ARGOS Project

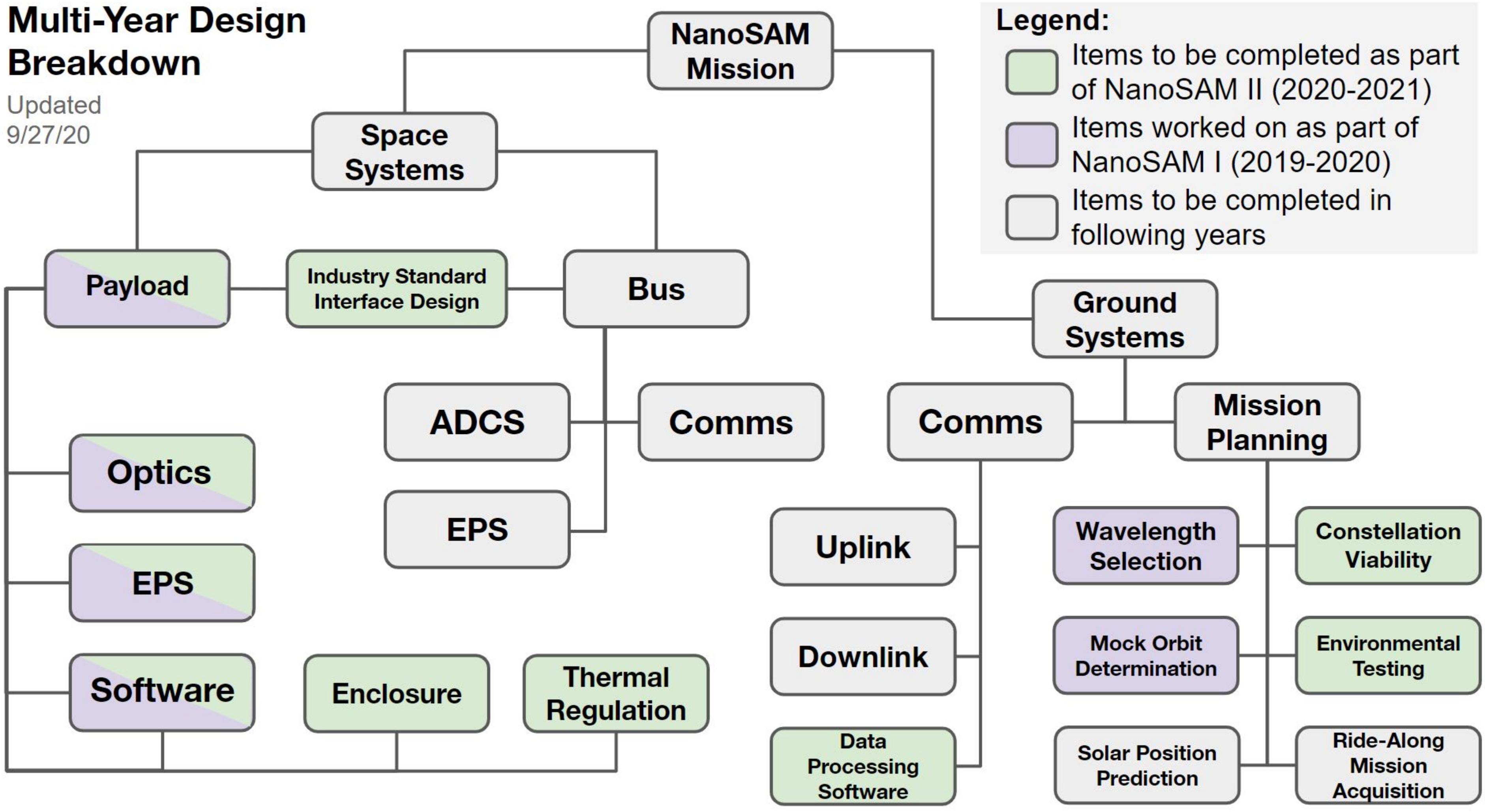
Shirvani, Philip & Saxena, Nirmal. "Software-implemented EDAC protection against SEUs" IEEE Transactions on Reliability 49(3), October 2000
See Here



Backup Slides: Management

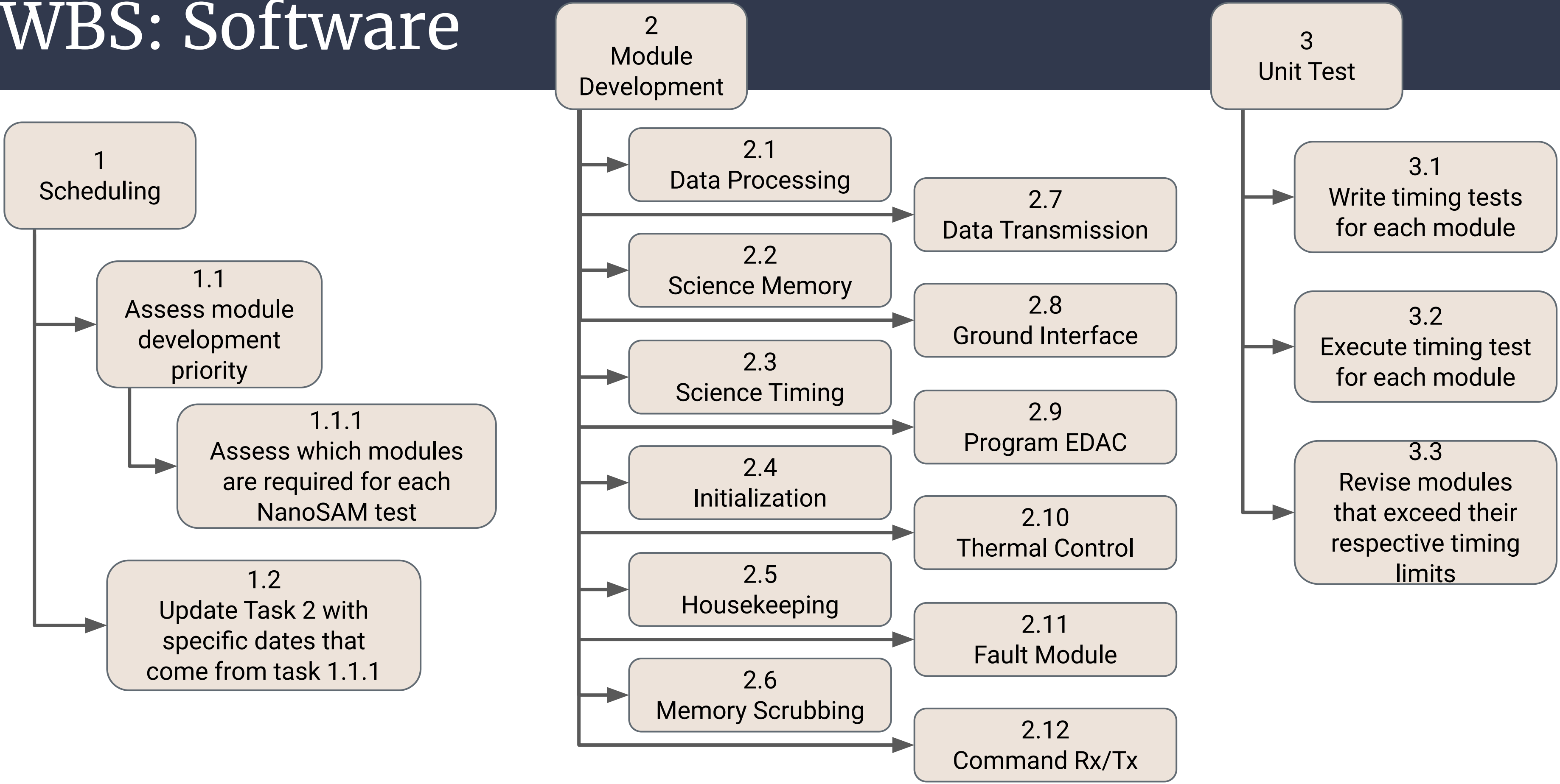
NanoSAM Mission CONOPS



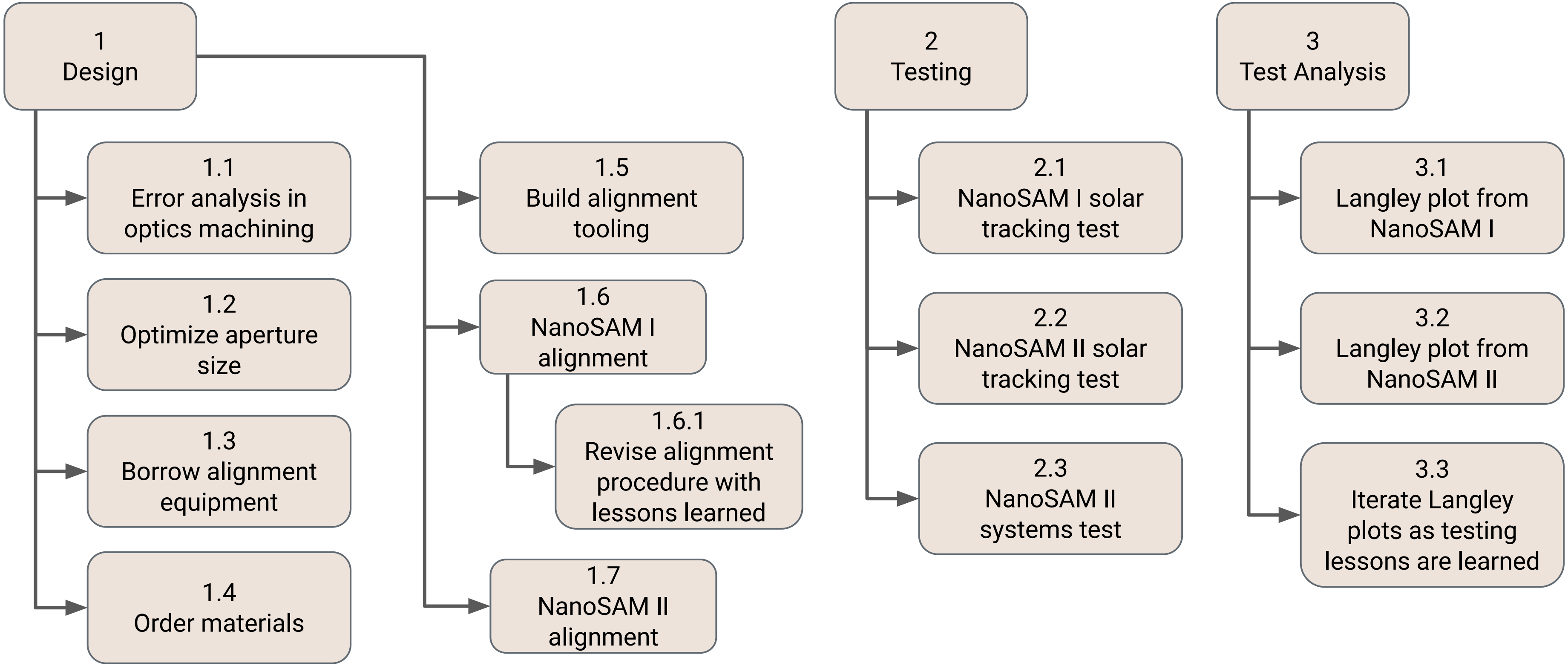


Multi-Year Design Breakdown
Updated 9/27/20
Legend:
Items to be completed as part of NanoSAM II (2020-2021)
Items worked on as part of NanoSAM I (2019-2020)
Items to be completed in following years
NanoSAM Mission
Space Systems
Ground Systems
Payload
Industry Standard Interface Design
Bus
ADCS
Comms
EPS
Optics
EPS
Software
Enclosure
Thermal Regulation
Comms
Mission Planning
Uplink
Downlink
Data Processing Software
Wavelength Selection
Constellation Viability
Mock Orbit Determination
Environmental Testing
Solar Position Prediction
Ride-Along Mission Acquisition

WBS: Software



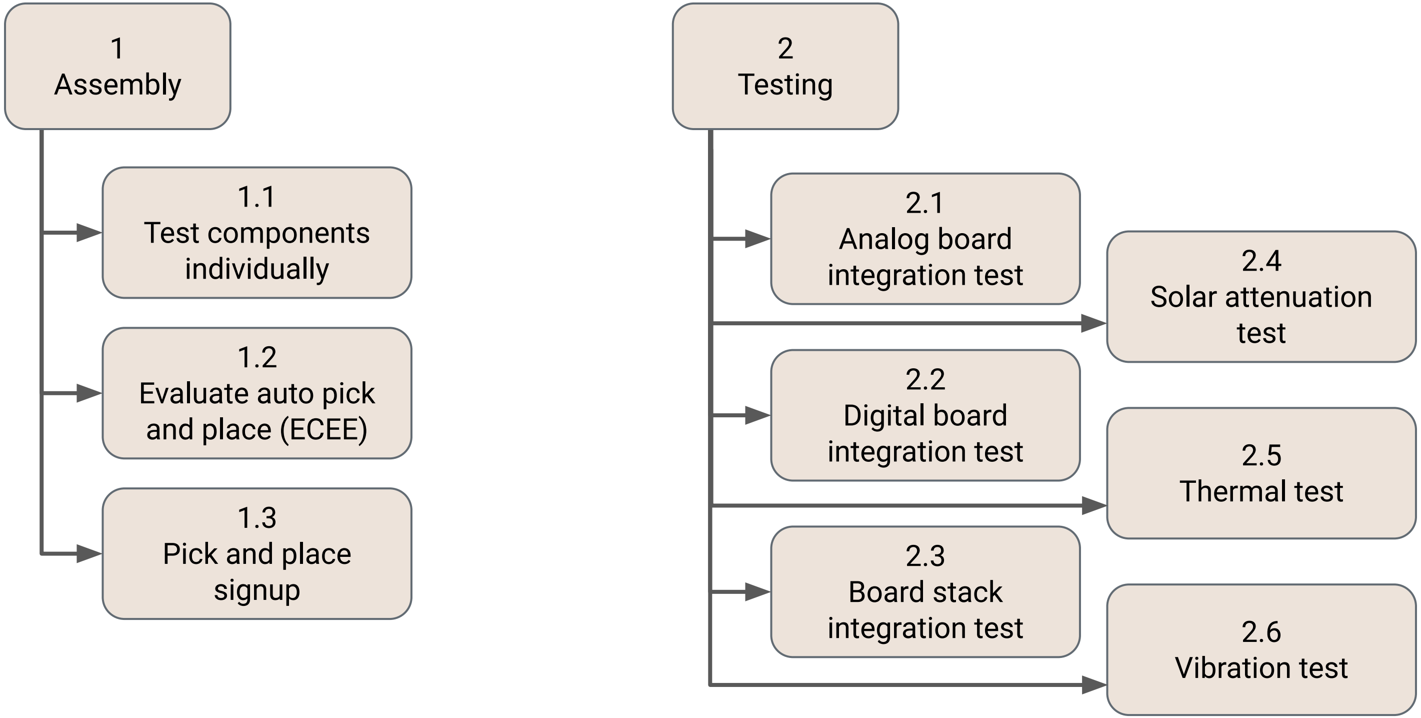
WBS: Optics


1
Design
1.1
Error analysis in optics machining
1.2
Optimize aperture size
1.3
Borrow alignment equipment
1.4
Order materials
1.5
Build alignment tooling
1.6
NanoSAM I alignment
1.6.1
Revise alignment procedure with lessons learned
1.7
NanoSAM II alignment
2
Testing
2.1
NanoSAM I solar tracking test
2.2
NanoSAM II solar tracking test
2.3
NanoSAM II systems test
3
Test Analysis
3.1
Langley plot from NanoSAM I
3.2
Langley plot from NanoSAM II
3.3
Iterate Langley plots as testing lessons are learned

WBS: Structures

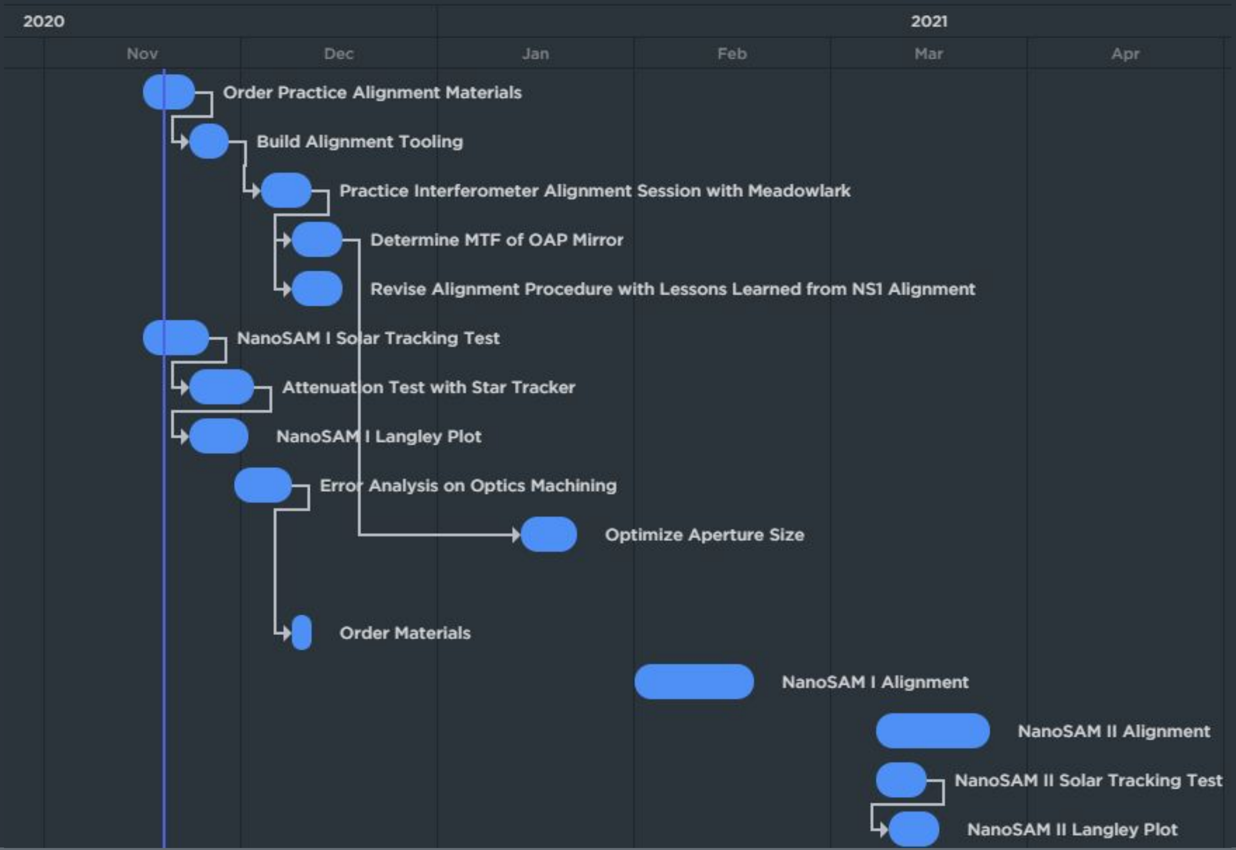
- 1 Design
  - 1.1 Error analysis for machining
  - 1.2 Order materials
  - 1.3 Send design to job shop
- 2 Assembly
  - 2.1 Assemble frame
  - 2.2 Remachine out of tolerance parts
  - 2.3 Integrate optics and EPS
- 3 Testing
  - 3.1 Solar tracking test
  - 3.2 Thermal testing
  - 3.3 Vibration testing

WBS: Electronics



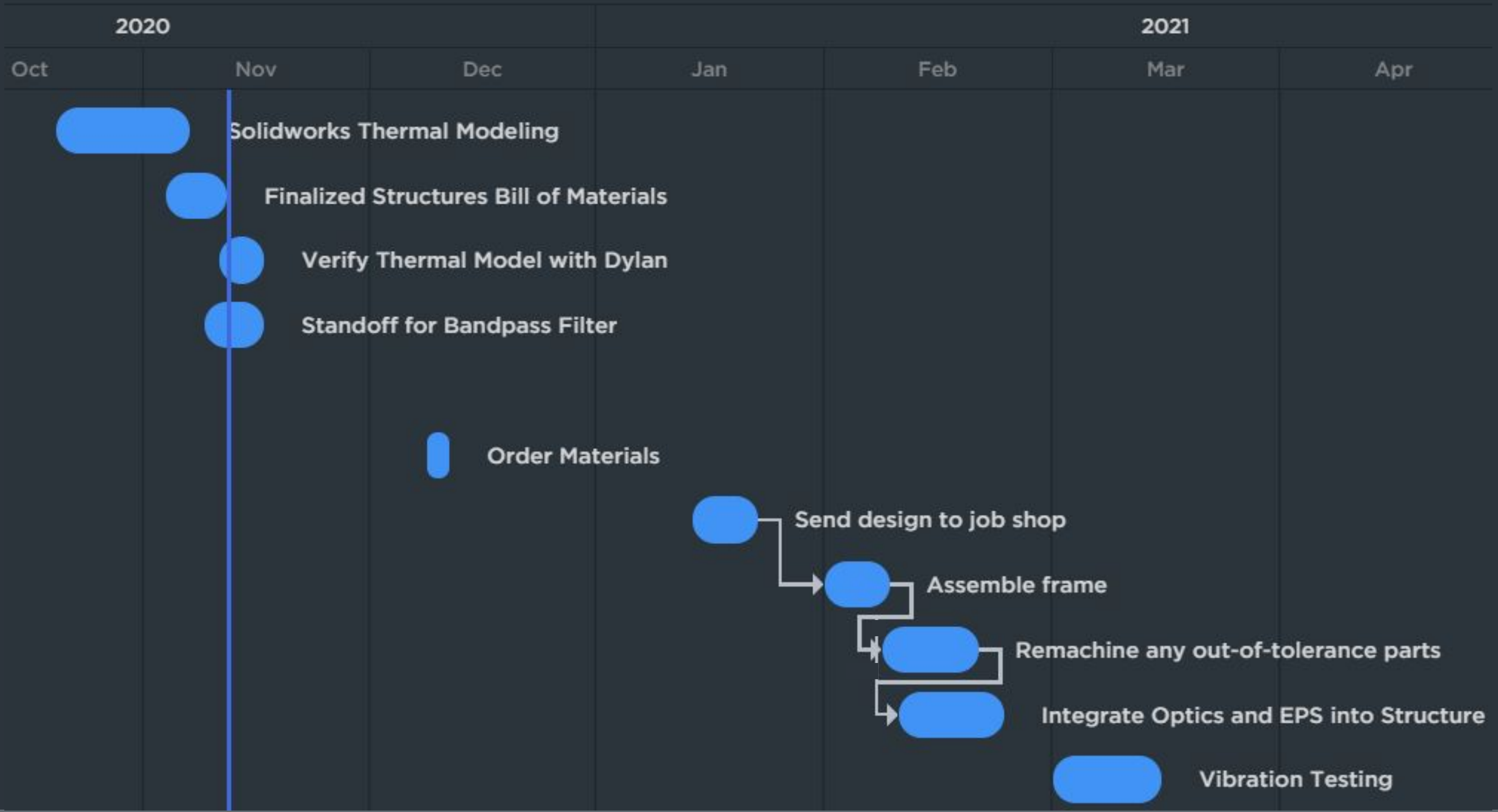
WP: Management

WP: Optics


2020
2021
Nov
Dec
Jan
Feb
Mar
Apr
Order Practice Alignment Materials
Build Alignment Tooling
Practice Interferometer Alignment Session with Meadowlark
Determine MTF of OAP Mirror
Revise Alignment Procedure with Lessons Learned from NS1 Alignment
NanoSAM I Solar Tracking Test
Attenuation Test with Star Tracker
NanoSAM I Langley Plot
Error Analysis on Optics Machining
Optimize Aperture Size
Order Materials
NanoSAM I Alignment
NanoSAM II Alignment
NanoSAM II Solar Tracking Test
NanoSAM II Langley Plot

WP: Optics Detailed Example

WP: Structures



WP: Electronics

WP: Software


2021
Dec
Jan
Feb
Mar
Apr
May
Develop Modules
Data Processing
Science Memory Handling
Housekeeping
Command Handling
Ground Interface
Command Transmission
Science Timing
Initialization
Memory Scrubbing
Data Transmission
Thermal Control
Fault Module
Program EDAC
Write timing unit test...
Execute timing unit t...
Revise modules that exceed their timing
SEE test

Backup Slides: Testing

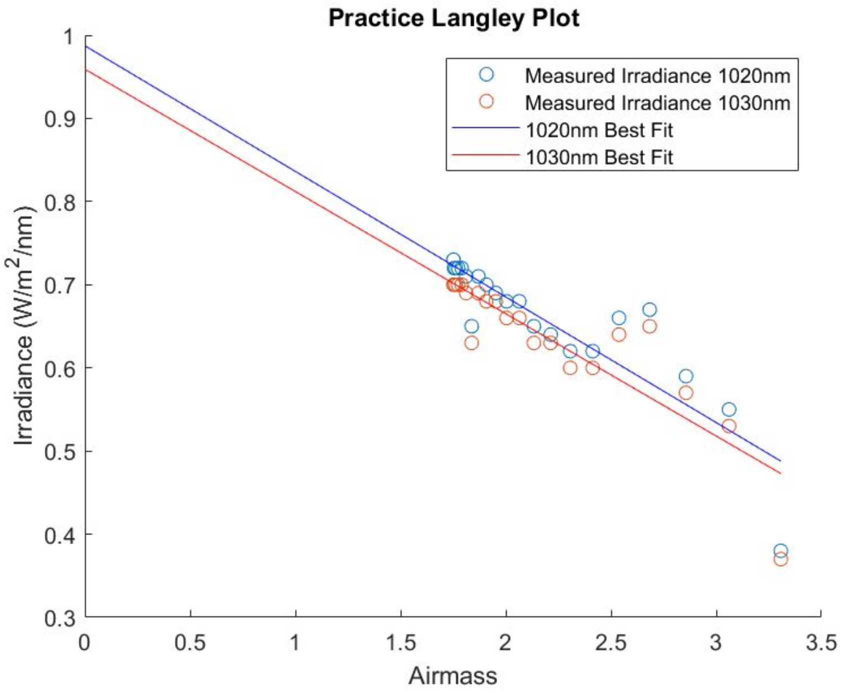
Solar Tracking & Langley Plot Test

Solar Tracking Test:

- Solar tracker purchased by NanoSAM 1
- Done prior to any solar attenuation test
- Ensure that our solar tracker meets the required 1 arcmin tracking accuracy

Langley Plot:

- Used to verify the accuracy of the overall irradiance measurement at the desired wavelength (1020 nm)
- Used to determine the gain of the system
- Data taken from CU Boulder skywatch observatory



Solar Attenuation Test, continued

Pre-test:	Measurements:	Analysis:

• Use NOAA Solar Position Calculator to characterize the zenith angle and air mass for test window
• Monitor weather forecast for optimal conditions
	• Irradiance
	  ○ Across desired range of AM
	• Simultaneous recording CU Skywatch irradiance measurements
		• Verify entire section 1 of requirements
		• Create a Langley plot, and extrapolate expected irradiance at 0 air-mass
		  ○ Compare value to expected flight conditions, quantify error in extrapolation
		  ○ Skywatch data will provide means of error analysis

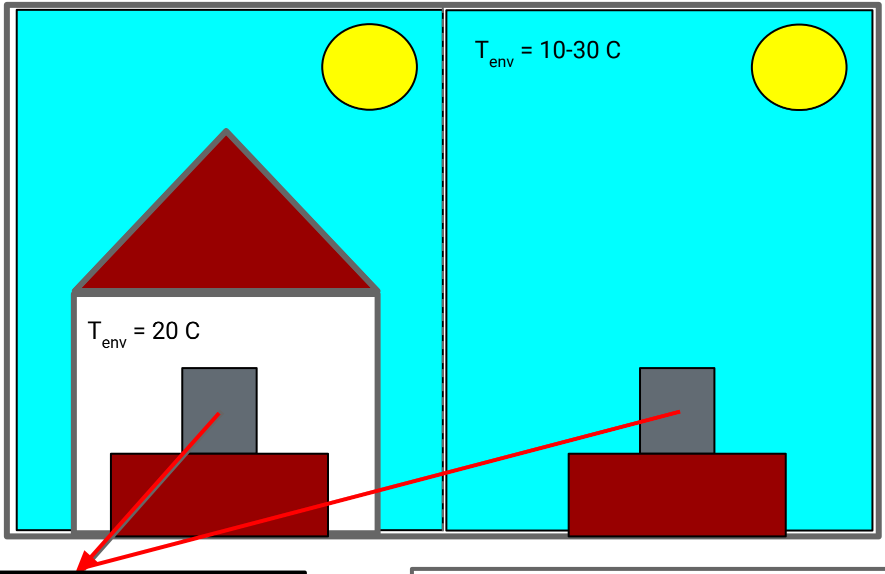
Regulated light test, continued

Pre-test:	Measurements:	Analysis:
● Estimate flux at system entry ○ Light source of known luminosity ○ Flux will be proportional to inverse square of distances ● Estimate amount of light filtered ○ Overlay filter frequency response and light source frequency range	● Irradiance ○ At three separate distances ○ Multiple trials	● Photodiode saturation ○ Looking for a plateau in photon count ● Signal to noise ratio ○ Compare to design margin ● Efficiency of optics ○ Compare pre-test predictions to data

Software: System State Monitoring

Goal: Confirm system housekeeping data is reporting correctly

- Set system to read off system housekeeping data
- Verify temperature, power, storage capacity through model and external measurements
- Test in different environments (outside, inside)



Read-off from computer: Temperature, storage capacity, component power usage

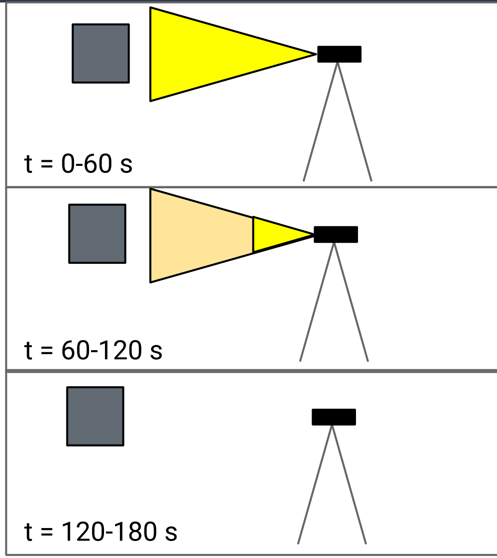
Software CPE

Timely and Reliable Data Collection

Software: Collection Timing Test

Goal: Confirm that software collect irradiance data during required window

1. Set up regulated light test
2. Run the system
3. Let system run at max brightness for 1 minute
4. Dim light to darkness and keep dark for 1 minute
5. Stop System and collect data
6. Verify data shows decreasing irradiance
7. Repeat for dark to light
8. Verify data shows increasing irradiance



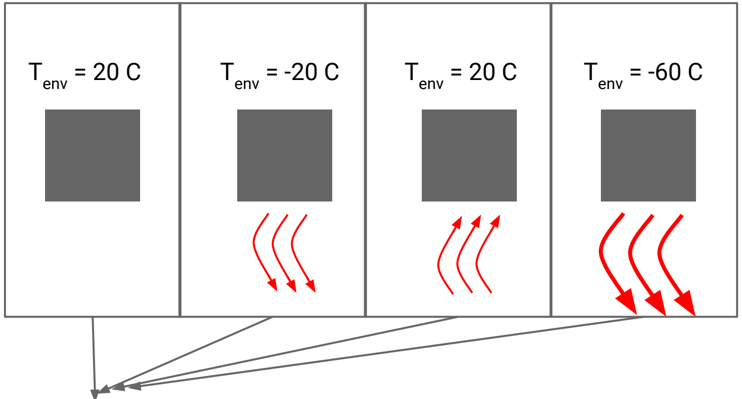
Software CPE

Timely and Reliable Data Collection

Structures : Thermal Test

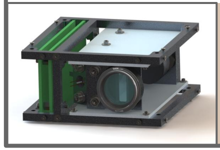
<u>Goal:</u> Verify heater functionality and overall system functionality over expected temperature range

- Set software to continuously output temperature housekeeping data
- Run data collection inside thermal test chamber at room temperature
- Keep running while decreasing to -20 C
- Return to room temperature
- Reduce temperature again, this time to -60 C



Verify housing data read off: System temp shouldn't drop below -20 C and electronics should remain functional within this range

Structure CPE



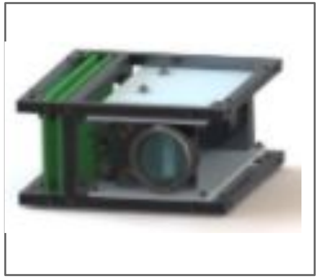
Vibrational Modes Simulation & Testing

Structures : Vacuum Test

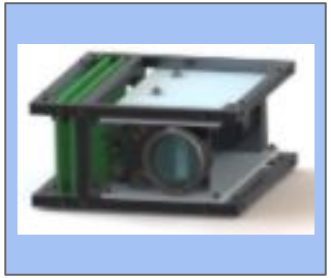
<u>Goal:</u> Verify heater functionality and overall system functionality over expected temperature range

- Run the system in vacuum chamber with atmospheric conditions for 1 minute
- Keep system running with vacuum chamber activated for 1 minute
- Continue running back up to atmospheric conditions and keep running for 1 minute

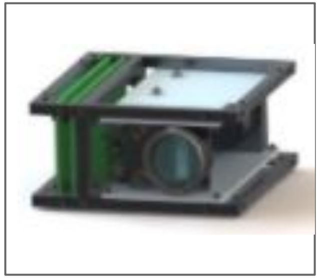
Off



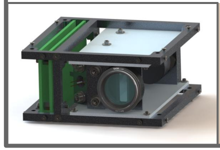
On



Off



Structure CPE

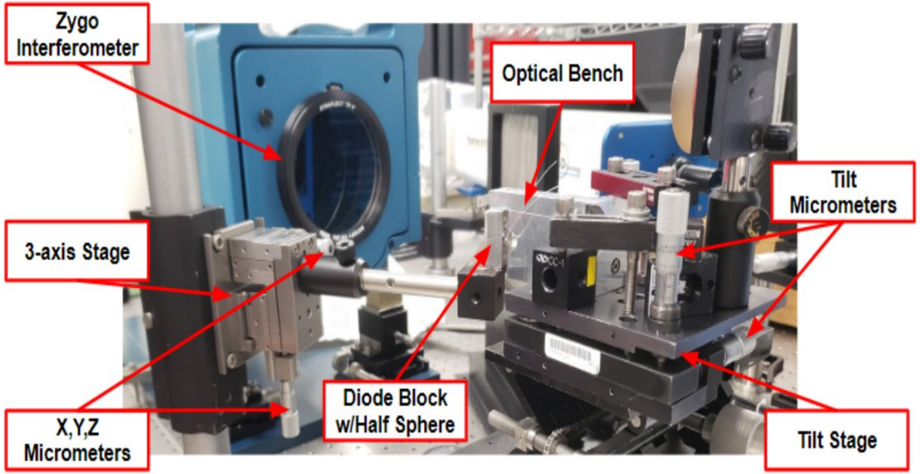


Vibrational Modes Simulation & Testing

Optics: Alignment Test

Goal: Sufficiently align optical system

Steps:
1. Align ball bearing to optimal optical axis by driving interferometer-measured zernike coefficients to zero
2. Align sighting tabs
3. Align diode block, again by driving zernike coefficients to zero
4. Measure MTF
5. Align the diode block to pinhole
    a. Correct defocus based on false interferogram
    b. Adjust shims until light passes unobstructed through the pinhole (corrects for vertical displacement)
6. Tighten diode block into final aligned configuration

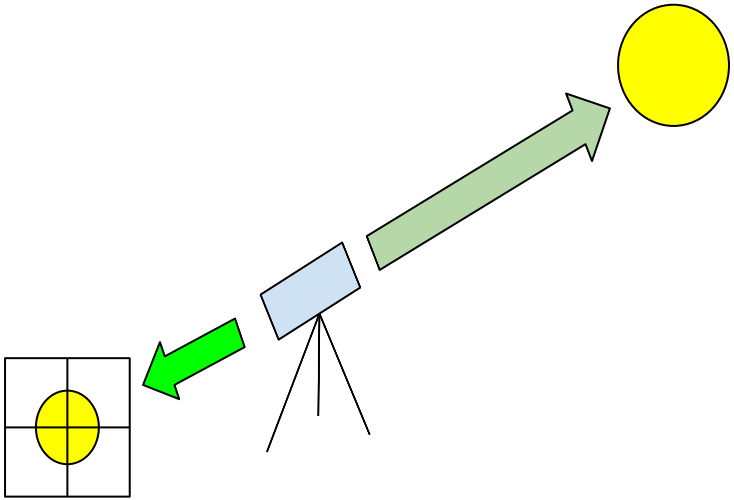


Tracking Accuracy Test

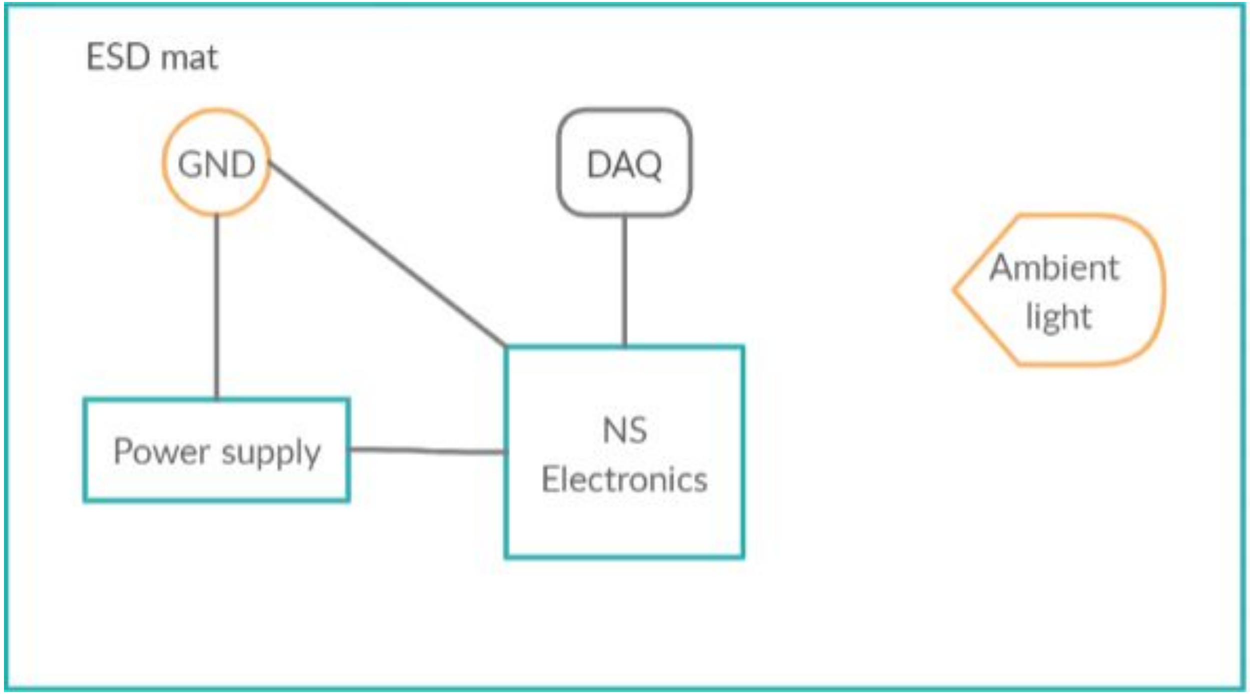
Goal: Ensure that the purchased star tracker can meet the 1 arc-min (.3 mRad) tracking accuracy requirement

Steps:

1. Pick a day when it is sunny outside (no clouds)
2. Align star tracker to the sun (following instructions provided in manual)
3. Use fishing wire over the scope to project a set of crosshairs and the view of the sun through the scope onto a piece of cardstock
4. Over the course of an hour, as the star tracker tracks the sun, use a cell phone camera to take pictures of the projected crosshairs and sun image every five minutes
5. Data process by pixel resolution to determine the accuracy of the star tracker



Data Collection/Electronic System Test Setup



Objectives:

- Verify baseline requirements, primarily in data conditioning
- Check electronic components' functionality

Baseline Data Collection Test

Goal: Confirm system provides data at the required specifications
Overall: Allow shining of a light source (arbitrary irradiance) onto the photodiode and measure outputs

1. Verify payload is connected as necessary and is connected to an external computer
2. Verify the ADC collects at 10 bits or greater.
3. Run the system for 1 minute, varying how much light goes into the system.
    a. Specific values are not necessary for this test
4. Complete the test and obtain test data
    a. Test data obtained means requirements 1.0, 1.1, 2.0 are verified
5. Compute sampling rate by dividing the samples taken by the test duration in seconds.
    a. Should be ~ 50 Hz
6. Determine storage capacity taken up by the data from the housekeeping data
    a. Extrapolate storage taken through 1 downlink period.

Electronics System Test

Goal: Determine the electronics power draw, and ensure proper component functionality

1. Transfer software to the ADC
2. With both electronics boards separated, connect the analog board to a 12V power source and ground
3. Measure voltage across board
4. Connect the digital and analog boards and connect them to 12V power and ground
5. Measure voltage across the two boards
6. Plug in the usb connection and connect to 12V power and ground
7. Measure voltage across
    a. If the voltages are not what was expected, test values at test points to find error
8. While connected to power, measure the voltage drop across the voltage regulator
9. Obtain voltage regulator current from the microcontroller
10. The power usage is the current times the voltage
    a. This is the maximum source of power draw of the system, total power would need values across more components