Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

Dust BUSTER

Boulder **U**nmanned **S**ensor for **T**ransport **E**vents and **R**epositioner

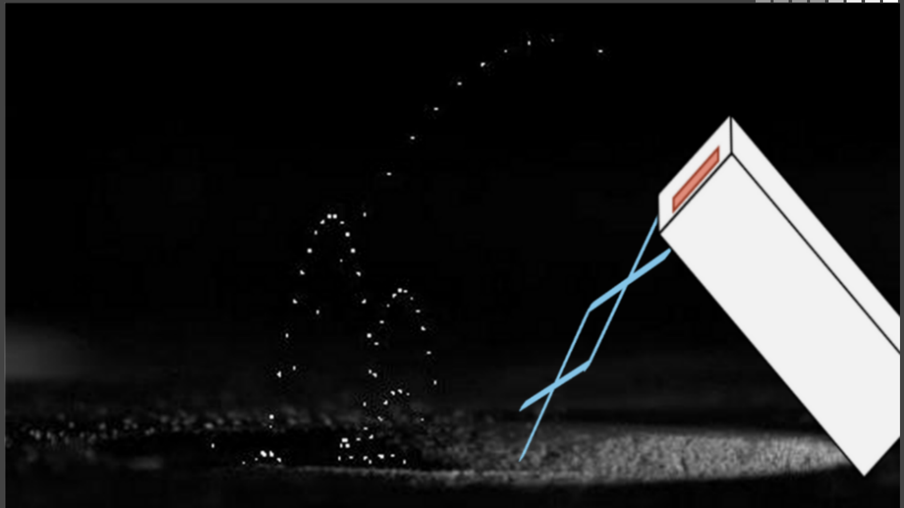
Manufacturing Status Review

Presenters: Alex St. Clair, Charlie LaBonde, Rachel Tyler, Robert Hakulin
Team: Christine Reilly, Ted Zuzula, Gabe Castillo, Jeff Jenkins, Leina Hutchinson, Reidar Larsen, Ryan Aronson
Customer: Dr. Xu Wang, Dr. Zoltan Sternovsky
Advisor: Dr. Torin Clark

Overview

Project Motivation

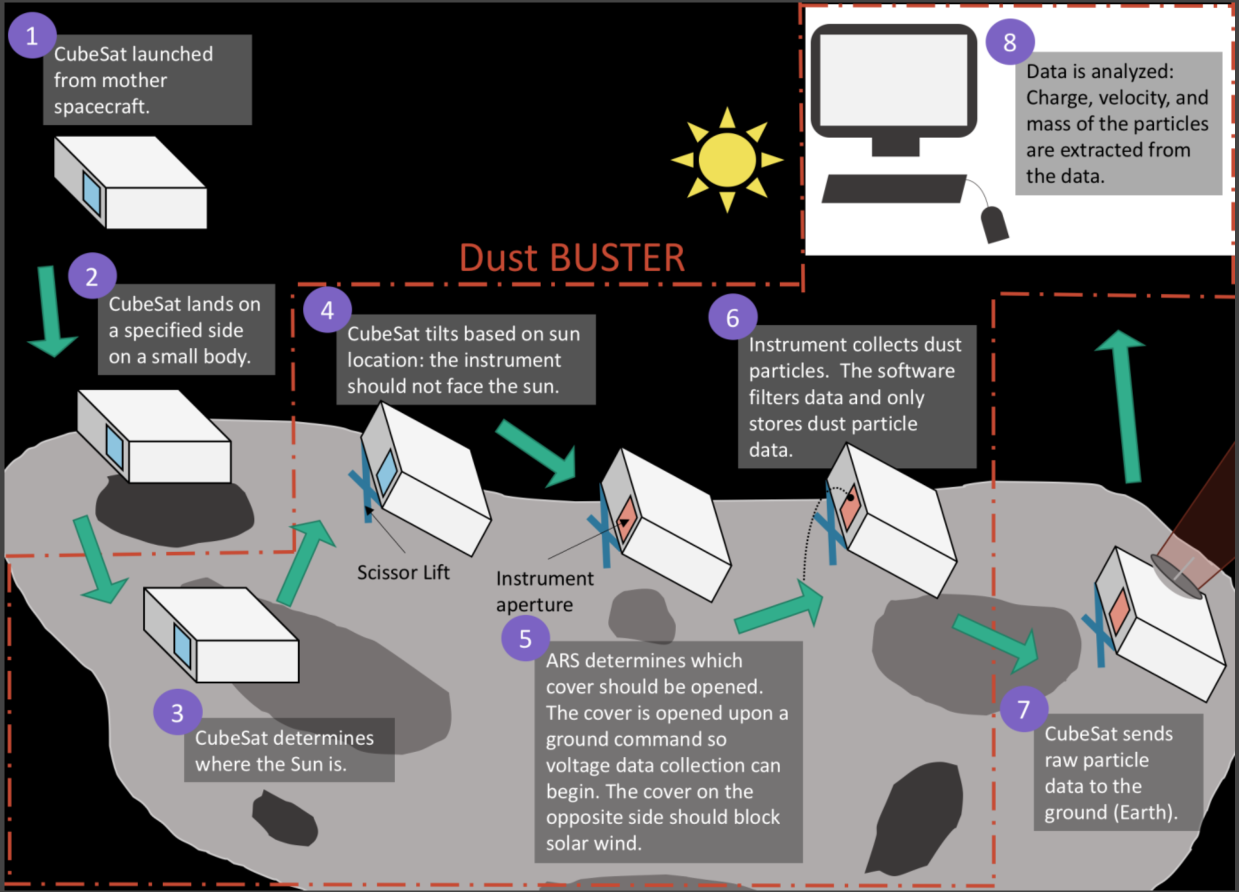
- Dr. Wang's research at LASP suggests that charged particles could be lifted by Coulomb force
  - **Dust transport events**: micron-sized dust particles are charged by various sources in space and ejected from the surface of low-mass bodies
- Current instrument is too large for a space application in low-gravity
- **Data could be collected with a smaller instrument in a CubeSat form factor, for a potential mission to an asteroid**



Project Statement

- Dust BUSTER will miniaturize, manufacture, and test a **Technology Readiness Level (TRL) 4** dust instrument to characterize dust transport events similar to those that occur on asteroids
- To aid the instrument, the team will also design and test an **Autonomous Repositioning System (ARS)** to tilt a 6U CubeSat to a specified angle for dust collection

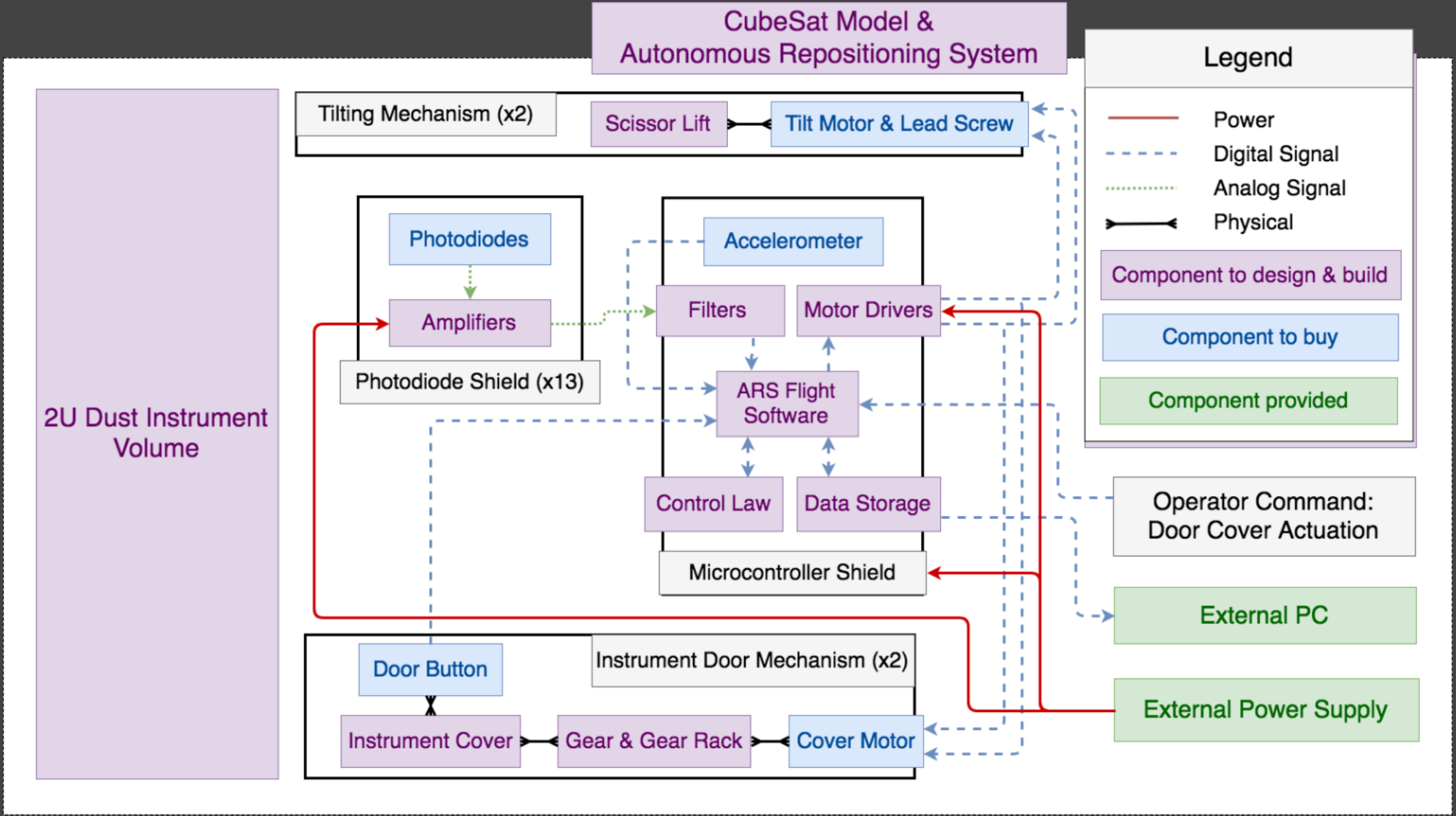
Overall Mission ConOps



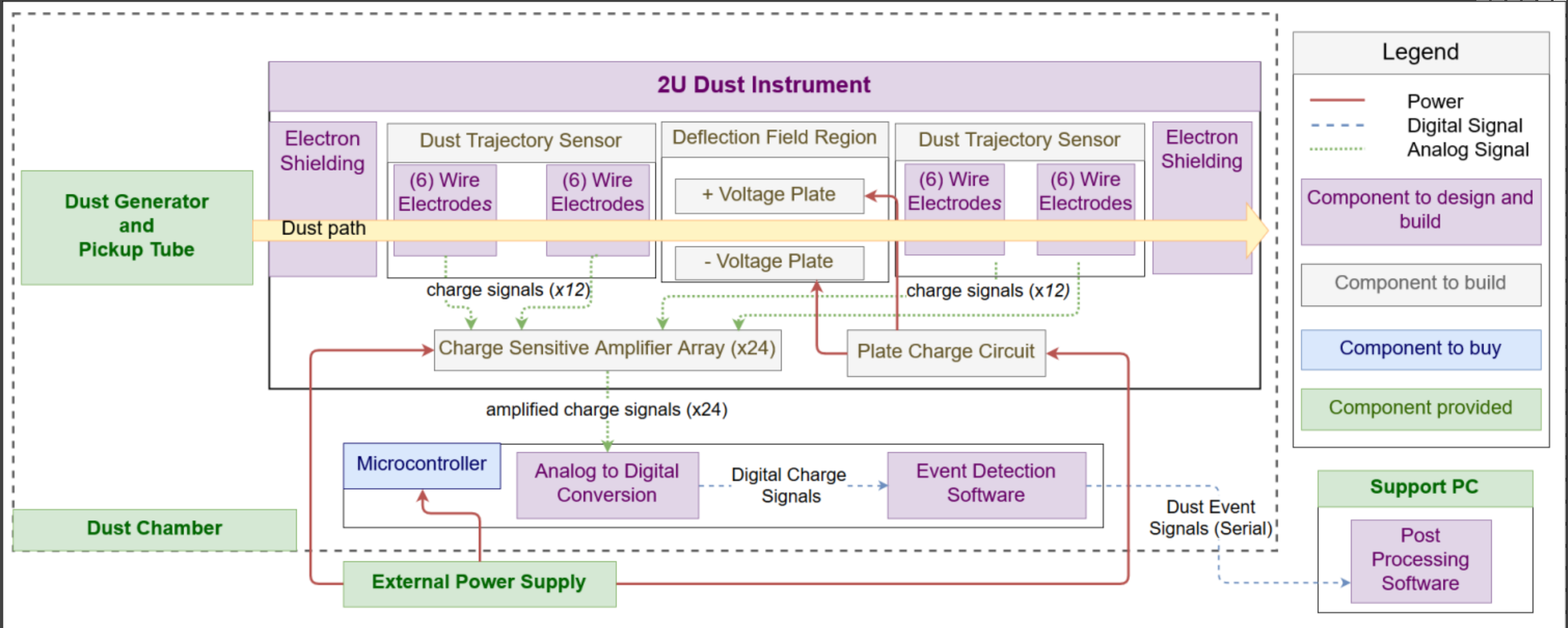
Levels of Success

	Level 1	Level 2	Level 3
Instrument	- 2U TRL 4 dust instrument - Operates in vacuum chamber - Interfaces mechanically with CubeSat	- Wire electrodes remain intact upon 10 m/s impact	-
CubeSat/ ARS	- Construct 6U CubeSat model - Tilt CubeSat model up to 45 degrees on a flat surface - Determine which side of the CubeSat has the least sun	- Open loop autonomous tilt with 5° accuracy - Operates on sandy surface	- Closed loop tilt with 1° accuracy - Instrument cover opens once under operator command
Software	- Detect dust via external trigger - Send dust data over serial - Post processing algorithm extracts mass, velocity, charge	- Self-triggering dust detection algorithm	- Determine uncertainty in mass, velocity, and charge

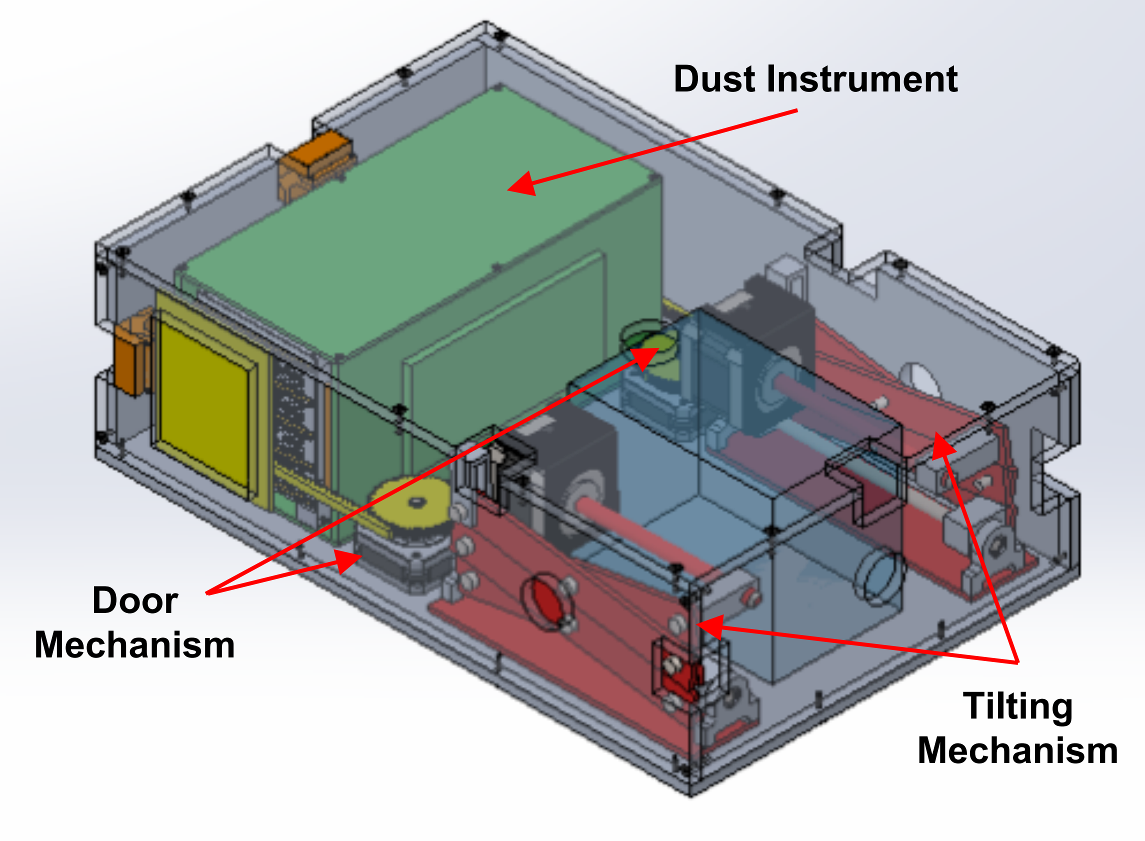
Autonomous Repositioning System FBD



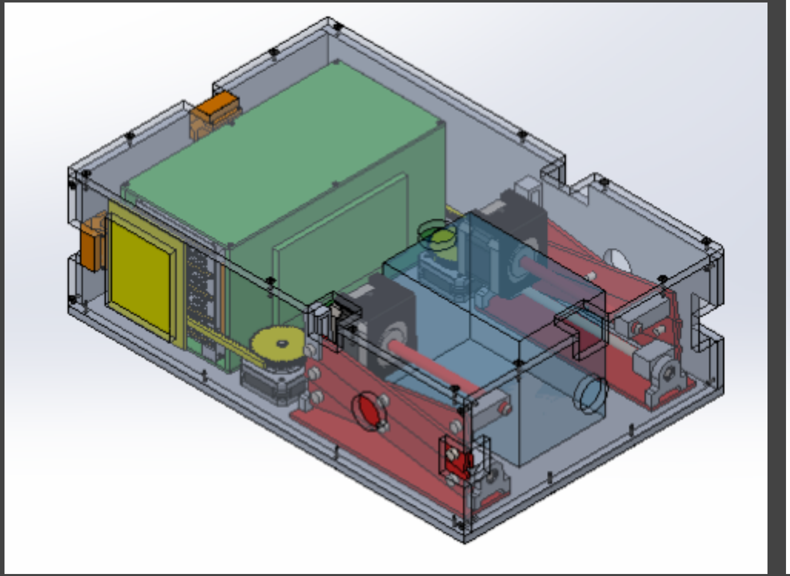
Instrument Functional Block Diagram

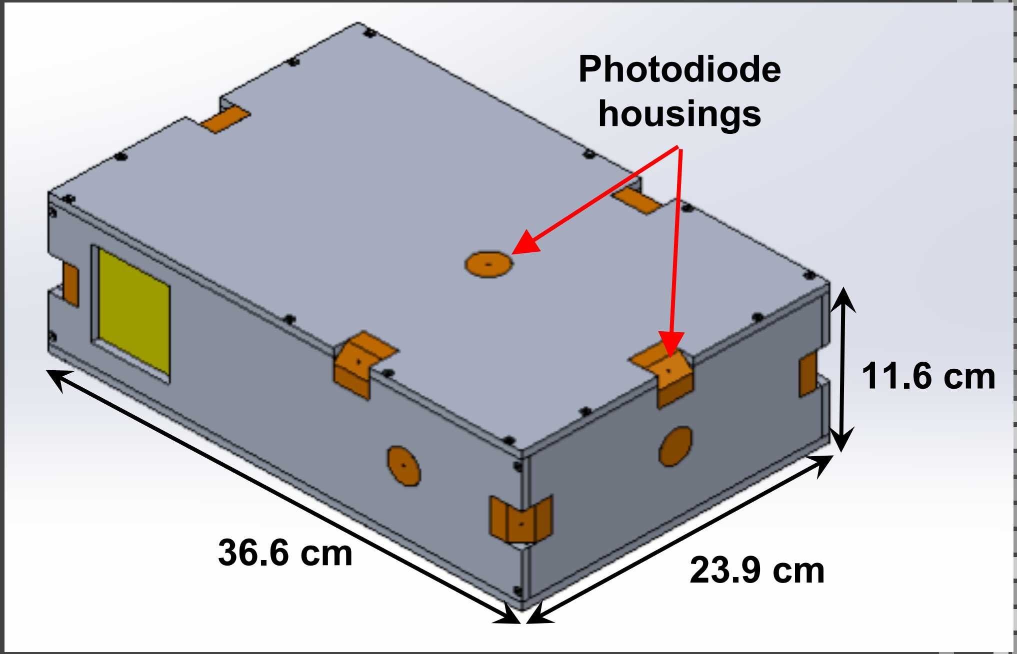


Design Recap

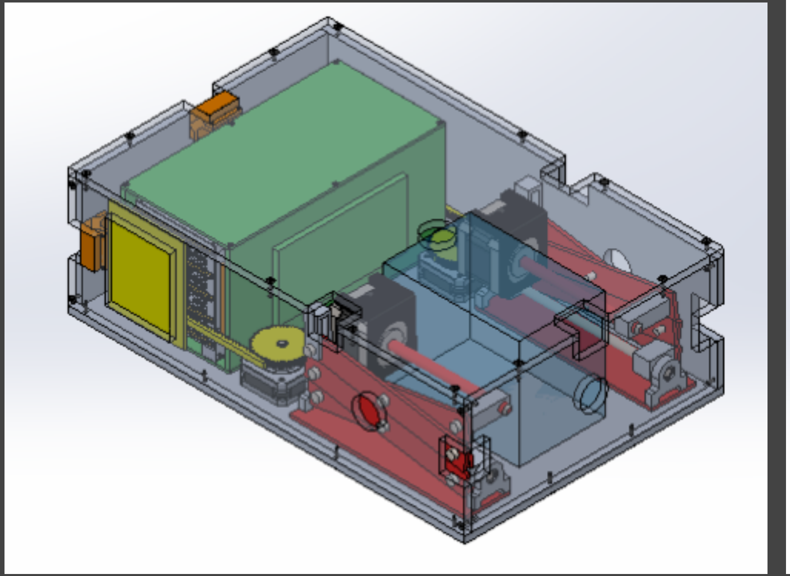


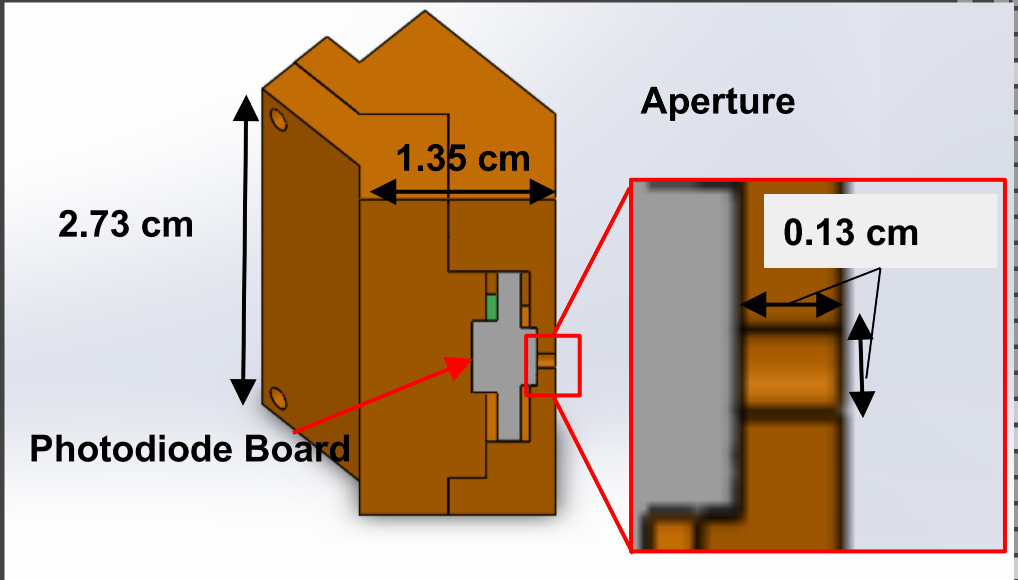
Design Recap -CS Model & Photodiodes





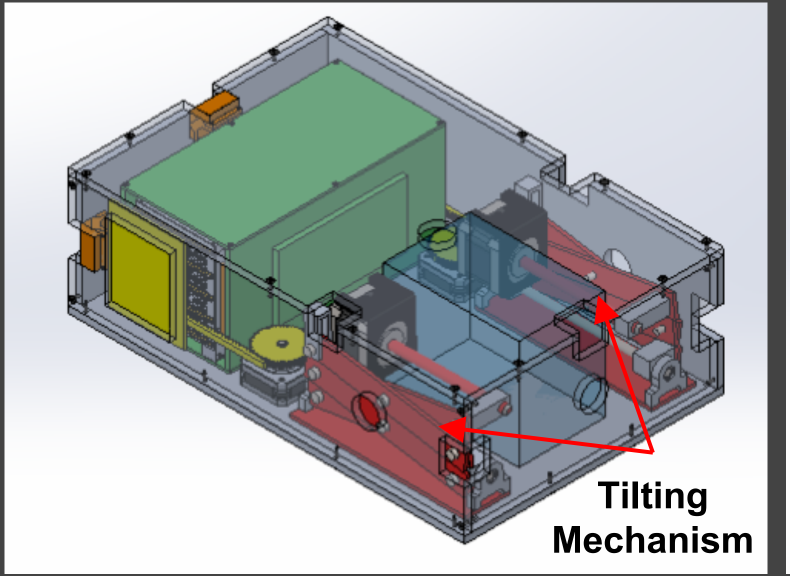
Design Recap - Photodiodes

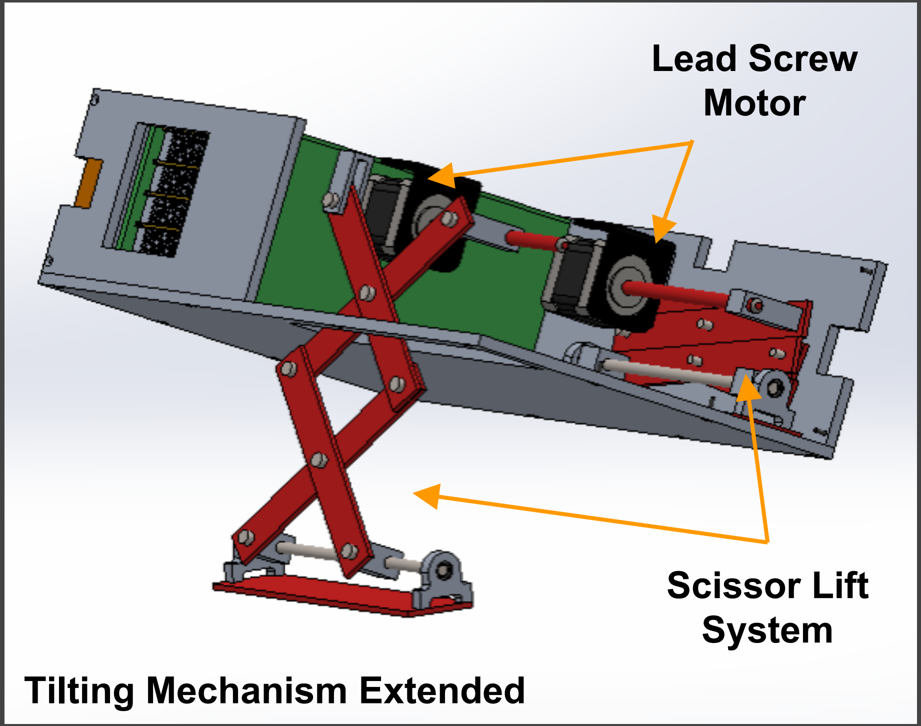




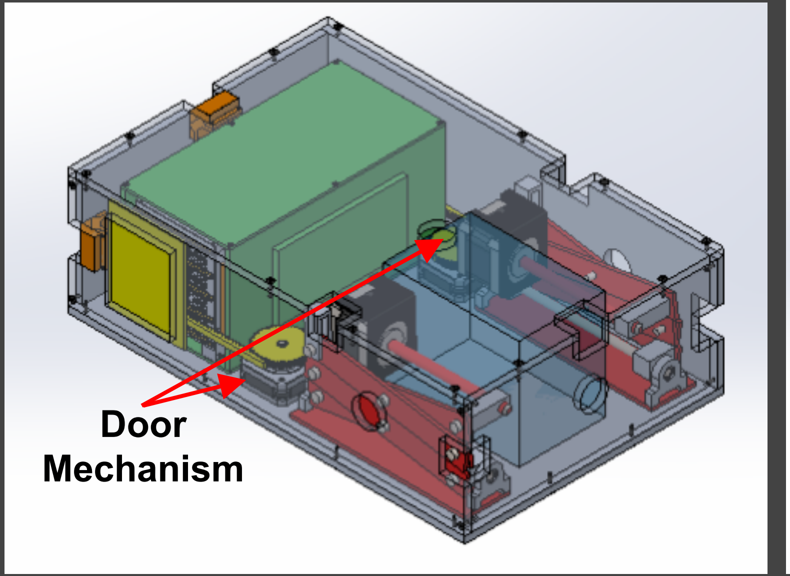
Photodiode Structure

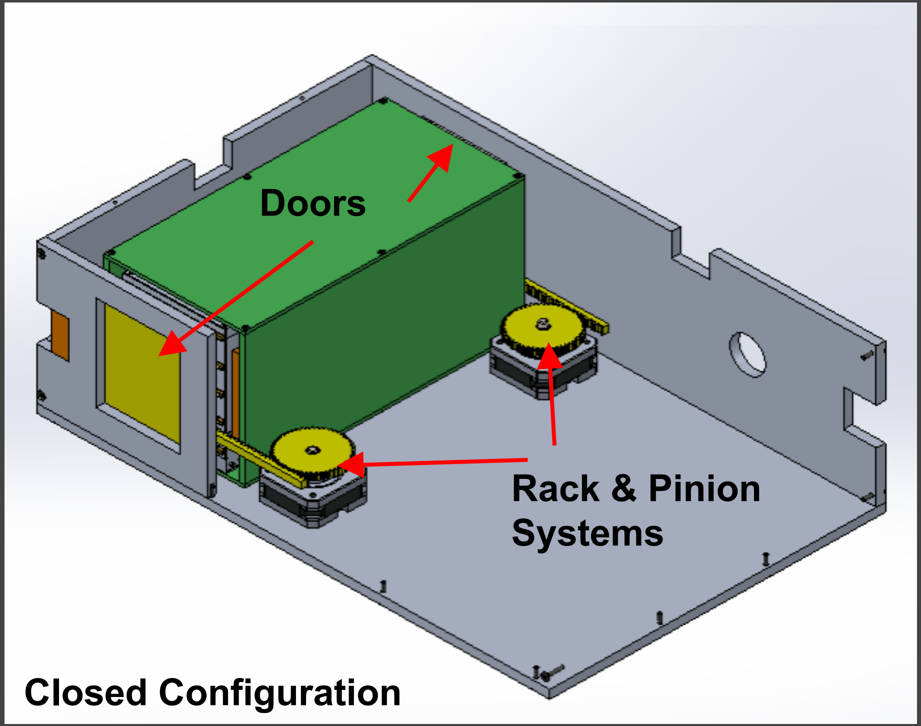
Design Recap -Tilting Mechanism



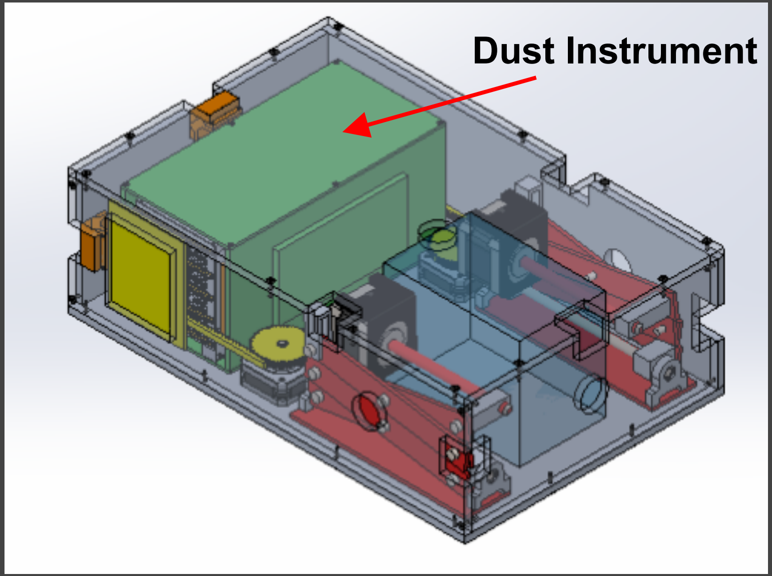


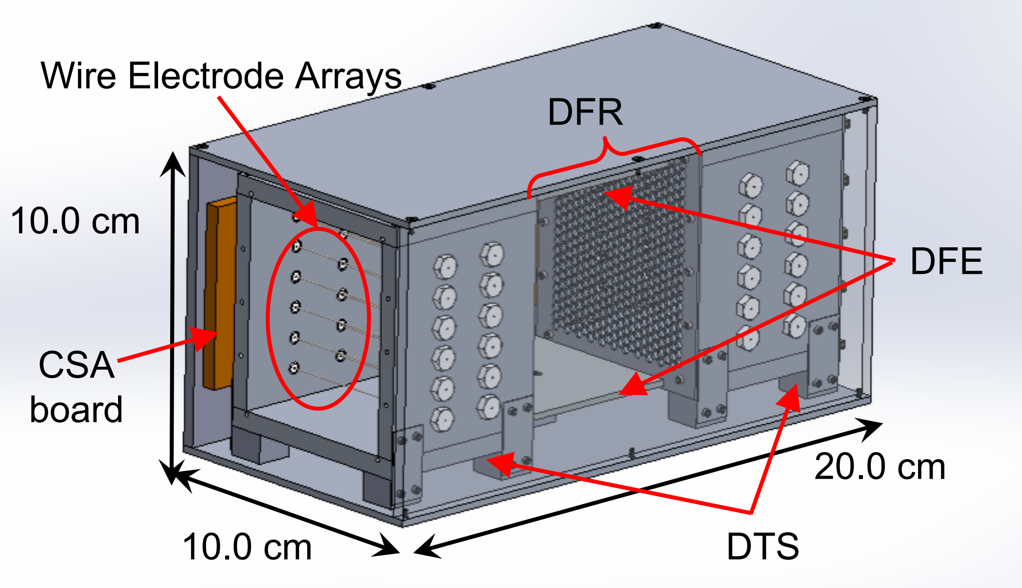
Design Recap -Door Mechanism





Design Recap -Dust Instrument



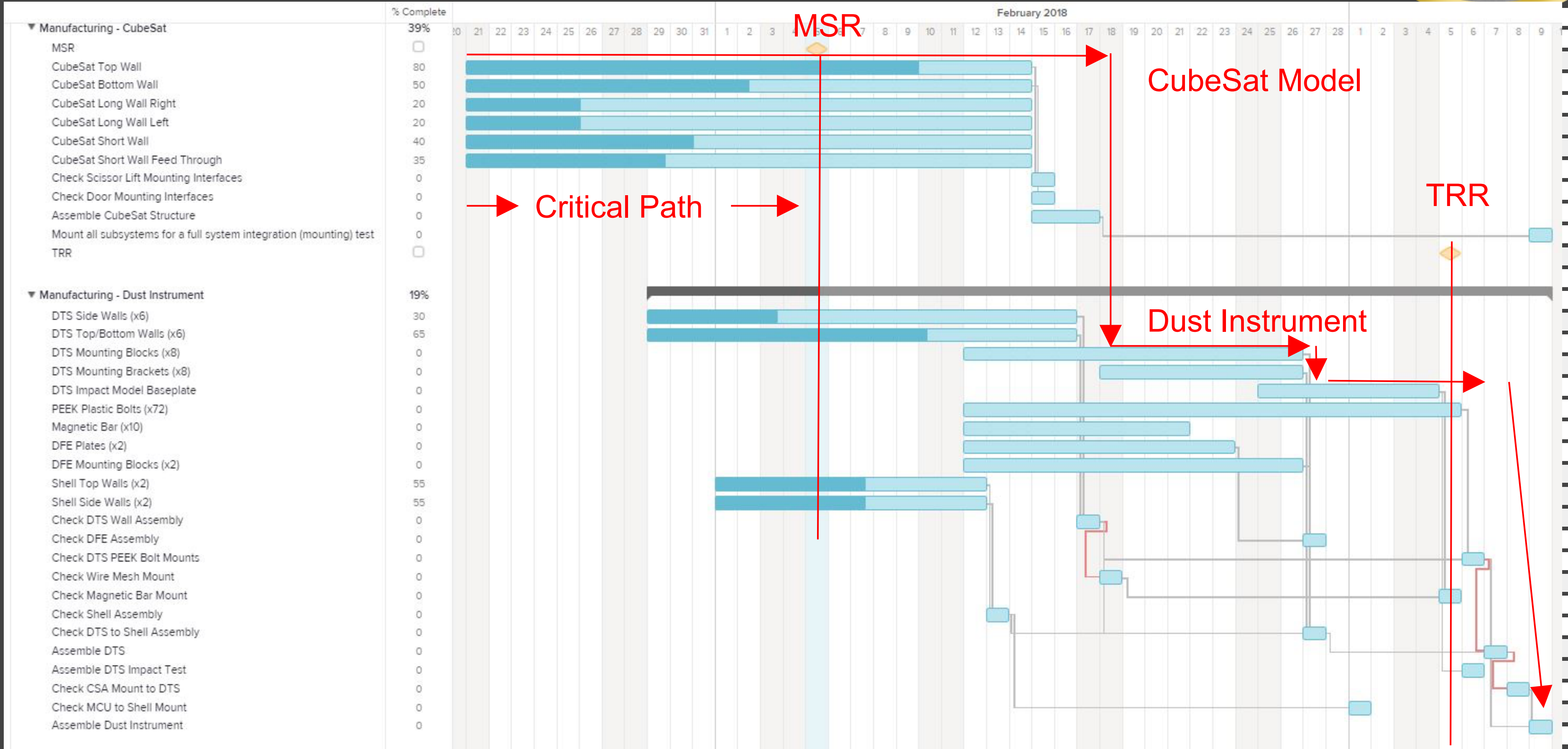


Critical Project Elements

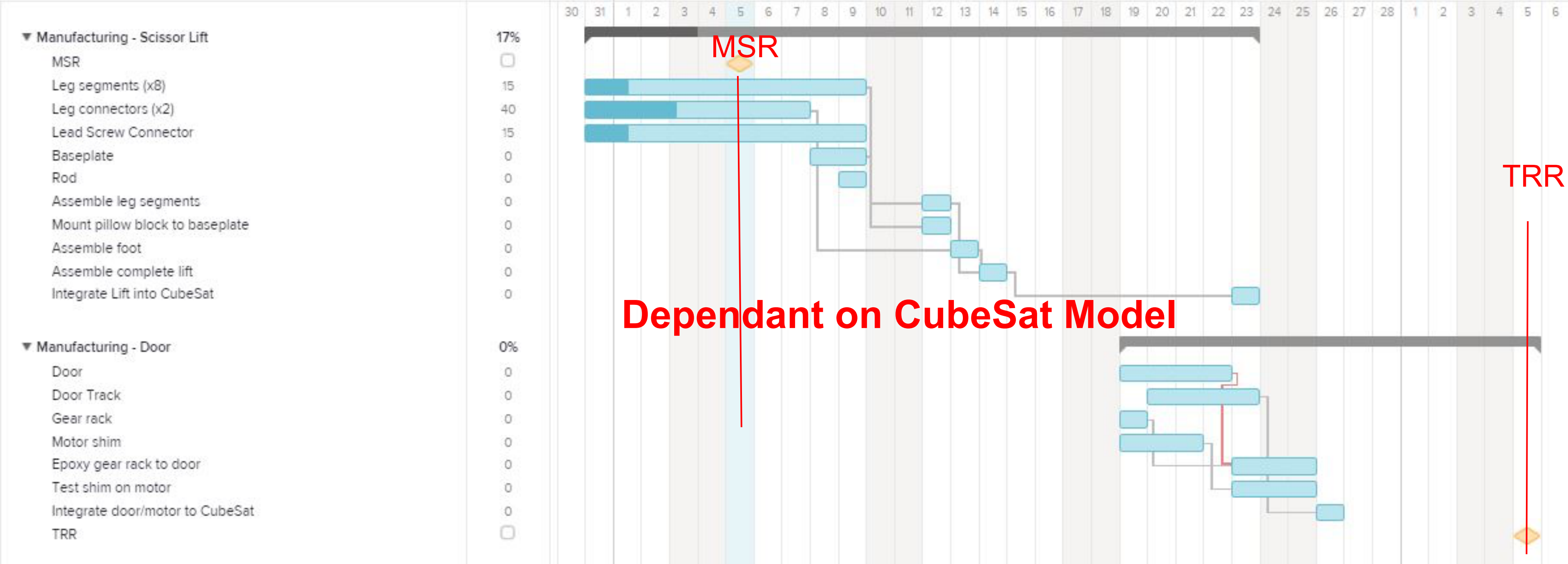
Critical Project Element	Relation to Manufacturing
Instrument Miniaturization	Custom parts and analog electronics in 2U instrument
Sun determination	Photodiode covers, PCBs, and software (sampling, calculations, and commands)
Tilting mechanism	Machining within tolerance for moving parts
Real-time event detection	Trigger algorithm, instrument sampling, PCB

Scheduling

Machining Schedule

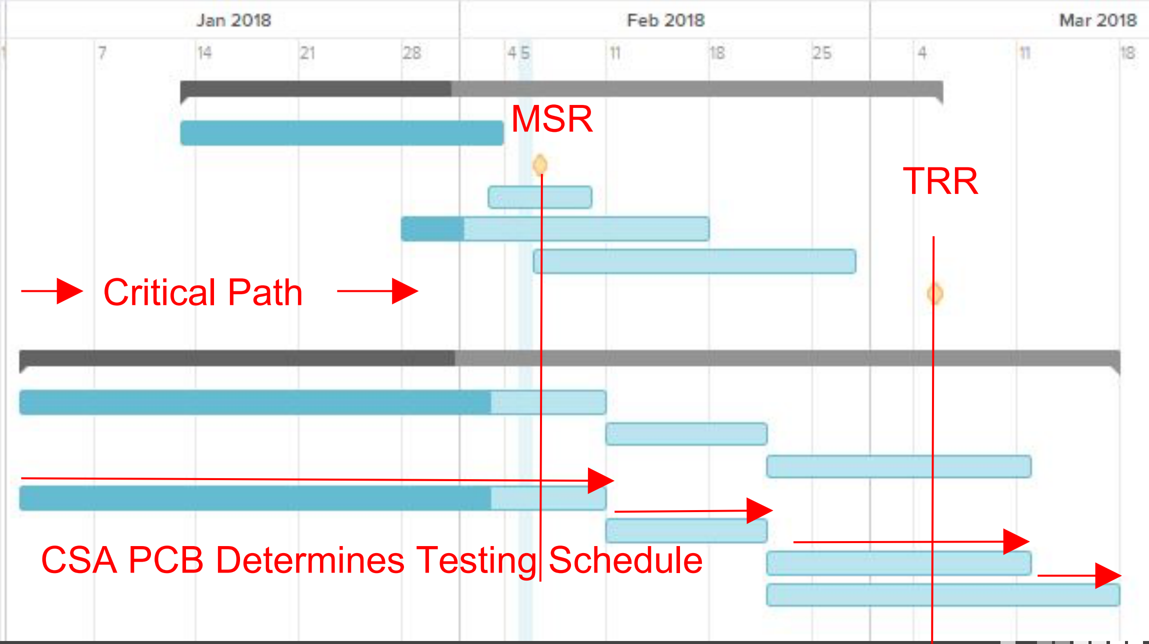


Machining Schedule

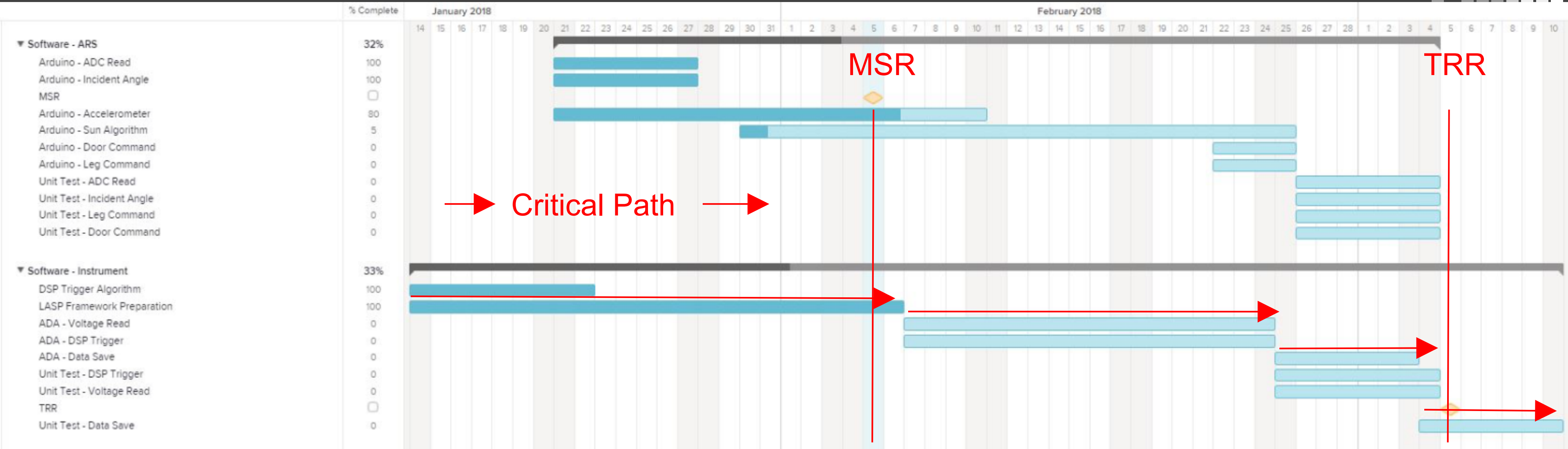


Electronics Schedule

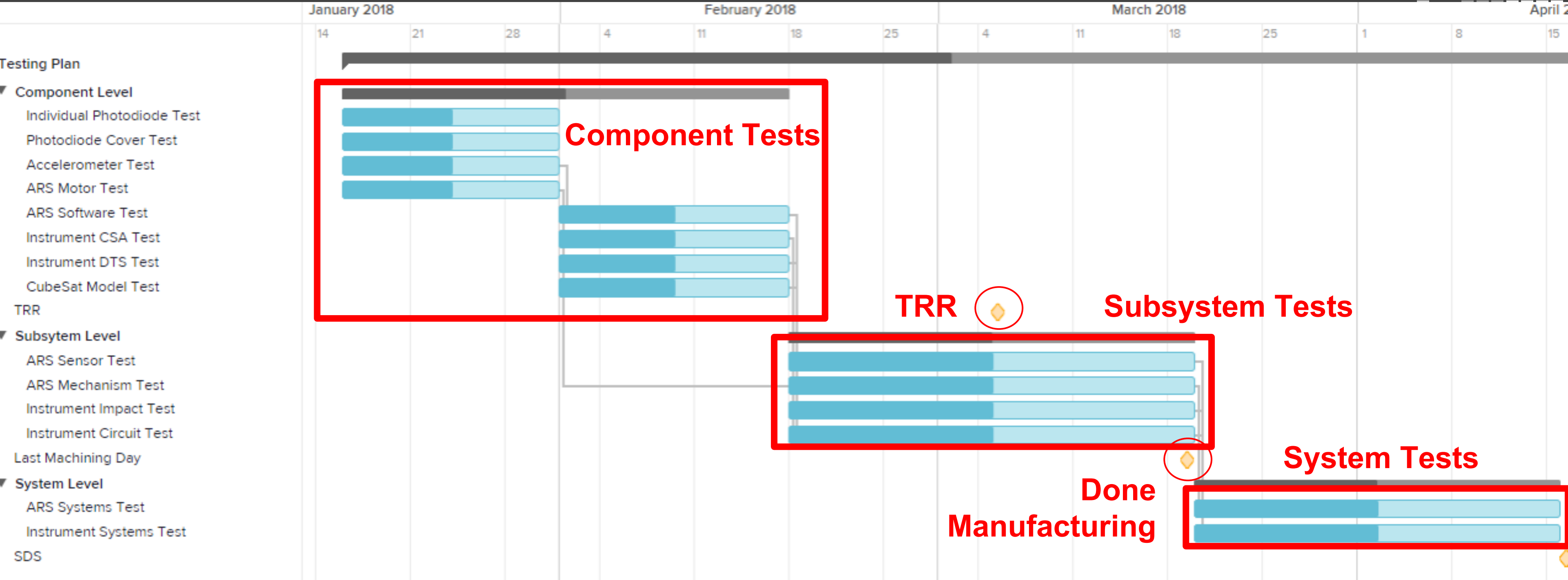
	% Complete
▼ Electronics - ARS	35%
Photodiode PCB Prototype	100
TRR	☐
Signal Conditioning circuits	0
ARS Teensy PCB Prototype	20
Photodiode PCB Final	0
TRR	☐
▼ Electronics - Instrument	40%
Microcontroller Prototype	80
Microcontroller Prototype Validation	0
Microcontroller Final (MARGIN)	0
CSA PCB Prototype	80
CSA PCB Prototype Validation	0
CSA PCB FInal MARGIN)	0
Electronics Integration	0



Software Schedule



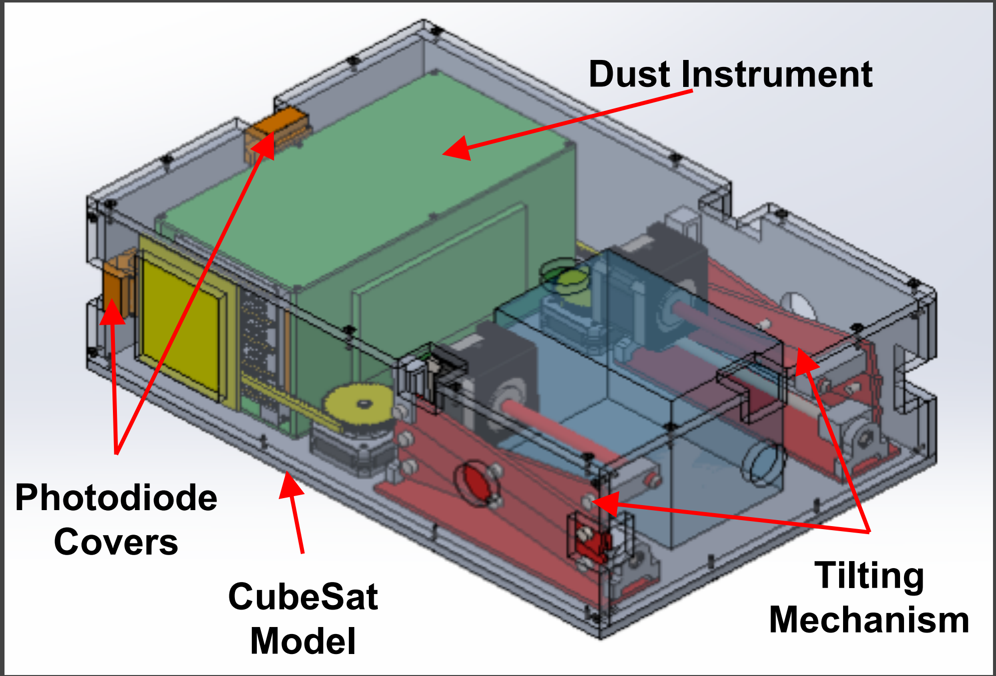
Testing Schedule



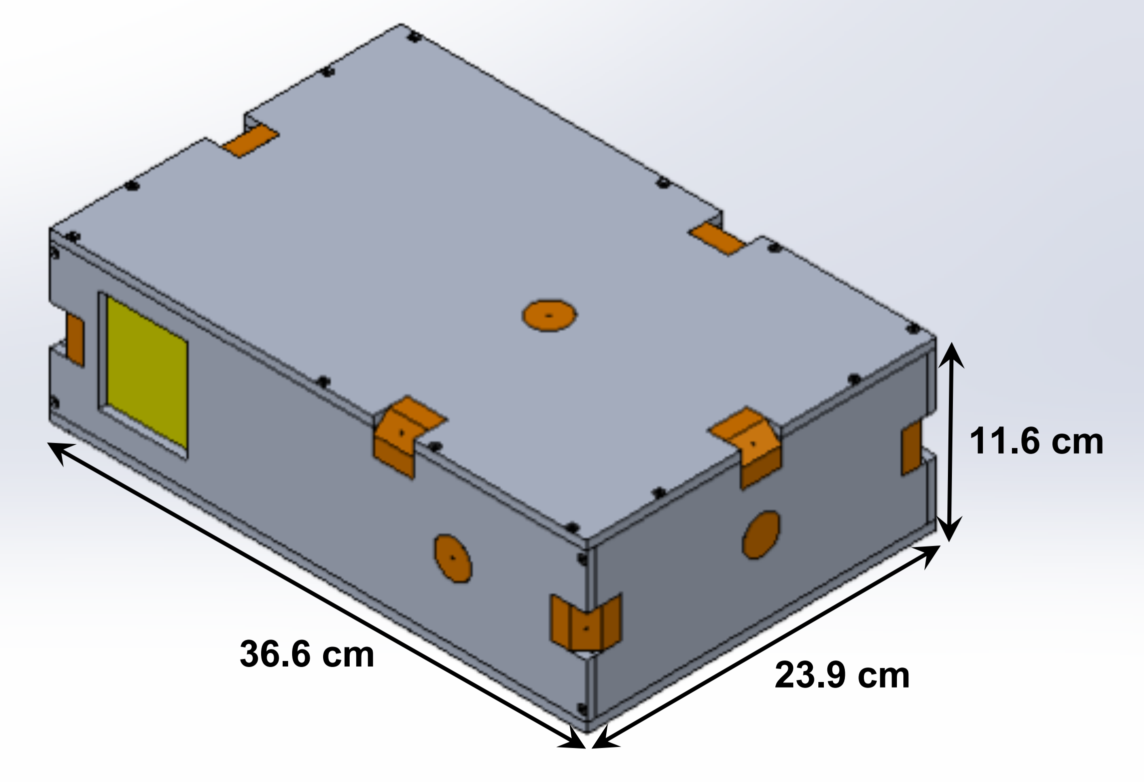
Manufacturing

Machining: Scope

- Critical machined components broken down into 3 groups
- 3D printing photodiode covers
- Machining will be done in the AES machine shop



CubeSat Model Overview



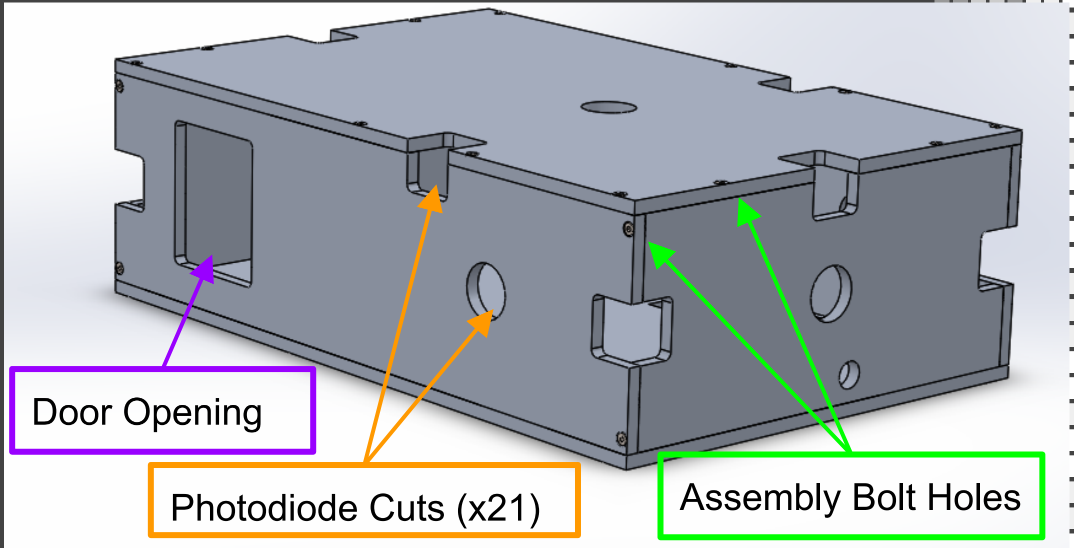
CubeSat Model Status

Stage	1	2	3	4
Criteria	No work done	Material Cut & Squared	Holes drilled & tapped; secondary cuts made	Completed

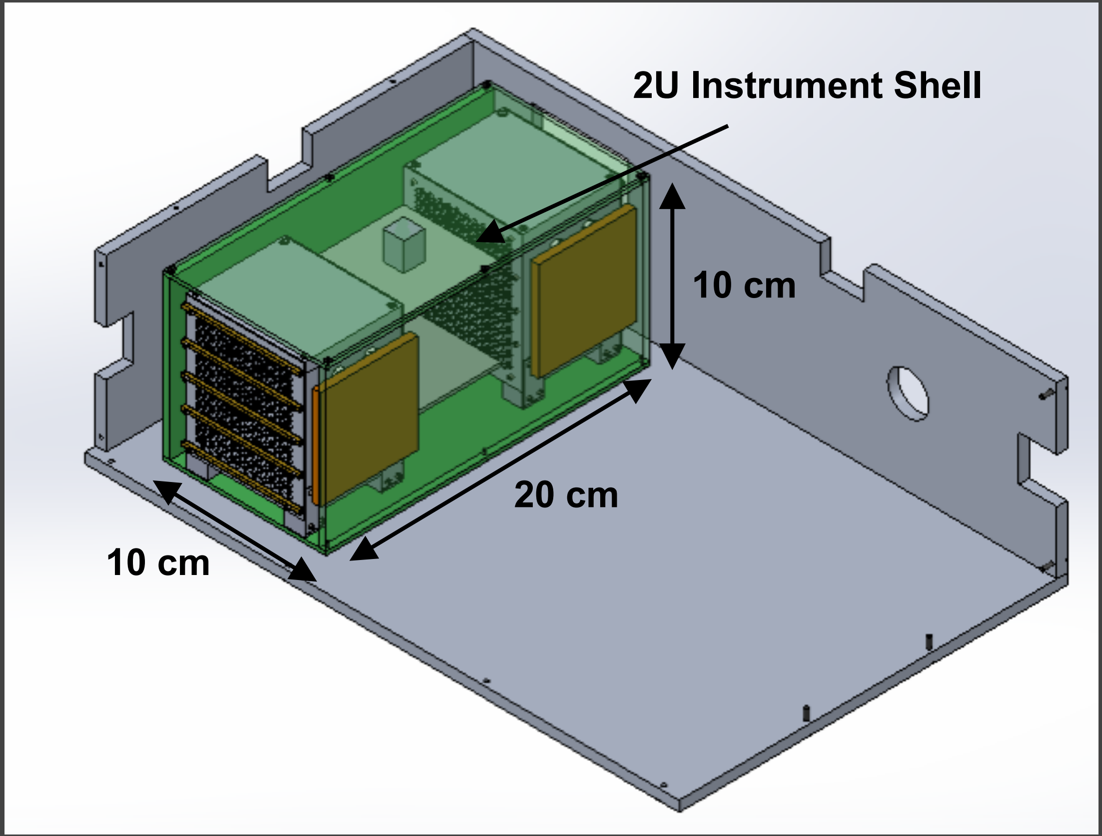
Difficulty

Component	Stage
CubeSat Bottom	3
CubeSat Top	3
CubeSat Long Wall (x2)	2
CubeSat Short Wall (x2)	2

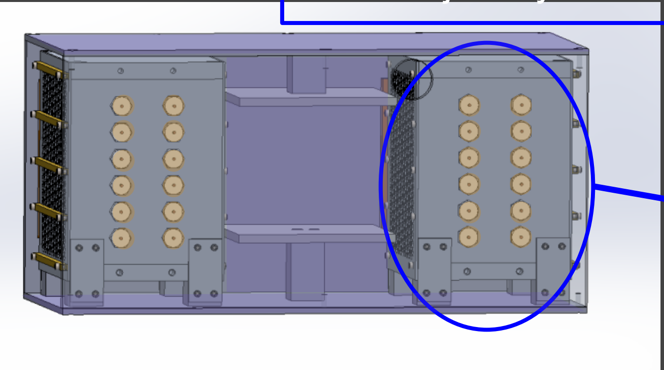
Most Difficult: Mounting holes - components tightly packed

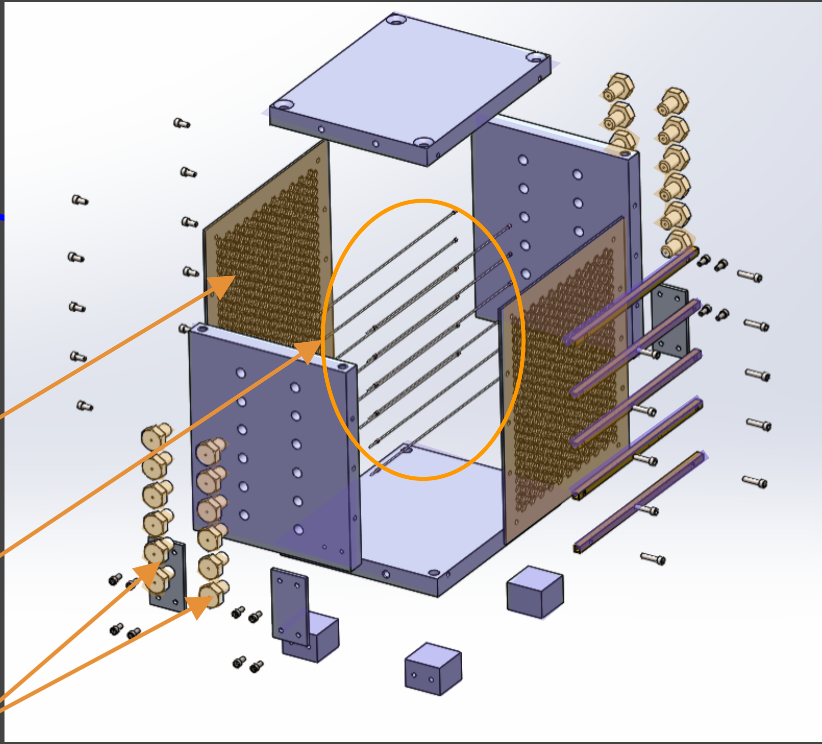


Dust Instrument: Overview



Instrument Model





Manufactured
Purchased

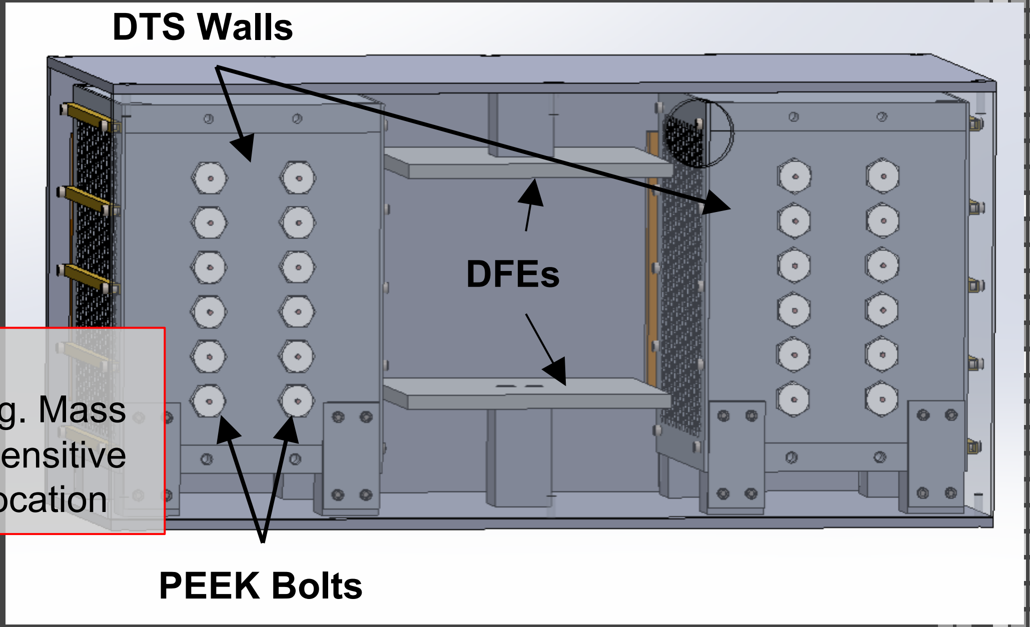
Dust Instrument Status

Stage	1	2	3	4
Criteria	No work done	Material Cut & Squared	Holes drilled & tapped; secondary cuts made	Completed

Difficulty

Component	Stage
PEEK Plastic Bolts (72)	1
DTS Walls (12)	3
Instrument Shell	3
DFE Plates (2)	1
Magnet Bars (10)	1
Mounting Blocks (10)	1
Mounting Brackets (8)	1

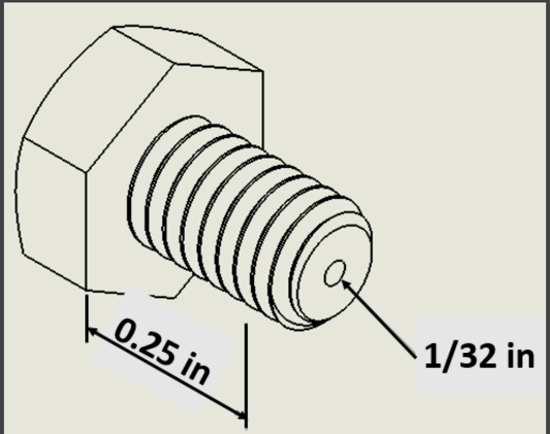
Most Difficult:
Time consuming. Mass measurement sensitive to center hole location



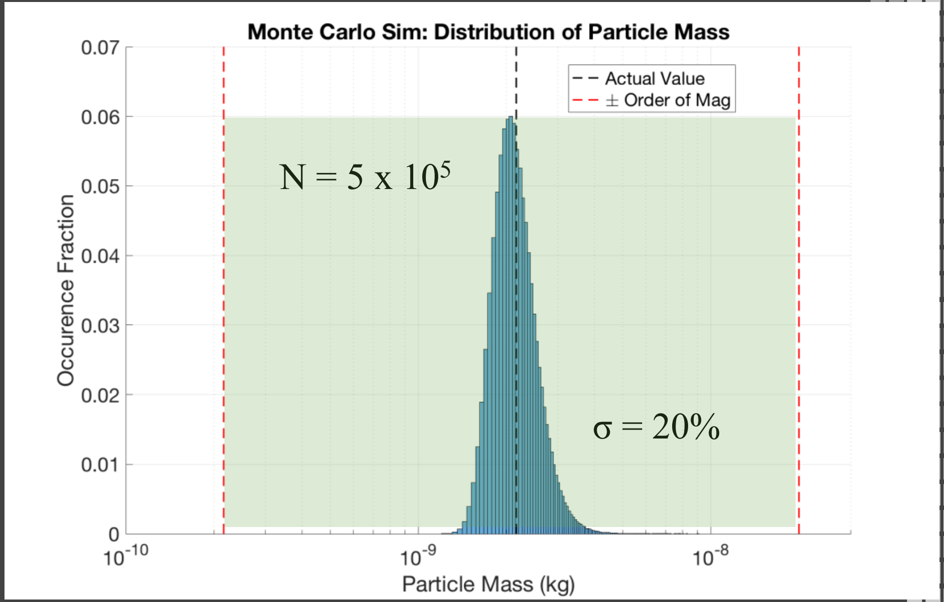
Wire Electrode Bolts

Attached to Dust Trajectory Sensor to hold wire electrodes in place

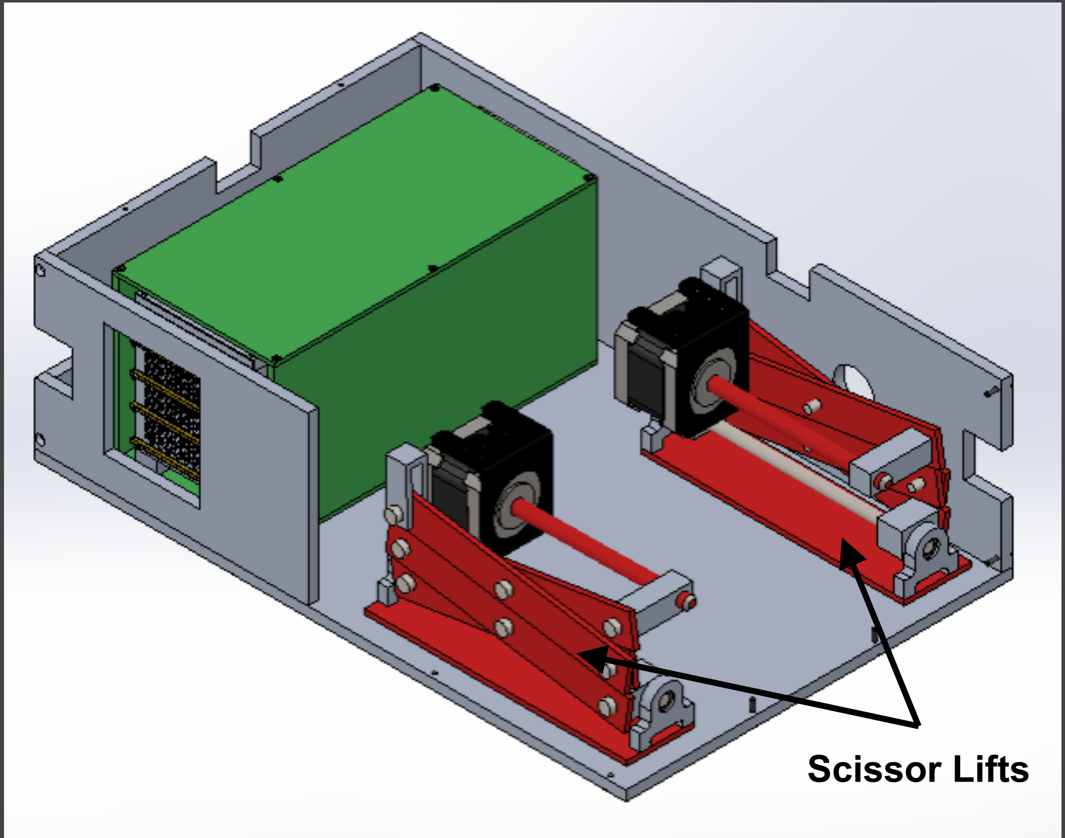
- Modifying PEEK Bolts
  - Drill through-hole for wire electrode
  - 72 bolts needed



- Monte Carlo Simulation
  - Varied wire position by 3σ = 0.02”
  - Distribution of measured particle mass



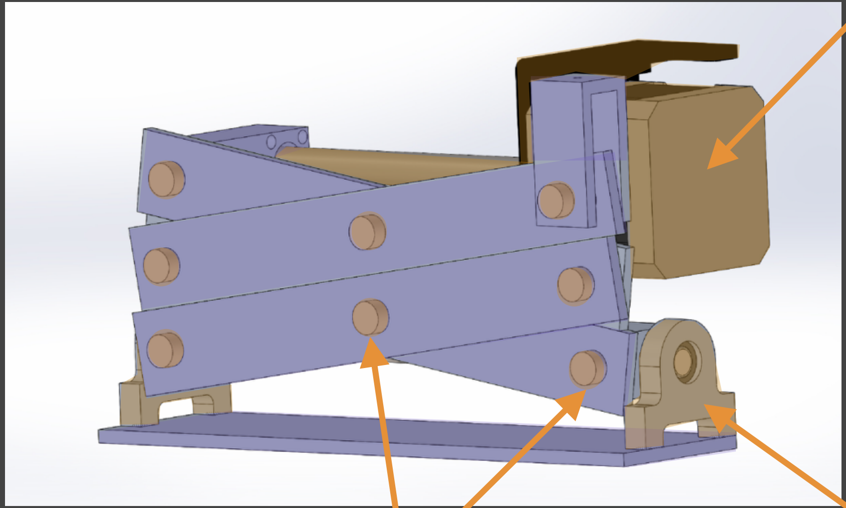
Scissor Lift: Overview

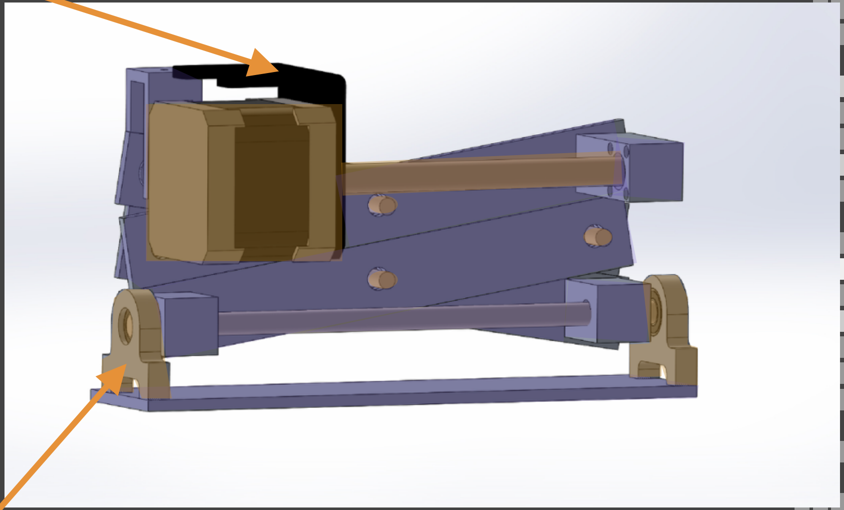


Scissor Lift Model

Mounted in CubeSat Body to tilt to 45 degrees

Manufactured
Purchased





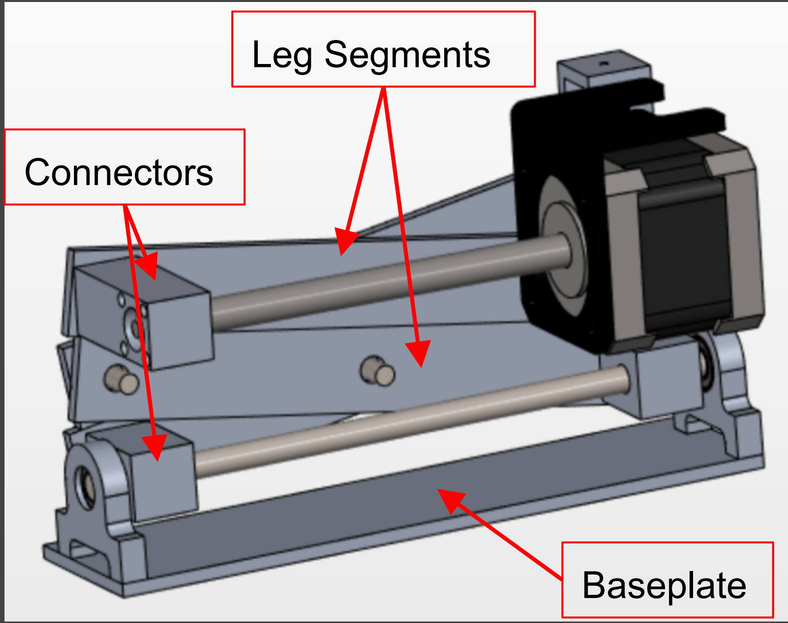
Scissor Lift Status

Stage	1	2	3	4
Criteria	No work done	Material Cut & Squared	Holes drilled & tapped; secondary cuts made	Completed

Difficulty

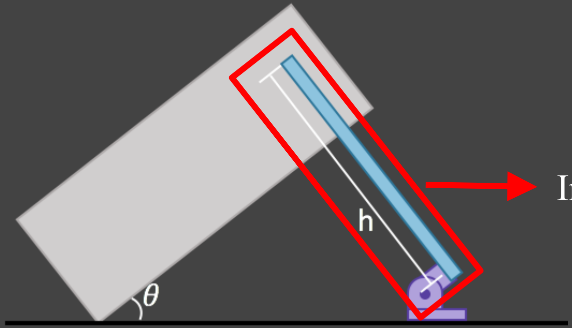
Component	Stage
Connectors (9)	2
Leg Segments (8)	2
Base plate (2)	1

Most Difficult: Tolerances
4.121 Tilt accuracy within ±0.5°

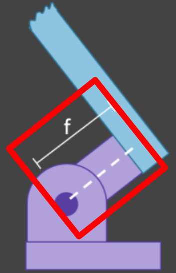


Scissor Lift Tolerance Stack Up

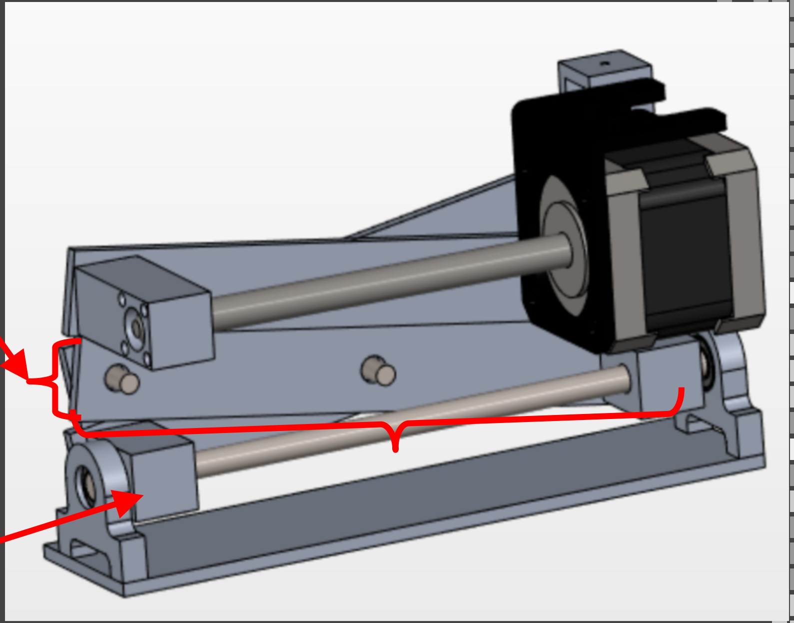
- Model to determine tilt angle error from CDR



Influenced by

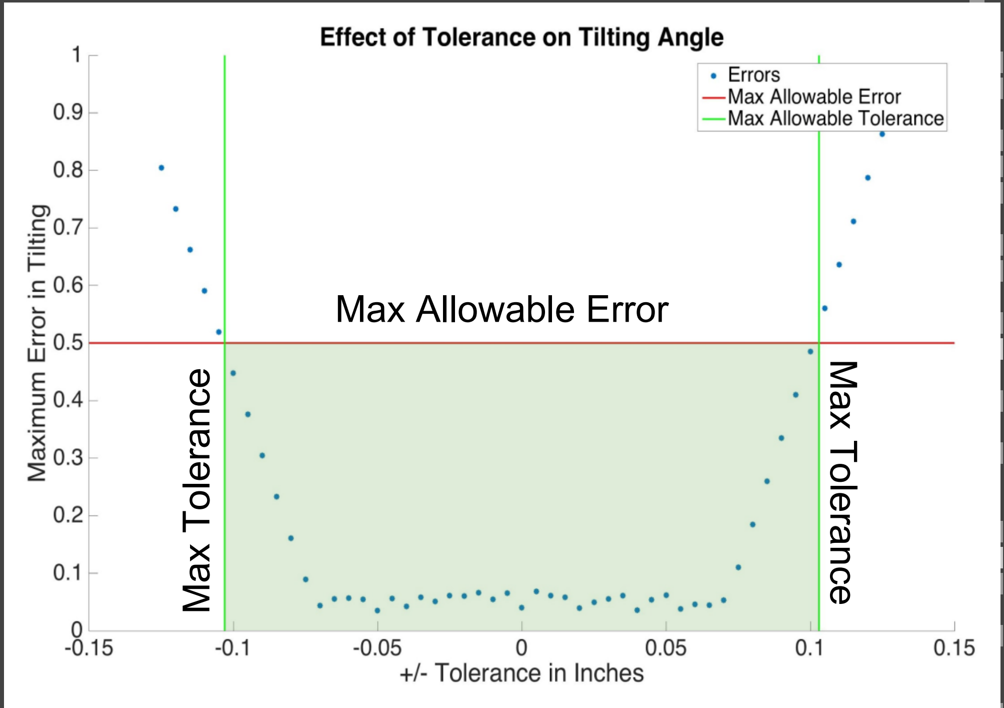


Influenced by

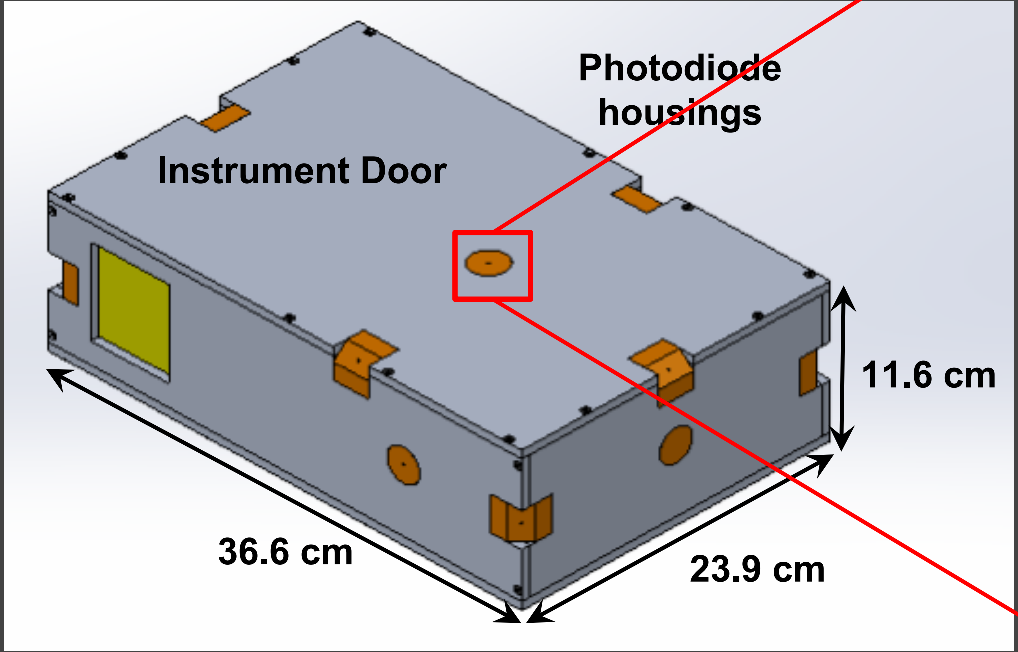


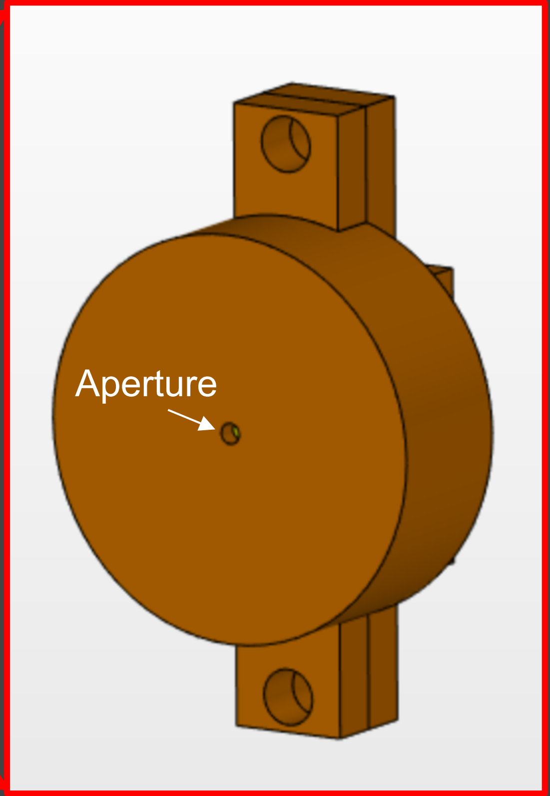
Scissor Lift Tolerance Stack Up

- If errors are added to dimensions, tilting errors start stacking up
- Max tolerance allowable ±0.1 in



Photodiode Housing





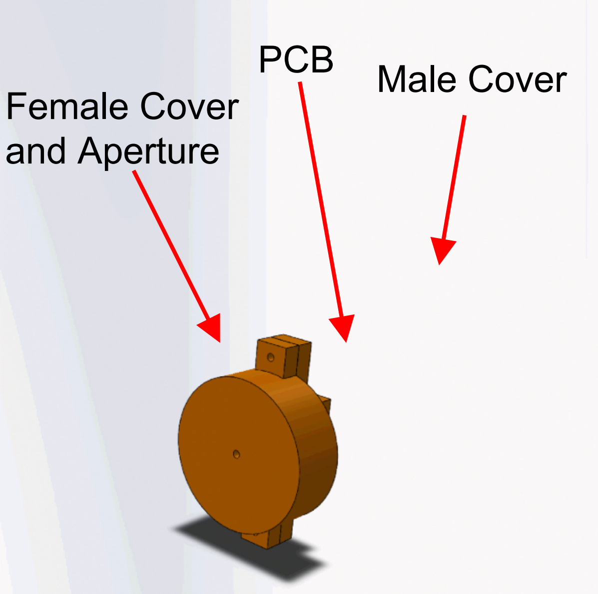
Photodiode Covers Status

Stage	1	2	3	4
Criteria	No work done	Printing started	Final Modifications	Complete

Difficulty

Component	Stage
Edge Cover Prototype	3
Face Cover Prototype	3
Edge Cover Manufacture	1
Face Cover Manufacture	1

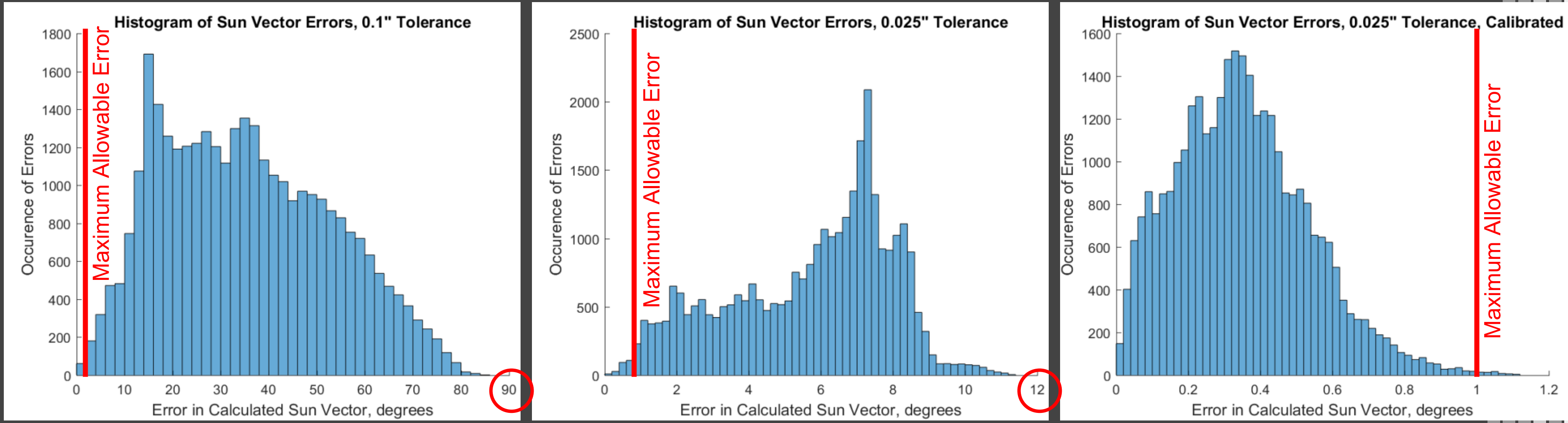
Most difficult: Sizing



Photodiode Covers

Contain 13 photodiodes, PCBs, and 3D printed covers to mount on CubeSat body

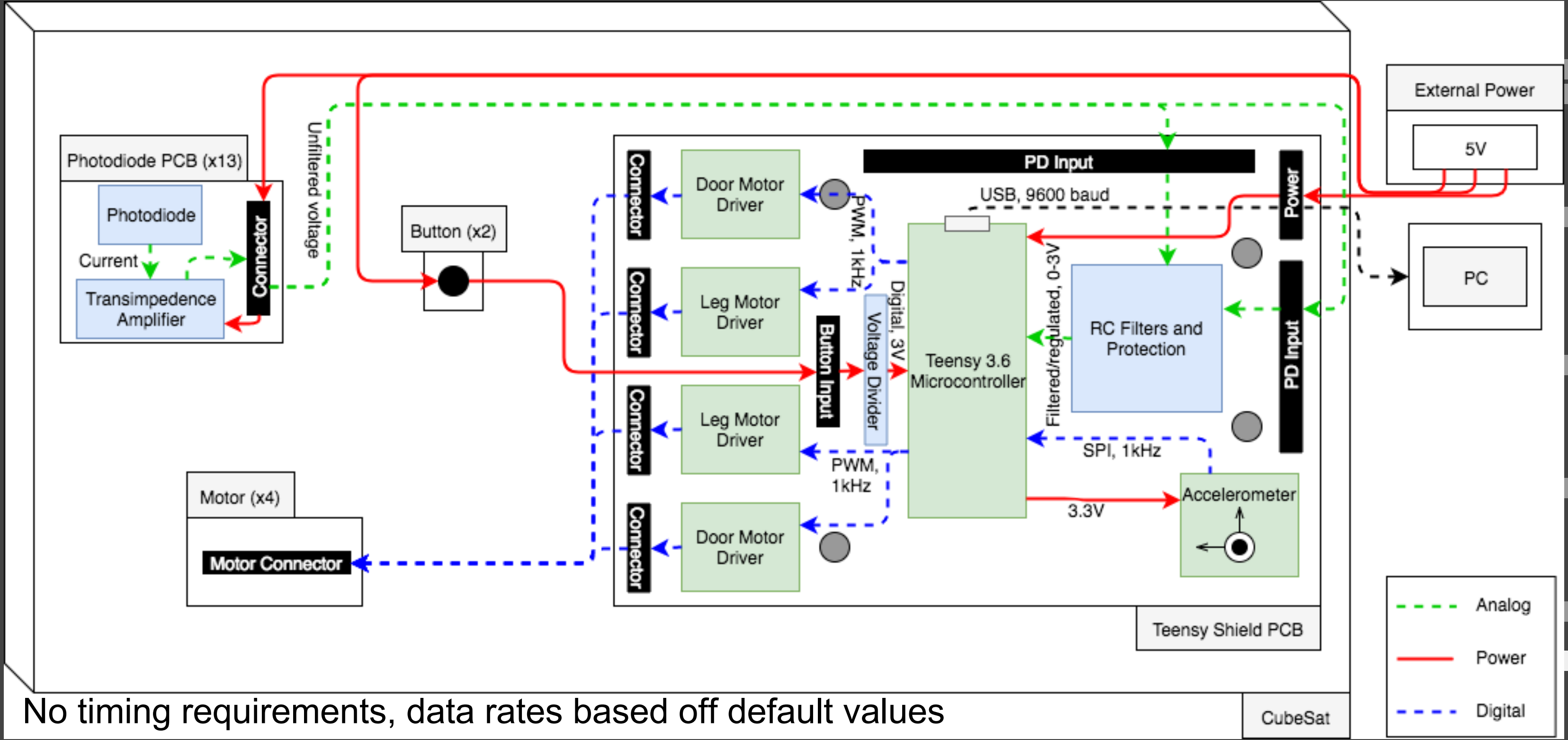
- FormLabs 3D printer must be used for tolerances
  - Tolerance of 0.025” and calibration will meet 1°
  - Modeled with 30,000 points in configuration



Electronics

ARS Electronics Overview

Photodiode signal conditioning, Sun calculations, motor commands, tilt and door verification



No timing requirements, data rates based off default values

ARS Electronics Status

Photodiode PCB (x13):

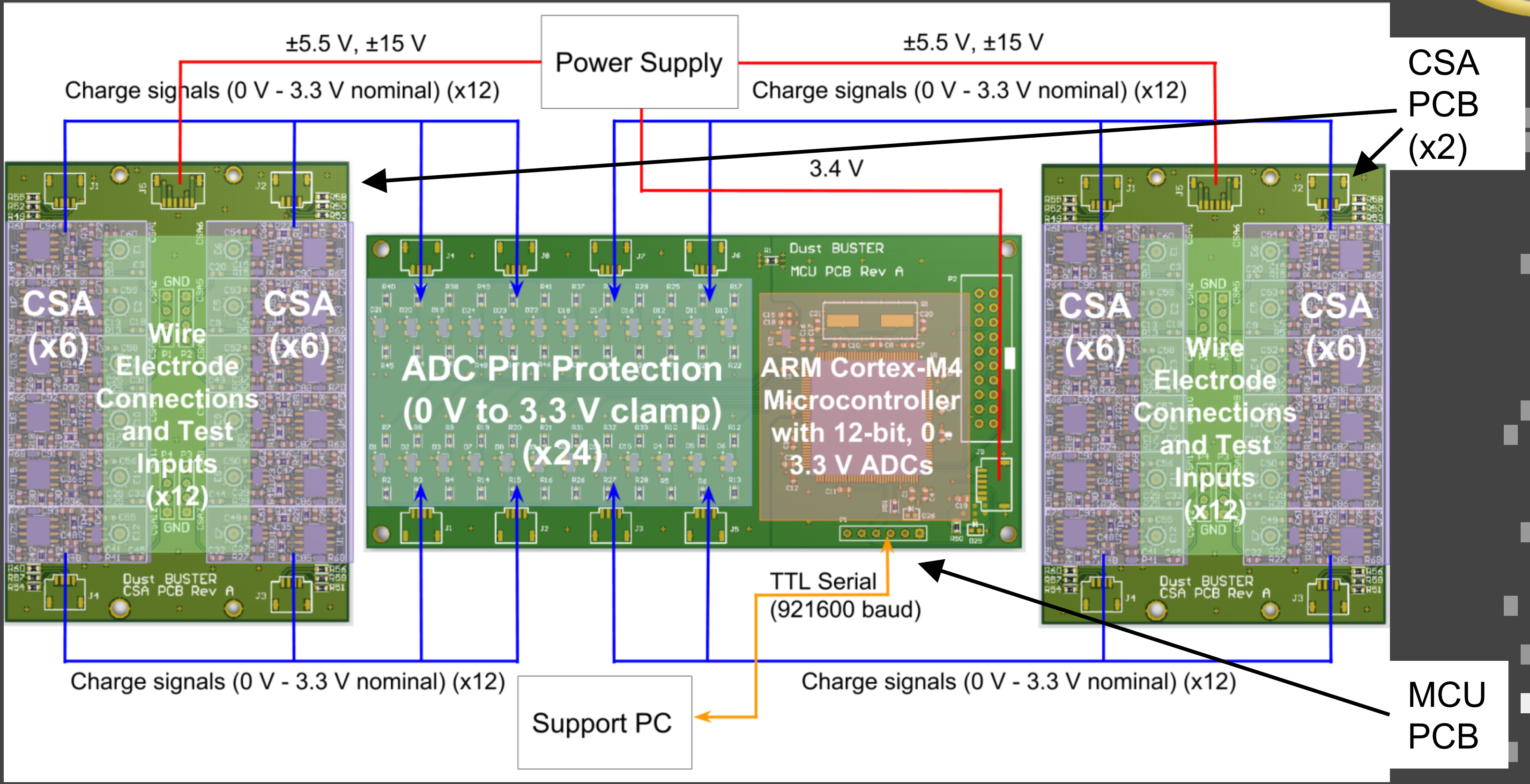
Status	*Prototyped*
Remaining Steps	*Perform Revision* *Order* - est. 2/9/18
Concerns	• Soldering small surface mount components on to many boards
Mitigation	Team members have experience hand soldering and using reflow ovens

Teensy Shield PCB:

Status	*Designed*
Remaining Steps	*Review* with Trudy and rest of electronics team *Order* - est. 2/9/18 *Populate* *Validate*
Concerns	• Integration of lots of components/sensors
Mitigation	Built in time for multiple revisions, components will be integrated one at a time and the board re-tested each time

Instrument Electronics Overview

Wire electrode signal amplification, 1 kHz sampling, trigger algorithm



Instrument Electronics Status

CSA PCB (x2):

Status	*Reviewed* by customers and Dr. Lawrence
Remaining Steps	*Order* - est. 2/5/18 *Populate* *Validate*
Concerns	• Hundreds of tightly-packed 0603 passives and fine-pitch ICs per board
Mitigation	Use some of remaining budget for professional population.

MCU PCB:

Status	*Reviewed* by customers, Dr. Lawrence, and ECEE TAs
Remaining Steps	*Order* - est. 2/5/18 *Populate* *Validate*
Concerns	• 144-pin 0.5 mm pitch LQFP MCU population
Mitigation	Electrical lead has been practicing 0.5 mm pitch LQFP soldering

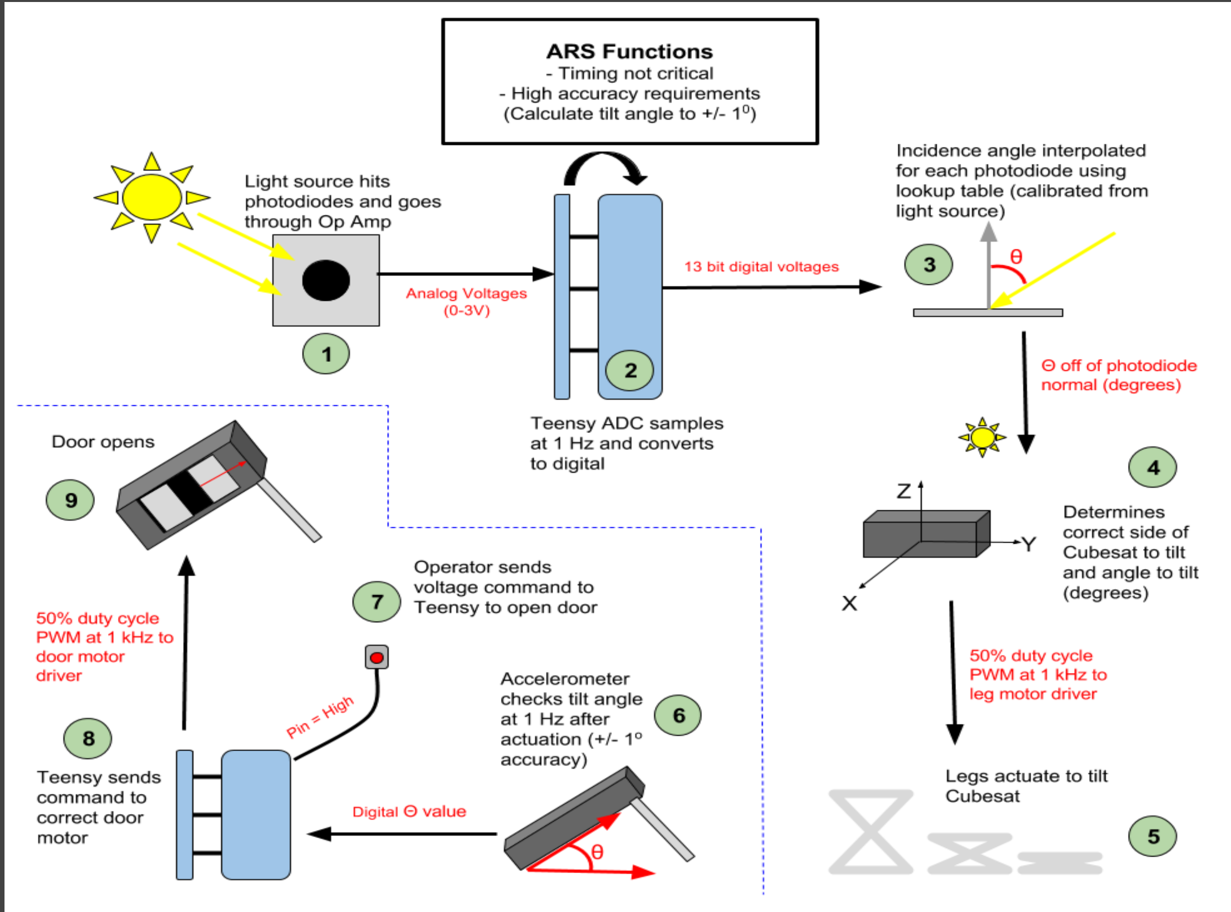
Manufacturing Concerns: Solder on SS

- Process for soldering on stainless steel wire electrodes
  - Apply flux to wire
    - Removes oxide layer
  - Flux is evaporated by soldering iron
  - Solder stainless steel
- **Dr. Sternovsky has experience with method**
- **Will be tested on prototype boards**

Software

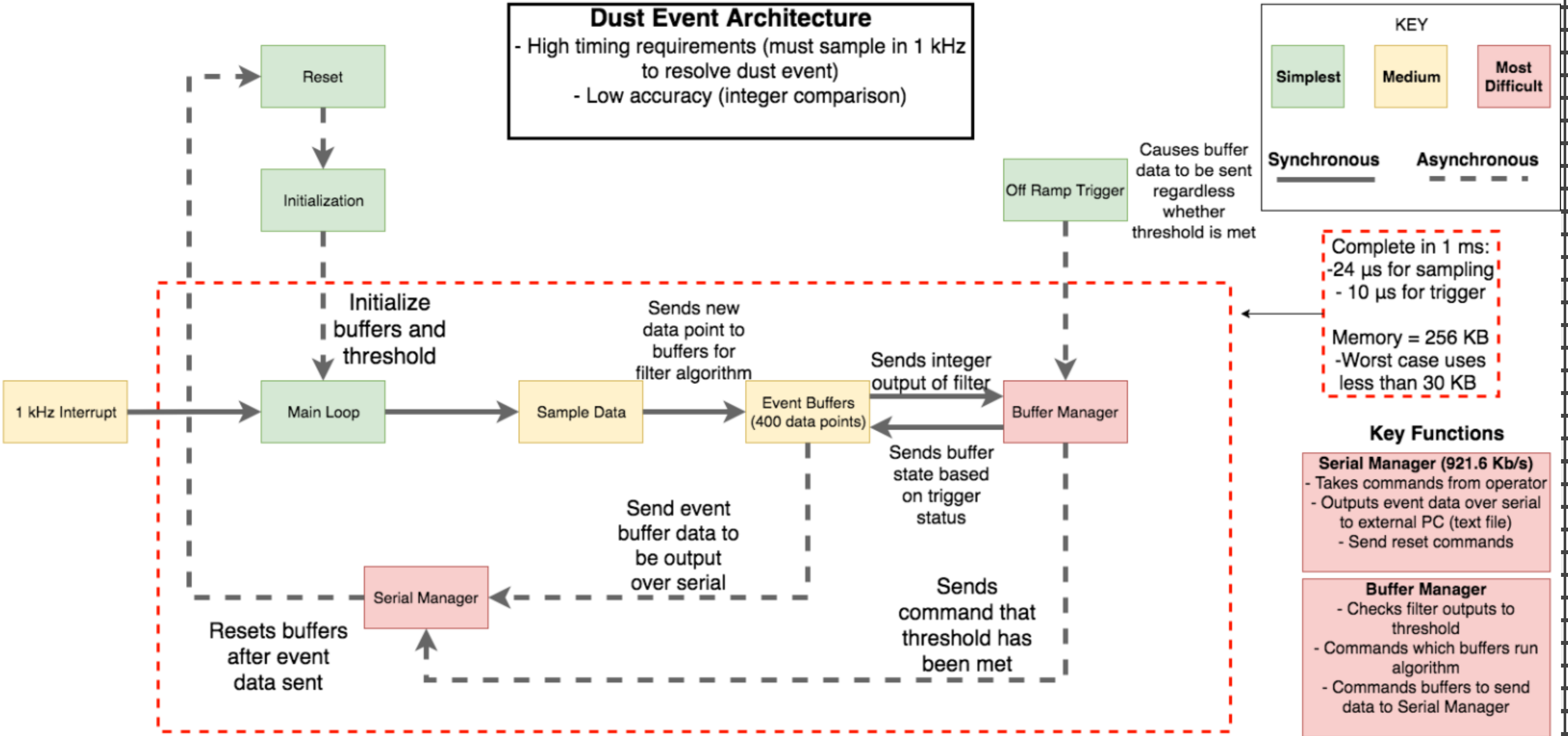
Software - ARS Function Scope

Photodiode data converted to sun location, tilt command with feedback, door command



Scope

Sample 24 channels at 1 kHz, trigger for dust event, output data from buffers



Key Functions

Serial Manager (921.6 Kb/s)
- Takes commands from operator
- Outputs event data over serial to external PC (text file)
- Send reset commands

Buffer Manager
- Checks filter outputs to threshold
- Commands which buffers run algorithm
- Commands buffers to send data to Serial Manager

Software - Status

Component	Subtasks	Status	Remaining
Post Processing	- Read text data file - Extract Q, m, v	Software Written	Continue unit testing with existing LASP data
ARS Sampling	- Read in voltage values (0-3 V) at 1 Hz for 10 seconds for each photodiode	Software Written	Unit Test in Progress
Tilt Angle Calculation	- Import lookup table for sensitivity - Integrate sun determination algorithm	In Progress: **15/20 Hrs**	Finish converting to Arduino
Accelerometer Feedback	- Sample accelerometer at 1 Hz for 10 seconds and average - Find actual tilted angle in degrees	In Progress: **5/10 Hrs**	Implement in Arduino
Trigger Algorithm	- Create components for buffers and data handling - Create connectors for component data transfer	In Progress: **15/45 Hrs**	Convert to Ada using LASP framework
Trigger Sampling	- Read in voltage values (0-3 V) at minimum of 1 kHz	In Progress: **2/15 Hrs**	Convert to Ada using LASP framework
Tilt and Door Commands	- Send step command to motor to actuate legs - Allow operator so send signal for door to open	In Progress: **1/5 Hrs**	Implement in Arduino
Unit Testing	- Test all components using existing data or test values	Pending: **2/15 Hrs**	Begin once each component is finished

Software - Difficult Components Status

Sun Determination:

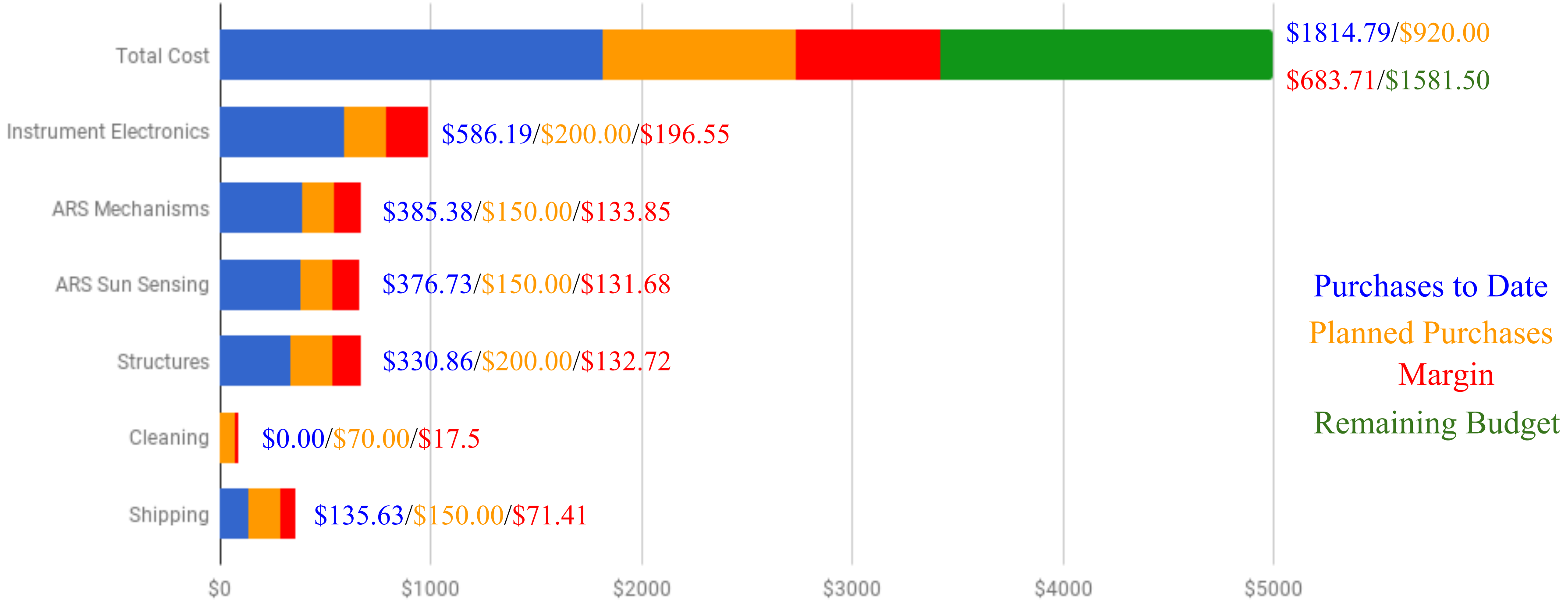
Status	Sampling and incident angle calculations done
Remaining Steps	- Sun position calculations - Calibrate lookup tables
Concerns	• Accuracy dependent on good calibration data • Error stack up propagating through multiple functions
Mitigation	Use QB50 turntable to calibrate at every incidence degree and filter circuits for each photodiode

Instrument Software:

Status	-Trigger algorithm functions correctly - Architecture defined
Remaining Steps	- Implement in Ada using framework - Unit test
Concerns	• Unfamiliarity with Ada and LASP framework • Unforeseen difficulties in setting up processor to sample data
Mitigation	Ability to meet with framework creator at LASP

Budget

Updated Cost Plan



Thank you!

Feedback?

Slide Directory

Purchasing Status

Subsystem	Purchases to Date	Planned Future Purchases
Total	$1814.79	$920.00
Instrument Electronics	$586.19	$200.00
ARS Mechanisms	$385.38	$150.00
ARS Sun Sensing	$376.73	$150.00
Structures	$330.86	$200.00
Cleaning	$0	$70.00
Shipping	$135.63	$150.00

Manufacturing Changes Since CDR

Item changed	Justification
Added 4 holes to lead screw connector	Cannot tap a hole to the lead screw, will instead use these 4 holes to mount onto the traveling nut provided with the lead screw
Increased size of actuation block, and two platform mounts	Make parts standard sizes to ease manufacture
Mounting CSA boards directly to DTSs	

Machined vs Purchased

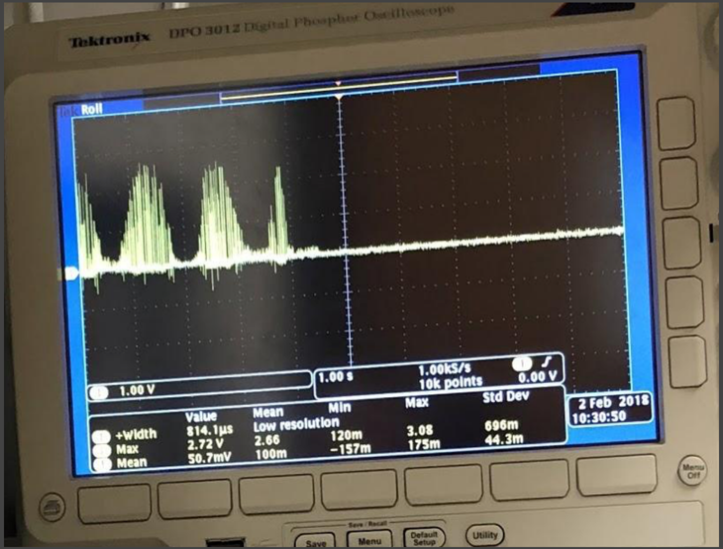
Subsystem	Machined Components	Purchased Components
CubeSat Model	- Top, bottom, and side walls	- Bolts for assembly and mounting other subsystems
Dust Instrument	- Instrument shell walls - Dust Trajectory Sensor walls - Deflection Field Electrode plates - Component mounting blocks - Wire electrode mounting bolts	- Wire Mesh - Magnets for magnetic shield
Scissor Lift	- Scissor Lift Bars - Lead Screw Connector - Tilting Platform - Tilting Platform Connector	- Motor, motor mounts, lead screw traveling nut - Shoulder Bolts, nuts - Pillow blocks

Manufacturing Logistics

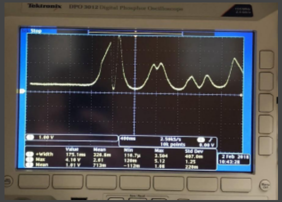
Machining	Electronics	3D Printing
AES Machine Shop	Trudy's Lab	Bobby's Lab
- Rachel Tyler - Edward Zuzula - Gabe Castillo	- Leina Hutchinson - Alex St. Claire	- Reidar Larsen - Edward Zuzula

Photodiode Noise

Significant noise, unfiltered output

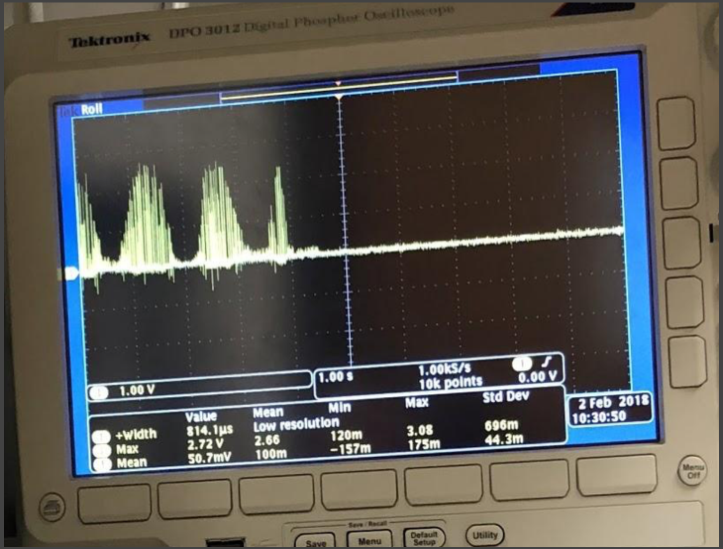


Less noise, with filter

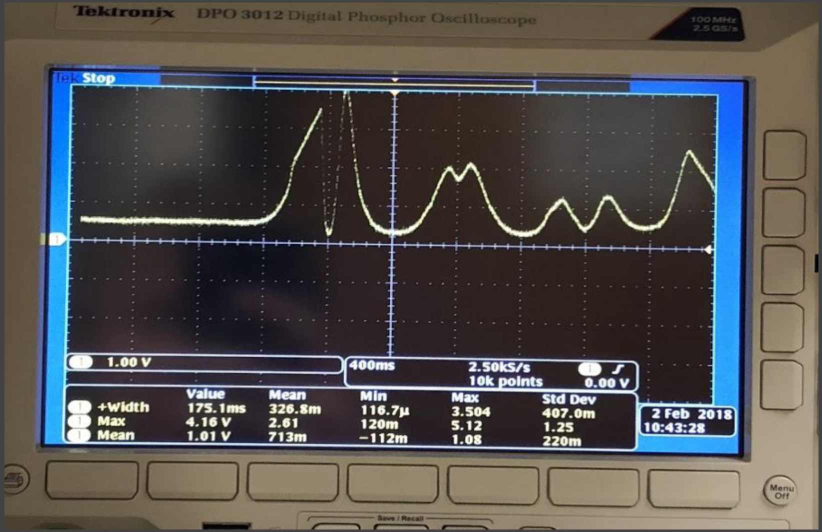


Photodiode Noise

Significant noise, unfiltered output

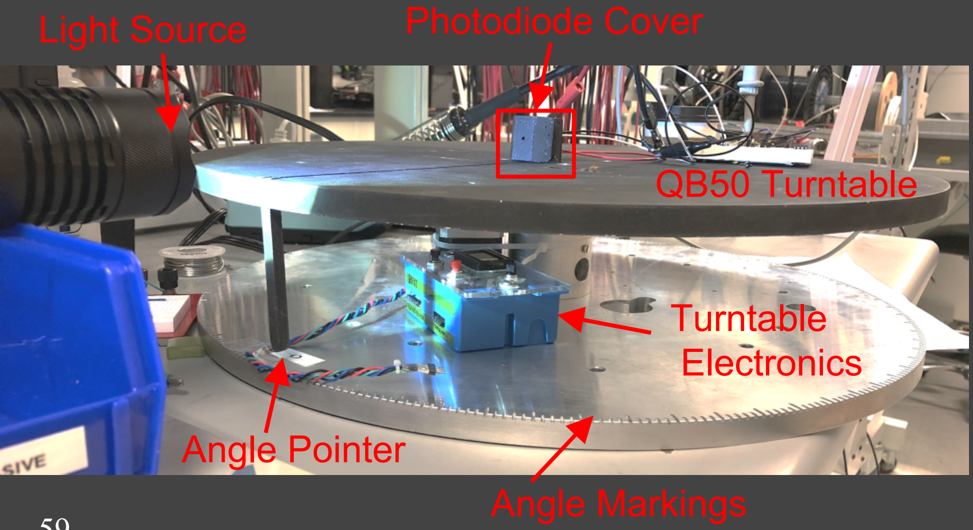


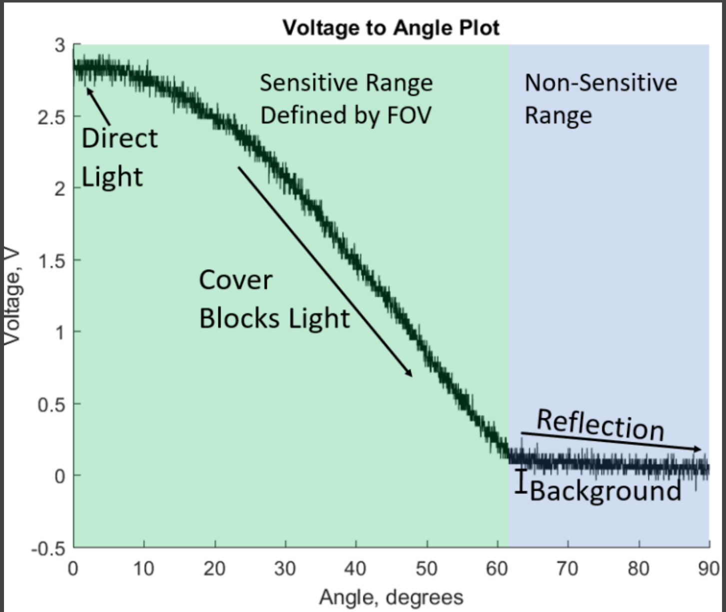
Less noise, with filter



Photodiode Calibration

- QB50 Turntable to measure angle
- Oscilloscope to measure voltage
- Build a table of Voltage vs Angle

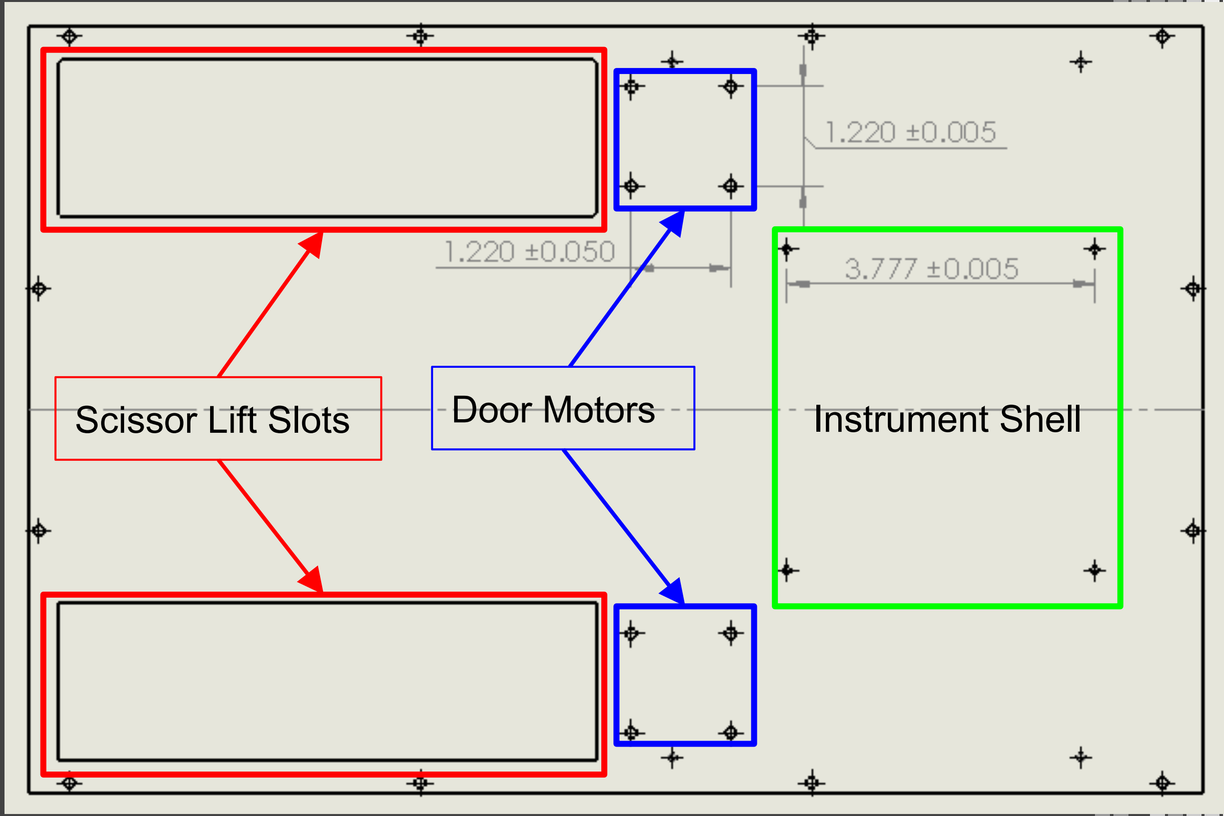




CubeSat Model

The CubeSat body houses doors, scissor lifts, dust instrument, and photodiodes

- Bottom Plate
  - 28 countersunk through holes
  - Tightly packed components



Monte Carlo Sim Details

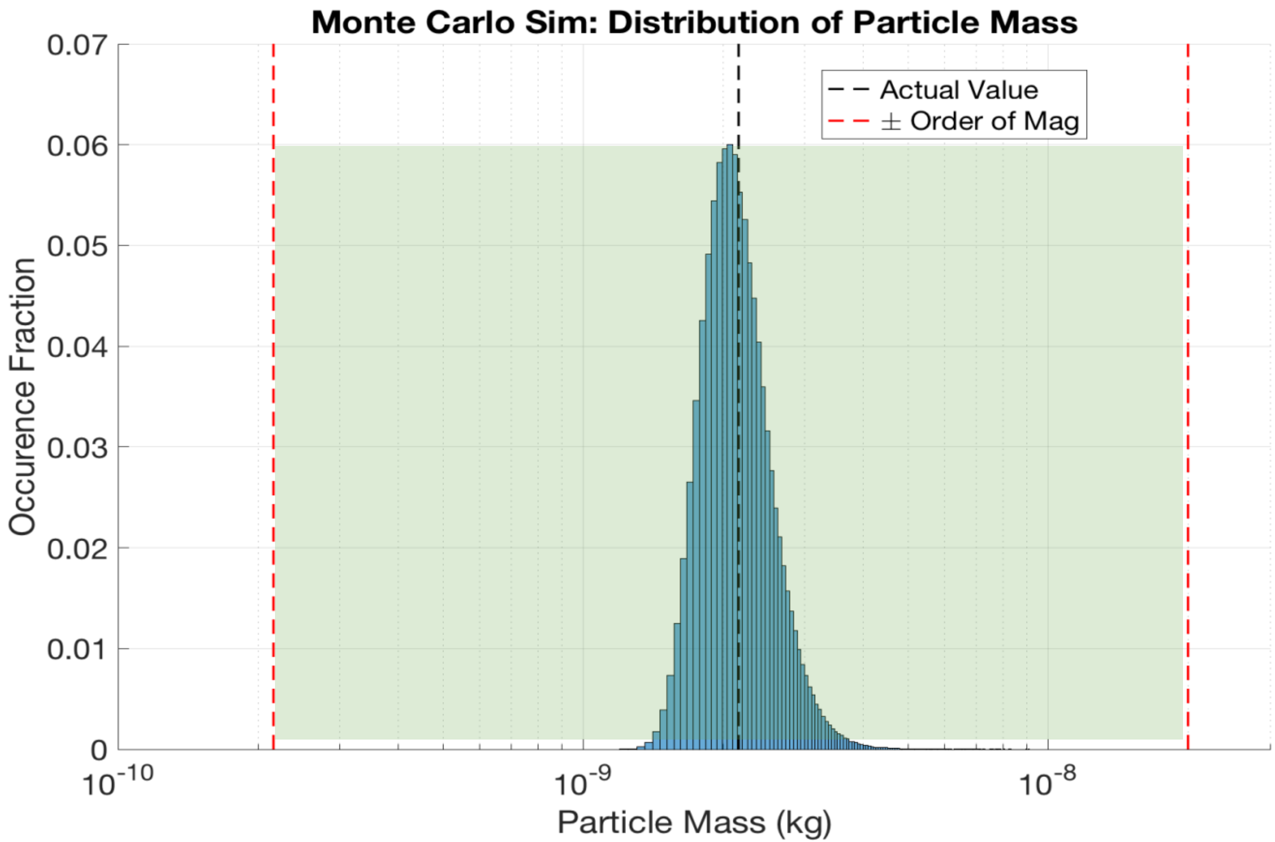
- Inputs:
  - Picked a characteristic set of *z* coordinate measurements (2.16 x 10^{-9} kg ≈ average particle mass)
  - Varied *z* coordinates by 3σ = 0.02” to account for mounting error in wire electrodes
  - N = 500,000 iterations
- Outputs:

$$\bar{m} = 2.23 \times 10^{-9}\ \text{kg}$$
$$\sigma = 19\%$$

  - Most importantly we can see that no measurements are greater than an order of magnitude off, satisfying our accuracy requirement

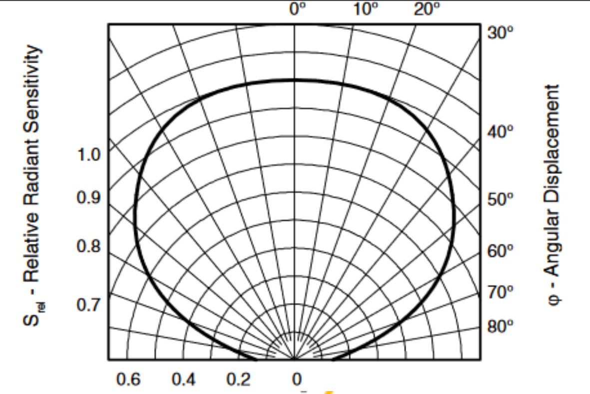
$$m = \frac{QEl}{v^2 \tan(\delta)} \qquad \tan(\delta) = \frac{\Delta x(z_1 - z_2 - z_3 - z_4)}{(\Delta x)^2 + (z_4 - z_3)(z_2 - z_1)}$$

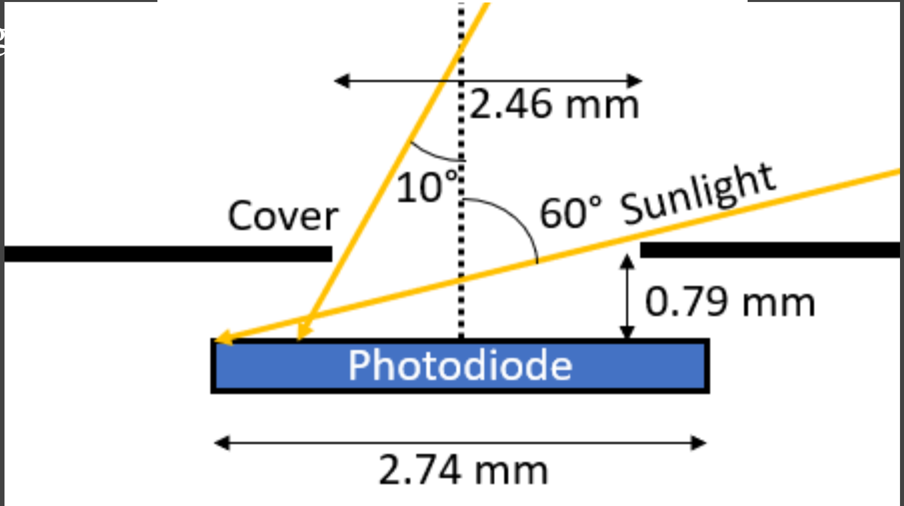
Monte Carlo Sim Details



Sun Knowledge - Accuracy

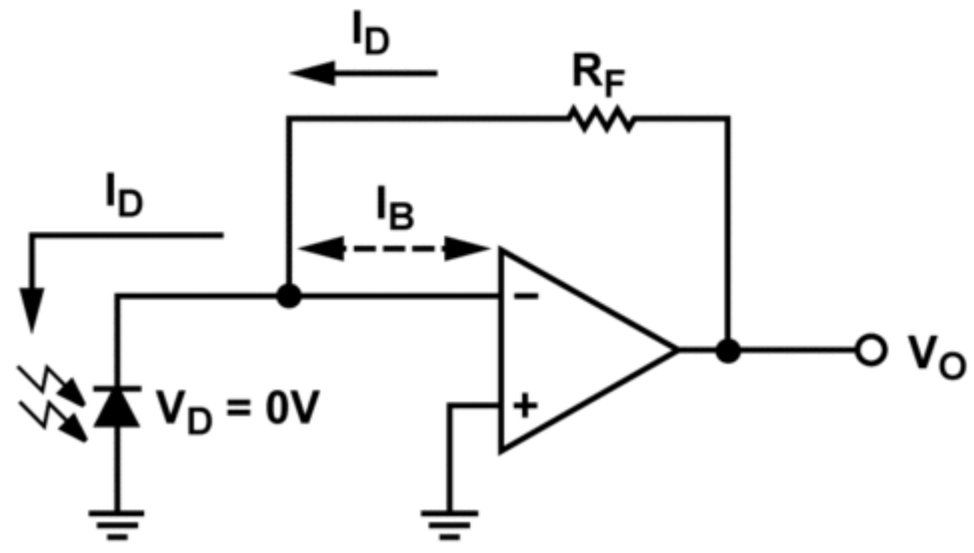
- Photodiode sensitivity must be high enough that the ARS system can determine where the sun is in the sky
- Photodiodes are not sensitive enough on their own
  - From 0° to 30° reduction is less than 99% of output
- Add a cover to restrict incoming sunlig
  - Maximum angle off center: 60°
  - Minimum angle off center: 10°
- Coverage map includes these considerations





Sun Knowledge - Accuracy

Implement a transimpedance amplifier to boost the signal and convert current to voltage.



Vo = Id*Rf

Maximum current of 30 µA

Rf of 200 kΩ

Vo max = 4.8 V

Output voltage is **within microcontroller range**

Sun Knowledge - Accuracy

What is the voltage change for 1° of sun position change?

10° power = 3.43 mW

11° power = 3.41 mW

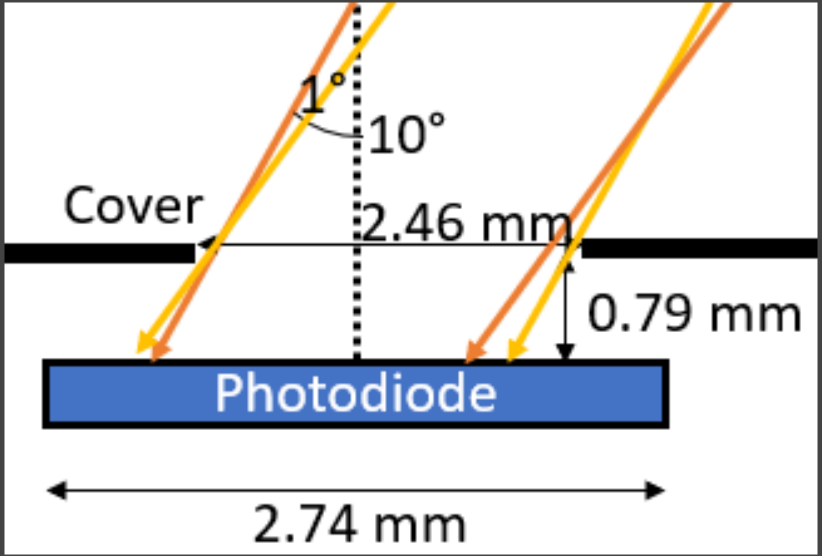
10° current = 30 μA

11° current = 29 μA

10° Voltage = 4.80 V

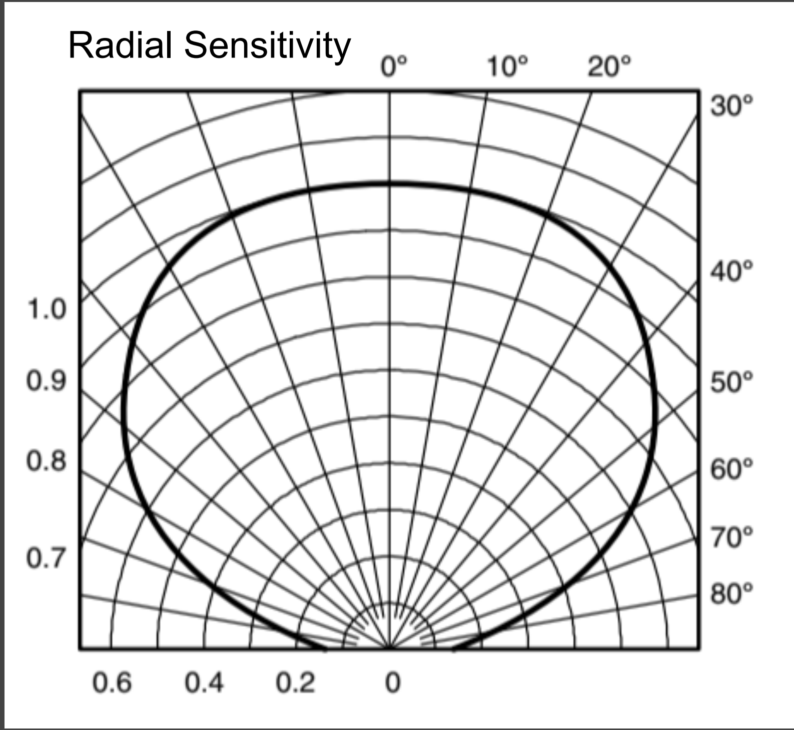
11° Voltage = 4.64 V

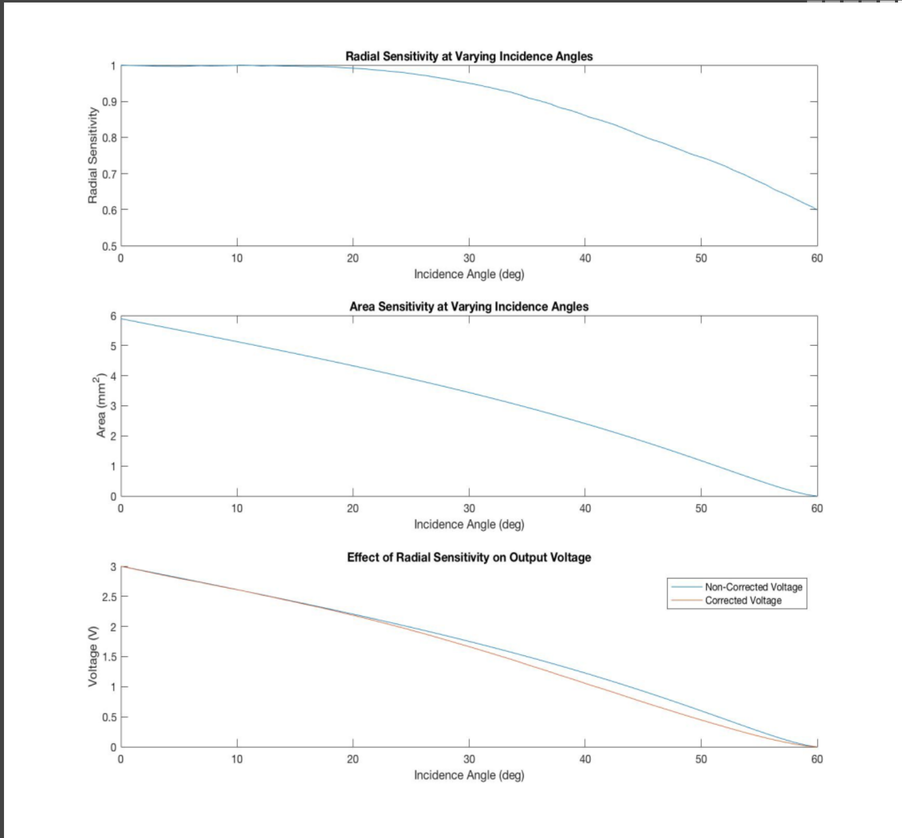
Teensy minimum voltage resolution is 0.0006 V



Sunlight on photodiode is less for 11° (orange) than 10° (yellow)

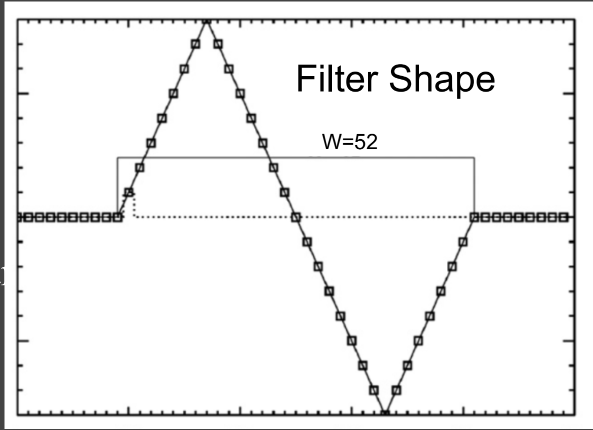
ARS Photodiode Sensitivity





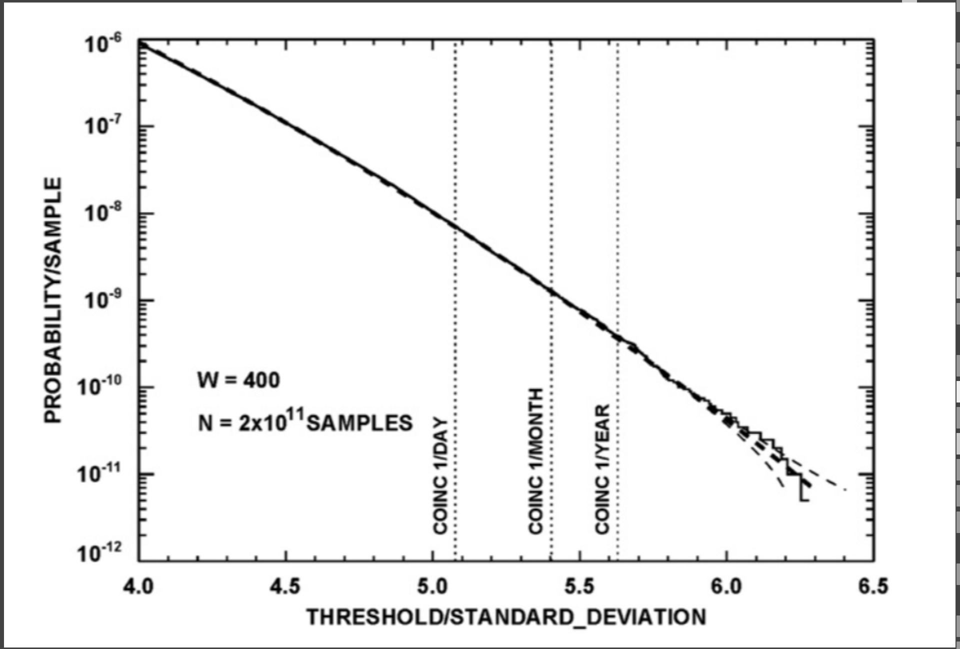
Filter Design

- Width of filter in number of samples not time
  - Must be divisible by 4 to ensure convolution algorithm is applied correctly
- $W = 4Sf/V \approx 52$
  - S is distance between wire planes, f is sampling frequency, and v is velocity of dust particle
- Single vs. Coincidence thresholds
  - Single threshold checks if signal on one wire exceeds 6*maximum expected noise
  - Coincidence compares adjacent wires to see if one exceed 5*noise a[illegible] exceeds 3*noise



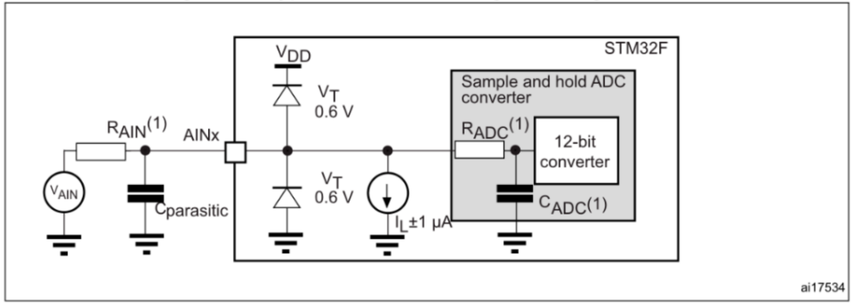
Trigger Rate

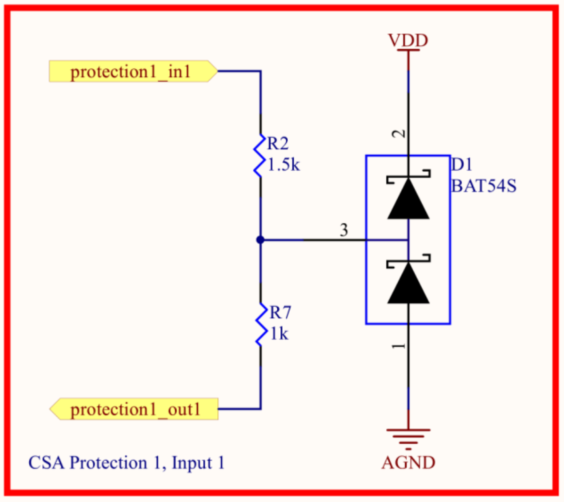
- False Trigger rate dependent on signal to noise ratio
  - QNR of 6.25 results in 1 false trigger per year



Pin Protection

Figure 51. Typical connection diagram using the ADC





Clamping circuit to maintain 0 V < ADC_in < 3.3 V

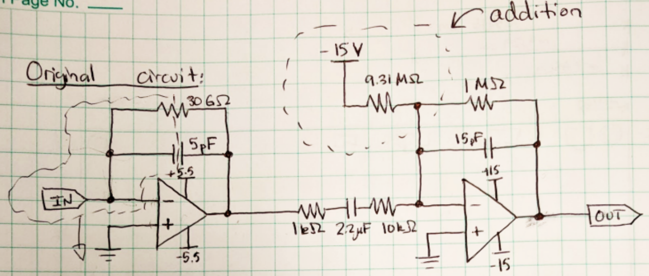
$R_{AIN,max}$ = 50 kΩ >> 2.5 kΩ = R_{AIN} ∴ acceptable input impedance for ADC

Need $V_{Shottky} < V_T$ = 0.6 V so that the MCU diodes don't burn out

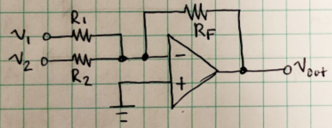
Maximum voltage difference is -15 V to GND. At 15 V, I_{R2} = 10 mA ⇒ $V_{Shottky}$ = 0.4 V

Project No. ______
Book No. ______ TITLE Add DC bias to CSA output
Page No. ___

Original circuit:



Use an adder on the second stage to bias to $\sim + \frac{3.3}{2}$ V $\cong 1.6$ V



$$V_{out} = V_1\left(\frac{-R_F}{R_1}\right) + V_2\left(\frac{-R_F}{R_2}\right)$$

We need $-V_1\left(\frac{-R_F}{R_1}\right) \cong 1.6$ V with $V_1 = -15$ V and $R_F = 1$ MΩ

$$\Rightarrow R_1 \cong \frac{(-15\text{ V})(-1\text{ M}\Omega)}{1.6\text{ V}} \cong 9.375\text{ M}\Omega$$

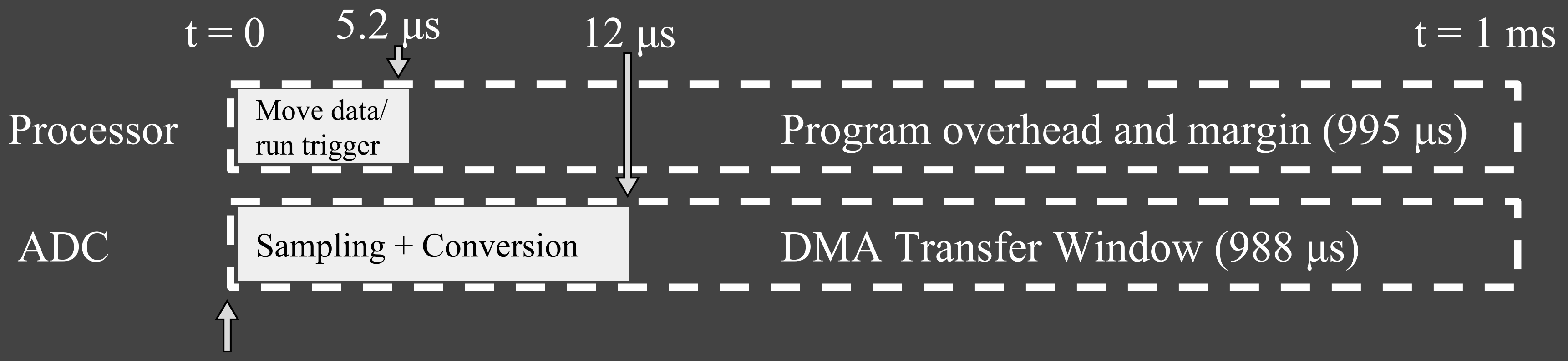
Can find **9.31 MΩ** 0603 SMD 1% in stock

$$\Rightarrow \text{bias} = (-15)\left(\frac{-1\text{ M}\Omega}{9.31\text{ M}\Omega}\right) = 1.61\text{ V bias}$$ ✓

To Page No. ___

Recorded by: | Date 1-26 | Verified by: | Date

Instrument - Real-Time Software



1 kHz Timer Interrupt

Dust event trigger meets real-time deadline

↓

Requirement 6.3.2 satisfied

Move data/run trigger (5.2 µs):

- Move data: 0.6 µs
- Run filter: 4.0 µs
- Thresholds: 0.4 µs

Sampling + conversion (12 µs):

- Sampling: 2.4 µs
- Conversion: 9.6 µs

DTS Wall Drawing